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Air Corridor-Based Optimization of Chinese Airspace and Carbon Emission Analysis

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ABSTRACT

This study theoretically delineates China's current airspace based on airspace management rules, primarily by constructing air corridors to optimize the existing structure, with validation through aviation carbon emissions analysis. First, seven air corridors were delineated based on route clustering analysis, and their significance was further evaluated through carbon emission efficiency comparison. The results show that: 1) the seven corridors are mainly located in central and eastern China, forming a "diamond-shaped three-dimensional structure"; 2) there are significant differences in operational scale among the corridors, with the Harbin-Haikou route being the most active and the Chongqing-Zhuhai route the least; 3) the total carbon emissions from the seven corridors amount to 619,431 tons, with carbon emissions and efficiency positively correlated with aircraft type, cruising time, and operational scale; 4) the flight density within established corridors is higher than before their formation, and they accommodate more flights. This study provides a broad coverage, highlighting the structural characteristics of China's airspace.

Keywords: Air corridor designation; Route clustering; Aviation carbon emissions; Efficiency.

INTRODUCTION

Airspace is the space of air above the surface of the Earth that supports the flight of aircraft and is an important strategic resource for the country (Han 2023). To ensure the safe and orderly flight of a large number of aircraft in the airspace, the civil aviation authorities have authorized "air highways" (Lili 2019), namely airways (Fig. 1). Airways are structured around a linear path connecting individual ground-based navigation facilities, with defined upper and lower limits in terms of both altitude and width. These airway networks are categorized into three tiers: the national hub airway network, the regional trunk airway network, and the regional feeder airway network. Routes refer to a predetermined navigational pathway followed by an aircraft during flight, encompassing both a designated starting point and an endpoint. Routes primarily encompass elements such as aircraft flight direction, starting point, endpoint, and any intermediate stopping points, without a specified width limit. On the other hand, air corridors, as described by Yang *et al.* (2022), are public routes connecting major urban centers (Lili 2012) where common flight paths converge. These corridors are characterized by being unidirectional, non-intersecting, high-speed aerial pathways, with specific restrictions and priorities designed for efficient long-range travel (Ye *et al.* 2019). With characteristics including high traffic volume, efficiency, and density (Yaqing *et al.* 2018), air corridors represent a revolutionary breakthrough in traditional air traffic management practices. Furthermore, they embody a new technological development known as dynamic

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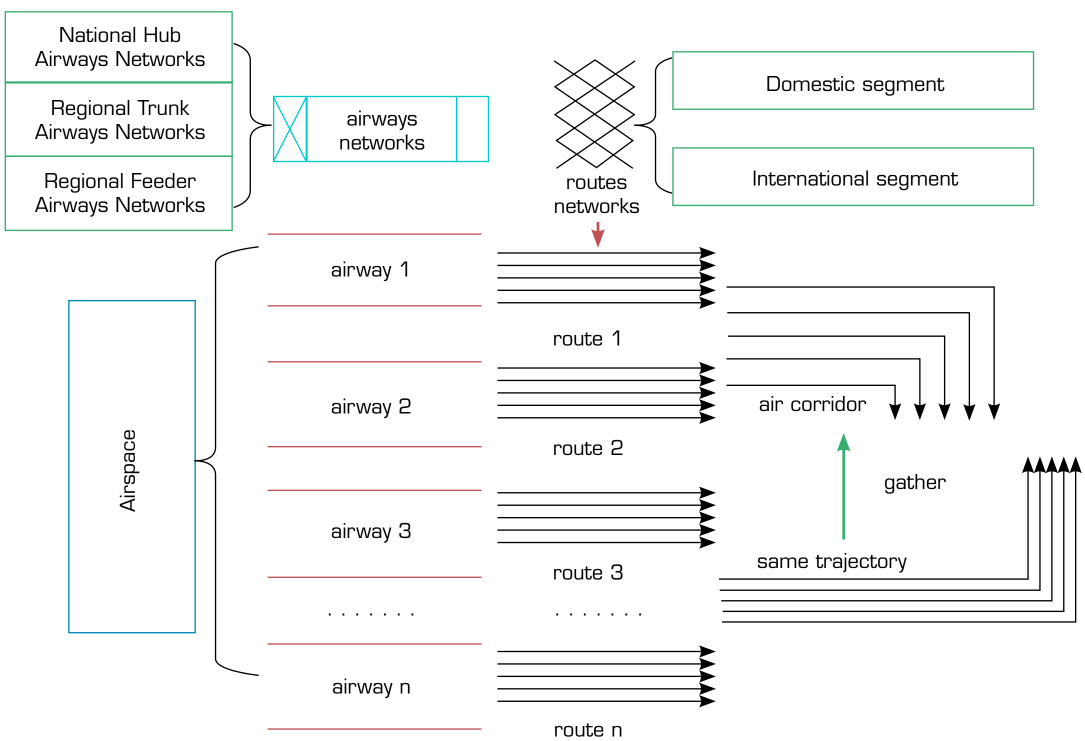
airspace configuration (DAC) (Ye *et al.* 2014). The concept of air corridors has gained significant attention as a new approach to airspace resource utilization (Lili 2012; Xue 2009). These corridors are also referred to as highways-in-the-sky, dynamic multi-track airways (DMA), flow corridors or ribbons, and super sectors (Hoffman and Prete 2008), and are designed to group air routes with similar trajectories within a corridor constrained by distance, reserving sufficient airspace for high-density routes (Sridhar *et al.* 2006). The establishment of air corridors involves determining both the location of the corridor and the participants in the routes. When determining the corridor location, Alipio *et al.* (2003), Hoffman and Prete (2008), and Yousefi and Zadeh (2013) proposed models based on priority sorting and hierarchical setting, velocity vector fields, and velocity vector clustering, as well as flight delay and cancellation evaluation. Through the identification of candidate airspaces for the corridor and the simulation of the its effectiveness, they developed a relatively complete approach for determining corridor locations based on high-load values and high flight volumes along major air routes. In determining the participants in the air routes, Xue (2009) proposed a method for incorporating more routes with fewer additional flight distances, based on the characteristic that many flights have similar flight trajectories. This method is constrained by three conditions: great circle distance, vertical distance at flight entry and exit, and an additional 5% flight distance. Thus, by determining air corridor locations based on high-traffic routes and including relevant flight participants through distance constraints, the establishment of an air corridor can be effectively completed (Yaqing *et al.* 2018).



Source: Elaborated by the authors.

Figure 1. Airspace structure diagram.

As the demand for air transportation continues to grow, the problem of insufficient supply capacity in the airspace system has become more noticeable, it is shown in four main aspects: 1) Regional disparities: an imbalance exists in regional development within China's airspace system. Eastern China boasts a dense network of routes, with approximately 90% of the nation's flight traffic concentrated east of the Beijing-Guangzhou air route. In contrast, the airspace in Western and Central China is relatively sparse. However, regional hubs such as Xi'an, Lanzhou, and Urumqi are quite tight on airspace resources (Chen 2022); 2) The expansion rate of airspace infrastructure lags behind the growth rate of the civil aviation industry (Ligang 2015). From 2000 to 2019, China's total civil aviation transportation turnover experienced a significant average annual growth rate of 12.51%. However, despite this growth, the average annual increase in total domestic route mileage, based on unduplicated distance, stands at only 9.65% (Han 2023). While there has been an increasing transfer of military airspace to civilian use in recent years, it remains insufficient to meet the growing demand; 3) Inadequate route design, with multiple routes converging at one point, making route intersections excessively busy (Yang 2023). There are also problems of uneven distribution of trunk and branch routes, poor straightness of flight paths (increasing the path of aircraft), and cut-off roads. It makes the existing air transportation network unable to match the traffic demand, which also creates congestion, traffic complexity, and safety issues (Wang *et al.* 2021); 4) The overall efficiency of airspace utilization requires enhancement. While there have been strides in fine-tuning airspace management (Chen 2011), challenges persist, including disparities in the spatial and temporal distribution of airspace traffic (Han *et al.* 2019), as well as shortcomings in dynamic airspace allocation (Yaqing *et al.* 2022).

Studies aimed at optimizing airspace utilization through air corridor analysis primarily concentrate on three key dimensions. Firstly, efforts focus on the identification and delineation of air corridors. The demarcation of these corridors serves multiple purposes, including the evaluation of safe flight zones within the corridor, potential collision trajectory assessment, identification of congested segments, and facilitation of space-time utilization analysis along with its associated benefits (Yousefi and Zadeh 2013). Specifically, the process of pinpointing and outlining continuous high-traffic air corridors necessitates consideration of nine crucial aspects: entrance and exit points, geometrical configuration, all-encompassing locations, accountable entities, utilization prerequisites, operational regulations within the corridor, accessibility parameters, restrictions, and the establishment of a comprehensive pipeline network (Hoffman and Prete 2008). Notably, the dynamic corridors intrinsic to the two major long-distance air highways traversing primary traffic conduits in Europe predominantly reside within a 150-nautical-mile radius of the busiest airports. Consequently, the application of the Hough transform methodology to discern clusters or groups of routes exhibiting congruent trajectories aids in the construction of an airborne "pipeline network." Such a network, characterized by its ability to accommodate heightened traffic volumes compared to linear air corridors, enhances airspace utilization efficiency, thereby augmenting its inherent value. Secondly, the optimization problem of air corridors, with the overarching objective of mitigating airspace flight complexity (Tian *et al.* 2019). Air corridor optimization endeavors encompass airspace reconfiguration strategies, notably through the dynamic deployment of air corridors to establish a network of temporally variable flow corridors. Such adaptive configurations confer advantages in terms of average delay, average occupancy, and activation time (Ye *et al.* 2022). This approach not only facilitates the augmentation of airspace capacity but also engenders reductions in airborne delays, thereby fostering enhanced self-separation control capabilities for aircraft. Notably, a significant portion of US scheduled flights, approximately 33%, are concentrated within a mere 10% of origin-destination (O-D) pairs (Ye *et al.* 2014). Therefore, the deployment of mobility corridors based on the frequency of daily operations between city pairs offers great potential for improving airspace utilization efficiency. However, it is imperative to acknowledge that certain flow corridors cater to only a fraction, approximately 4.05%, of the total traffic demand, indicative of a pronounced coverage deficiency. Through the optimization of air corridors, the amalgamation of actual flight trajectories yields discernible benefits, culminating in a noteworthy 20% reduction in aircraft fuel consumption and an average 4% reduction in aircraft flight time without extending the overall flight duration (Takeichi and Abumi 2016). Thirdly, identifying and assessing potential aircraft collision risks os essential (Zhang and Sherry 2015). The nexus between collision risk and airspace capacity necessitates delineation to mitigate flight conflicts within air corridors, consequently enhancing operational throughput and stability. For instance, the implementation of self-separation algorithms integrating route adjustments and speed modifications (Nakamura *et al.* 2014) within strip airspaces characterized by constrained widths enables conflict-free aircraft operations within narrow air corridors.

The study of airspace optimization and carbon emission analysis has become a central focus in air traffic management and sustainability research. To ensure both safety and efficiency in air operations, several approaches have been proposed to enhance airspace utilization. Babinski *et al.* (2024) investigated air traffic safety management in Brazilian airspace using a matrix-based approach to assess perceived safety levels. This study highlights the importance of structuring airspace in a way that optimizes both safety and operational efficiency, which aligns directly with the goals of this work to optimize Chinese airspace. Additionally, Xiang *et al.* (2023) analyzed airspace capacity improvements and optimization, providing an important foundation for incorporating carbon emission reduction strategies into optimized air corridors. Their work emphasizes the relevance of efficient airspace management to minimize environmental impacts, a theme that is central to this study. To regulate air traffic flow by optimizing the airspace structure to match the flow with the capacity of the airspace, the establishment of air corridors is an effective way to form a regular and systematic airspace network structure. In addition, since the allocation of airspace resources has a direct impact on the operational efficiency of air traffic flows, it also has a direct impact on aviation carbon emission results. Therefore, this study attempts to study to analyze total aviation carbon emissions and the efficiency of the corridors based on improvements to the existing methodology for delineating air corridors in China's airspace. First of all, based on the researched route data, clustering and extraction of routes are carried out to identify air corridors and their route participants. Then, the high-traffic air corridors are determined to analyze the structure of China's existing route network and designate air corridors. Second, the aviation carbon emissions of each corridor are measured and characterized based on indicators such as the number of flights, aircraft type, and aircraft cruise time of each route participant within the delineated air corridors. Finally, the carbon emission efficiency of the seven air corridors is compared and analyzed to justify the existence of air corridors. This study attempts to explore airspace optimization from the perspective of air corridor delineation and to verify the results of delineation for carbon emission reduction. Furthermore, breaking through the limitations of the previous airport-centered aviation point carbon emission research, and actively expand the research perspective on aviation carbon emission. This will provide a theoretical reference for the balanced and rapid development of the national civil aviation industry, enrich the theoretical content of aviation carbon emission research, and assist in promotion of China's 14th Five-Year Plan for green aviation development.

As global climate change becomes an increasingly urgent issue, reducing greenhouse gas emissions has become a critical challenge that governments and businesses worldwide must address. The aviation industry, as one of the significant sources of global carbon emissions, faces tremendous pressure to mitigate its impact. Under the United Nations Framework Convention on Climate Change (*UNFCCC*), the aviation sector's emission reduction targets have been incorporated into global climate action agendas, with a particular emphasis on reducing aviation carbon emissions in Sustainable Development Goal 13. At the same time, the aviation industry is also an energy-intensive sector, where fuel consumption not only affects operational costs but also has a profound impact on global energy structures and sustainable development. Therefore, optimizing airspace management and designing aviation corridors to improve flight fuel efficiency has become a crucial method for enhancing the aviation industry's energy efficiency and advancing Sustainable Development Goal 7. This research focuses on optimizing China's airspace, aiming to explore how to reduce redundant flight routes, lower fuel consumption during flights, and subsequently decrease carbon emissions in the aviation sector through an air corridor-based aviation optimization model. As one of the largest aviation markets in the world, China accounts for a significant portion of global aviation-related carbon emissions. Therefore, by optimizing China's airspace layout and improving flight fuel efficiency and air corridor fluidity, this study can not only reduce operational costs for airlines in the short term but also make a positive contribution to reducing energy consumption and greenhouse gas emissions both in China and globally. This research not only provides scientific support for Sustainable Development Goal 13 but also offers practical pathways to achieve Sustainable Development Goal 7 by promoting energy-efficient practices in the aviation industry.

METHODOLOGY

Data sources

The route data used in this paper is mainly based on the research obtained from the FlightAware Big Data platform (https://map.variflight.com) and the FlightAware website (https://zh.flightware.com). Specifically, route data (excluding Hong Kong, Macao, and Taiwan flights, cargo flights, and international flights) for all airports in China were collected over 4 weeks from January 1st to 28, 2023, taking into account the cyclical characteristics of flight schedules of air carriers. The data includes fields such as the number of flights, aircraft type, operating carrier, connecting city, departure time, arrival time, etc. During data processing, shared flights were deleted, and direct flight routes were combined with stopover routes, such as decomposing the Dalian-Tianjin-Xining routes into two routes, Dalian-Tianjin and Tianjin-Xining. This was collated to get 5,224 one-way routes with 277,069 flights. For geographic location identification, the coordinate data (latitude and longitude) of all routes involving airports are picked up and entered into the ArcGIS10.4 software with the help of the Baidu map pickup coordinate system as a tool. Furthermore, with the help of ArcGIS 10.4 software, the latitude and longitude coordinate data of the vertical position of the aircraft entering and exiting the air corridor from each airfield point was identified for the distance calculations. When measuring the carbon emission efficiency of aircraft in air corridors, the input-output indicators were selected according to the principles of comprehensiveness, comparability, indirectness, and accessibility, and the carbon emission efficiency was evaluated in the landing and take-off (LTO) and climb, cruise, and descent (CCD) phases, respectively. The input indicators included the number of air corridor route participants, the average flight distance of route participants (km), and the average cruise time of aircraft (s); the desired output indicators included the number of air corridor flights (sorties), while the undesired output indicators included the total amount of carbon emissions from the air corridor (t).

Research methodology

K-means clustering method

This study introduces the K-means clustering method for route clustering analysis. Each route is treated as a data sample. Utilizing the K-means clustering algorithm, all routes are grouped into K different route clusters (ROC) based on similar route directions and smaller Euclidean distances between routes. This aids in identifying route features and their relationships. Referring to previous research on the structure of domestic scholars' route networks (Ligang 2015; Yaqing *et al.* 2018), the value of K was determined to be 16 based on the rule of thumb. The K-means clustering method was employed to assign original route samples to K group classes based on the similarity of Euclidean distances between them. This ensured that each sample was closest to the center of its respective group class, resulting in the formation of K groups of ROC. Each group of ROC possesses an ROC centerline.

Air corridor establishment method

The width of air corridors is typically designed to be 7 km (Zhang and Sherry 2015). Currently, two main delineation steps have been proposed by relevant scholars: 1) covering flights with 99.99% of their flight time within 133 km of the corridor centerline and 2) identifying the two-dimensional location of the corridor by combining the Hough transform with a genetic algorithm. Routes with an additional flight distance ratio of ≤ 5% are identified as route participants in the air corridor (Xue 2009). This study enhances the air corridor delineation method from existing literature (Yaqing *et al.* 2018), taking into account the characteristics of the research subjects. To encompass more route participants, routes with a distance-to-extra-flight ratio (d_{extra}) ≤ 10% are considered as route participants in the corridor.

Initially, ROC centerlines of longer than 600 km were extracted using the *K*-means clustering method to determine the air corridor locations. Then, the additional flight distance for each route was calculated based on great-circle flight trajectory distances for aircraft entering and exiting the air corridor vertically at an airport point, aircraft flying in the air corridor, and routes before the delineation of the air corridor. Routes with d_{extra} ≤ 10% were included in the air corridor. The air corridor was named according to the most frequented routes within the ROC. It extended from the centerline of the initially selected ROC to the last airport with routes joining the air corridor, following a great circle trajectory to complete the air corridor establishment. Then, the additional flight distance for each route (d_{extra}):

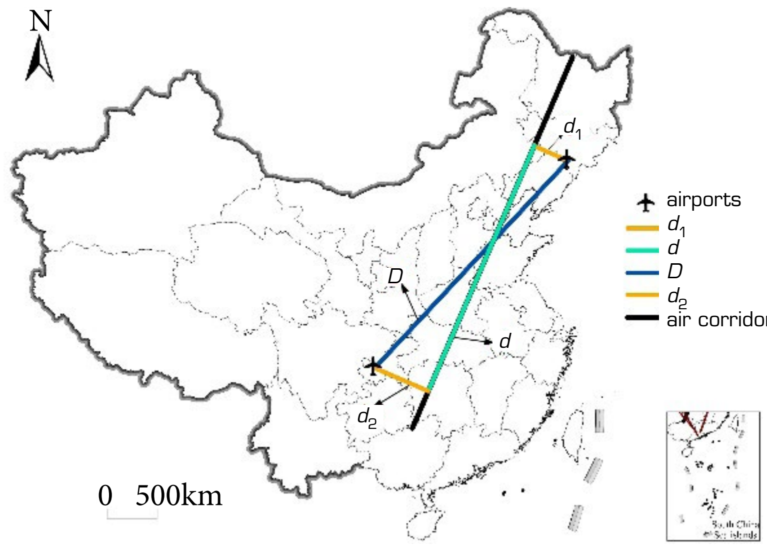
$$d_{\text{extra}} = \frac{(d_1 + d_2 + d) - D}{D} \times 100\% \tag{1}$$

where d_{extra} represents the extra flight distance ratio, d_1 and d_2 represent the great-circle flight trajectory distances for flights entering and exiting the air corridor vertically, respectively, d represents the great-circle flight trajectory distance on the air corridor, and D represents the great-circle flight trajectory distance before the air corridor is delineated.

Taking D as an example, the calculation formula is as follows:

$$D = R * \arccos\left(\cos(latA)\cos(latB)\cos(longB - longA) + \sin(latA)\sin(latB)\right) \tag{2}$$

where R is the radius of the earth (6,371 km) $latA$, $longA$ and $latB$, and $longB$ are the latitude and longitude for points A and B, respectively (Fig. 2), the latitudinal and longitudinal coordinates of the vertical positions of entering and exiting the air corridor, respectively, and d_1, d_2, and d are computed in the same way as D.



Source: Elaborated by the authors.

Figure 2. Schematic diagram of d, d_1, d_2, and D flight paths and air corridors.

Aircraft carbon emissions measurement method for different flight phases

The International Civil Aviation Organization (ICAO) divides the entire flight process of an aircraft into the LTO and CCD phases. Previous studies have found that aviation fuel consumption and CO_2 emissions primarily occur below 1 km and between 8-12 km (Jun 2022). This paper calculates carbon emissions during the LTO and CCD phases of flights based on the ICAO standard emission calculation model and the carbon emission accounting model for the CCD phase.

- LTO phase carbon emissions calculation methodology

Carbon emissions from aircraft flying through air corridors are measured based on aircraft engine type data using a "bottom-up" methodology based on operational data established by ICAO. The ICAO has calibrated the duration of operation for each phase of the aircraft LTO phase as follows: take-off (0.7 min), climb (2.2 min), approach (4 min), and taxi (26 min) (Lu *et al.* 2018), with the following equations:

$$F_i = \sum_j T_{ij} \cdot R_{ij} \cdot N_i \tag{3}$$

$$E_{LTO} = \sum_i F_i \cdot I \cdot n_i \tag{4}$$

where i is the aircraft type, j is the four different phases of LTO operation, F_i is the fuel consumption (kg) of a category i aircraft during LTO, R_{ij} is the fuel consumption rate ($kg{\cdot}s$) of a engine of aircraft of category i in phase j, N_i is the number of engines of aircraft of category I, T_{ij} is the operating time of aircraft of category i in phase j (s), E_{LTO} is the carbon emission of aircraft in LTO phase (kg), I is the fuel carbon emission coefficient, which is a constant of 3.15 (kg/kg) (Liu *et al.* 2019), and n_i is the LTO of aircraft of category i cycle total number (min).

- CCD phase carbon emission calculation methodology

The aircraft's engine settings vary at each phase of flight. The ICAO Engine Emissions Database Attachment 16 provides specific thrust parameters, with engine thrust values of 100, 85, 65, 30, and 7% for take-off, climb, cruise, approach, and taxi phases, respectively. By fitting a binomial equation to the thrust-specific fuel consumption data and performing interpolation, the fuel flow rate for aircraft engines at 65% thrust during each LTO phase can be derived. This enables the calculation of carbon emissions during the CCD phase of an aircraft.

The formula is as follows:

$$T_{\mathrm{CCD}} = T_{\mathrm{TOTAL}} - T_{\mathrm{LTO}} \tag{5}$$

$$E_{\mathrm{CCD}} = N_{\mathrm{CCD}} F_{\mathrm{CCD}} I \tag{6}$$

where, T_{CCD}, T_{TOTAL}, and T_{LTO} are the operating time (s) of the CCD phase, full flight process, and LTO phase of an aircraft, respectively, E_{CCD} is the carbon emission (kg) of CCD phase of an aircraft, N is the number of engines of an aircraft, F_{CCD} is the fuel flow rate of an engine of an aircraft in the CCD phase (kg·s), and I is the fuel carbon emission coefficient, which is a constant 3.15 (kg/kg) (Liu *et al.* 2019).

Aviation CO_2 emission factors

Aviation CO_2 emission factors represent the CO_2 emissions per unit flight kilometer of an aircraft type (Lyu *et al.* 2022) and serve as an important criterion for determining carbon emissions. The formula is as follows:

$$X_i = (E_{i/LTO} + E_{i/CCD})/L \tag{7}$$

where X_i is the aviation CO_2 emission factor (kg·km), $E_{i/LTO}$ and $E_{i/CCD}$ are the carbon emissions in the LTO and CCD phases of aircraft of category i, respectively, and L is the flight mileage of the aircraft (km).

SBM model of super-efficiency based on undesired outputs

In traditional efficiency evaluation models, usually only desired outputs are considered, such as corporate profits or product quantities. However, in the actual production process, there will also be undesired outputs, such as pollutant emissions, energy waste, etc. The super-efficiency slacks-based measure (SBM) model based on undesired outputs is designed to evaluate the efficiency of decision-making units (DMUs) more comprehensively and accurately, especially in the presence of undesired outputs.

It is an efficiency evaluation model based on slack variables, which is non-radial and non-angular. It measures efficiency by taking into account the slack variables for inputs, desired outputs, and undesired outputs. Compared with the traditional data envelopment analysis (DEA) model, the SBM model can handle the non-proportional changes in inputs and outputs as well as the problem of undesired outputs more effectively.

Specifically, in the super-efficiency SBM model based on undesired outputs, the concept of input is as follows: input refers to the resources required in the production or service process, and these resources usually have an impact on outputs – the input indicators used in this paper are the number of air routes in the corridor, the flight volume, and the average distance of route participants; desired output: this is the output that is expected to be increased as much as possible in the model, representing positive results – the desired output indicator used in this paper is the average cruising time of the air routes in the corridor. undesired output: this is the result that is not desired or is hoped to be minimized as much as possible in the production process, usually an environmental burden, such as carbon emissions, exhaust gas, etc. – the undesired output indicator used in this paper is the carbon emissions of the corridor.

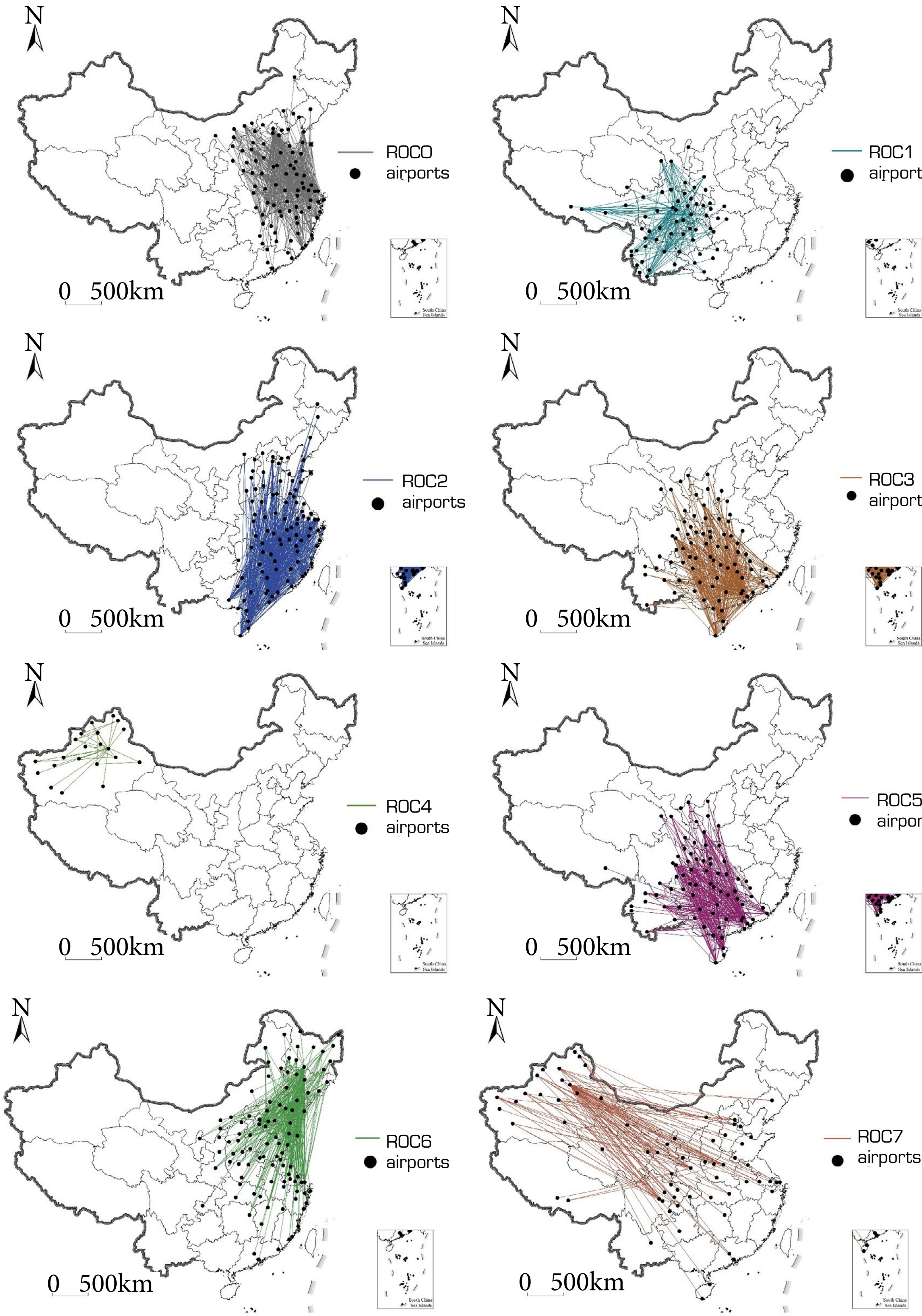
The non-radial slacks-based variable super-efficiency SBM model is selected to measure the efficiency of aircraft carbon emissions in air corridors. It incorporates slack variables in the objective function, which effectively solves the problem of slackness of input and output variables when air corridor aviation carbon emissions are used as an undesired output indicator for efficiency evaluation (Tone 2001).

RESULTS

Results of air corridor establishment

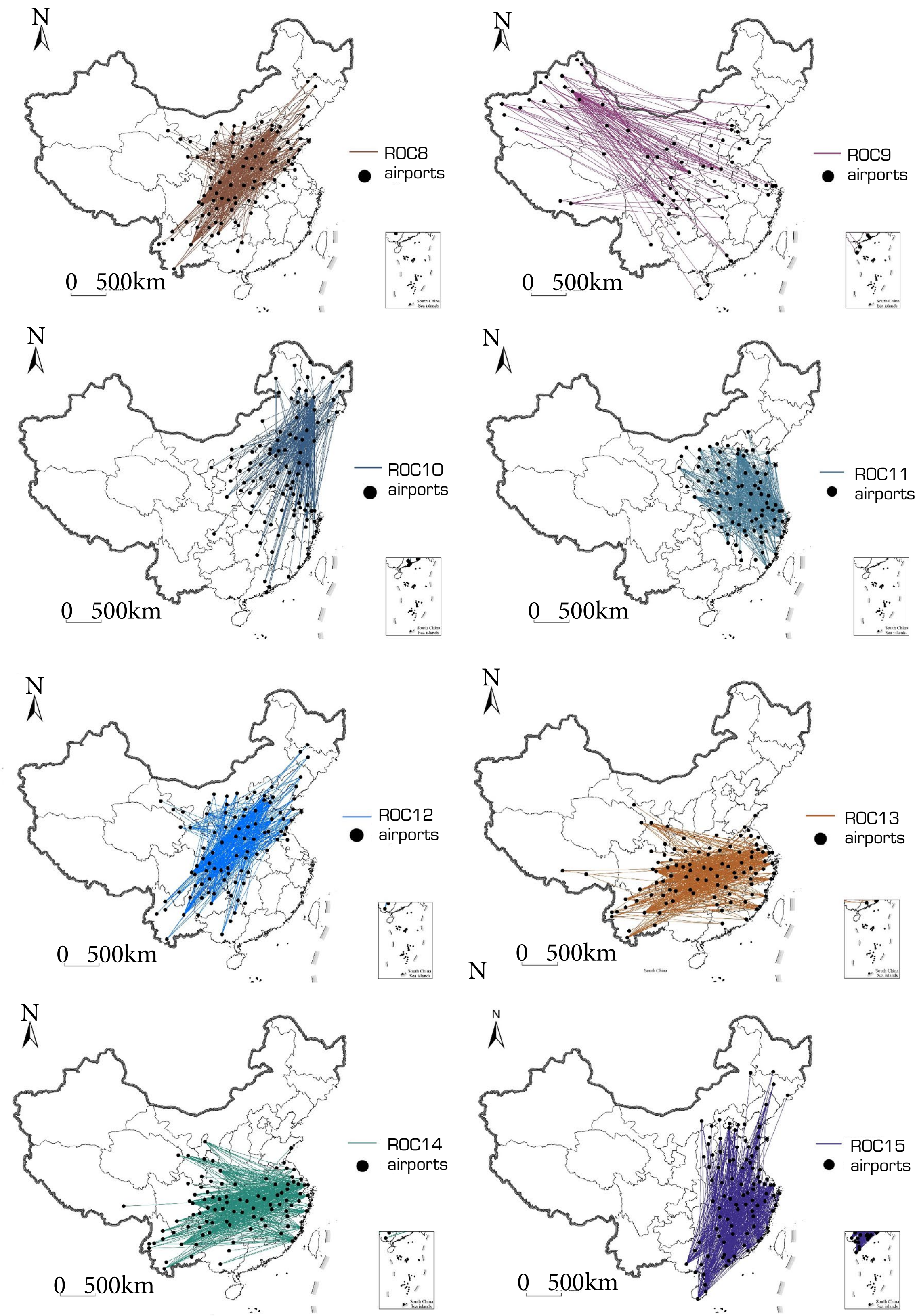
Route cluster aggregate results

China's route network exhibits a diamond-shaped three-dimensional structure. Utilizing the K-means algorithm, 16 groups of ROC were identified, numbered from 0 to 15 (Figs. 3 and 4 and Table 1). Air corridors were delineated and located based on the centerlines of these 16 ROC groups. As the centerline length of ROC 1 and 4 is shorter than 600 km, they were not considered for reference. Upon examining the distribution characteristics of the remaining 14 ROC groups and their centerlines, a noteworthy observation emerged: the centerlines of ROC roughly coincide with the location of other ROC. Consequently, the centerlines of overlapping ROC merged to form a diamond-shaped structure (Fig. 5).



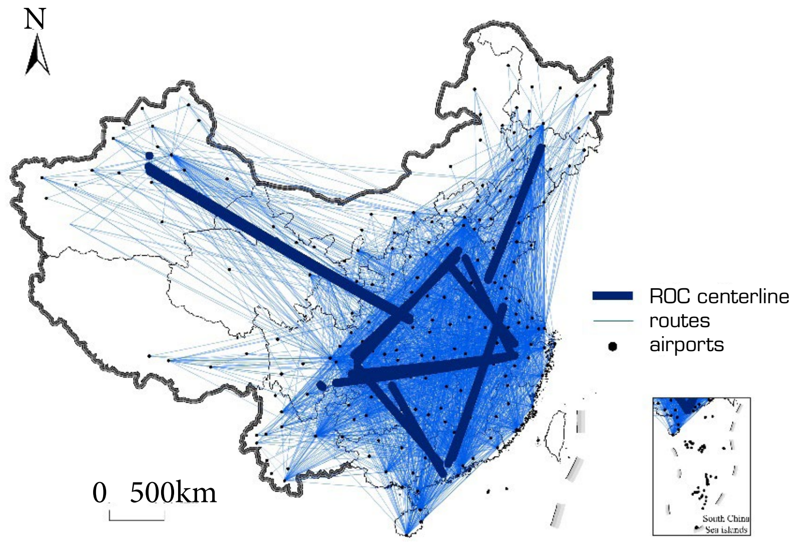
Source: Elaborated by the authors.

Figure 3. ROC 0-7 and their including airports.



Source: Elaborated by the authors.

Figure 4. ROC 8-15 and their including airports.



Source: Elaborated by the authors.

Figure 5. ROC centerline diamond-shape structures.

Table 1. Length of each ROC centerline and the number of routes in the ROC.

ROC groups	Distance of ROC centerline/km	Number of routes	Number of flights
ROC0	846	442	20,287
ROC1	28	335	14,975
ROC2	1140	526	34,449
ROC3	785	368	19,300
ROC4	3	58	2,658
ROC5	977	282	15,483
ROC6	1062	315	15,669
ROC7	2430	107	5,270
ROC8	1119	350	13,975
ROC9	2410	116	5,465
ROC10	1147	289	14,951
ROC11	829	443	4,884
ROC12	1190	325	13,916
ROC13	1328	368	22,416
ROC14	1277	397	24,869
ROC15	1236	502	33819

Source: Elaborated by the authors.

Table 2 shows the centerlines of the five groups of ROC that form the diamond-shaped structure and their connecting areas.

Table 2. The centerline of the five groups of ROC that form the diamond-shaped structure and their connecting regions.

ROC centerline group	Connect regions
ROC0 & ROC11	Beijing-Tianjin-Hebei Airport Cluster-Yangtze Delta Airport Cluster
ROC2 & ROC 15	Yangtze Delta Airport Cluster-Guangdong-Hong Kong-Macao Greater Bay Area Airport Cluster
ROC3 & ROC 12	Beijing-Tianjin-Hebei Airport Cluster-Chengdu-Chongqing Airport Cluster
ROC5 & ROC 8	Chengdu-Chongqing Airport Cluster-Guangdong-Hong Kong-Macau Airport Cluster
ROC13 & ROC14	Yangtze Delta Airport Cluster-Chengdu-Chongqing Airport Cluster

Source: Elaborated by the authors.

The four vertices of the diamond are situated in Beijing-Tianjin-Hebei, the Yangtze River Delta, the Guangdong-Hong Kong-Macau Greater Bay Area, and Chengdu-Chongqing. This indicates that airports within and between these four major urban areas in China experience more intense air traffic and serve as key clusters and connecting corridors within the domestic aviation network. The results are consistent with studies that have been done (Yang *et al.* 2022). China's route network covers about half of the country's cities in terms of routes distribution. The framework of a broad spatial connectivity network was essentially established on a national scale, and the main lines of the network consist primarily of long-distance lines connecting different regional economic hubs.

Table 3 shows the coordinates and connection locations of the centerline vertices of the remaining two sets of ROC. The two ROC effectively connect the above rhomboid structure to northwest and northeast China, forming a trans-regional air trunk community. This will promote the balanced development of the aviation network layout in China. Additionally, the project will significantly enhance inter-regional economic and trade exchanges, supporting the advancement of national strategies such as the Belt and Road Initiative and the revitalization of the northeastern region of the country.

Table 3. The coordinates of the centerline of the outer ROC of the diamond-shaped structure and its connecting region.

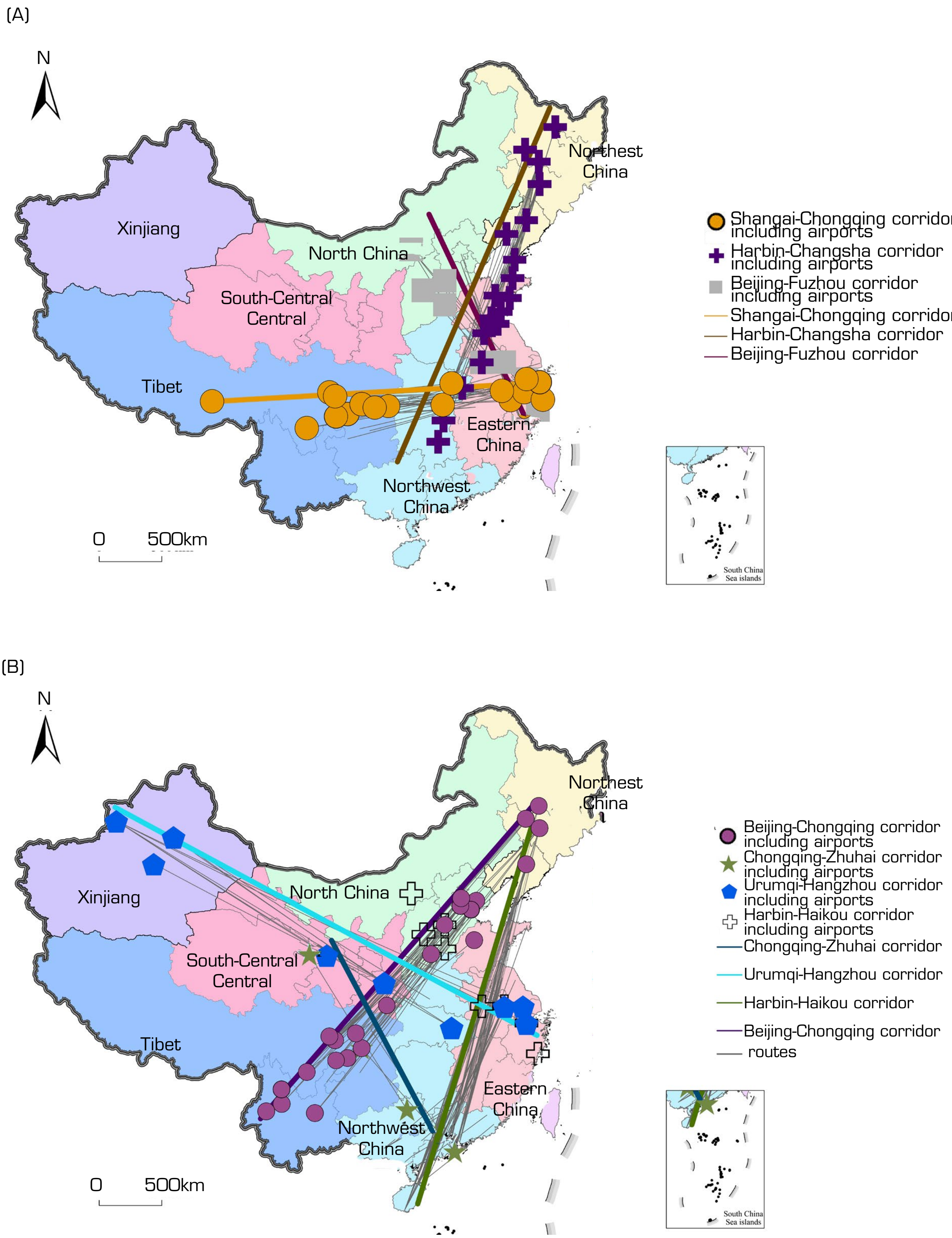
<table>
<tr><th>ROC centerline</th><th>Vertex coordinates 1</th><th>Vertex coordinates 2</th><th>Direction</th><th>Connect regions</th><th>Connect regions</th></tr>
<tr><td>ROC7</td><td>(85.49E, 42.67N)</td><td>(110.67E, 33.09N)</td><td rowspan="2">Northwest-southeast</td><td rowspan="2">Xinjiang Autonomous Region</td><td rowspan="2">Shaanxi province</td></tr>
<tr><td>ROC9</td><td>(110.68E, 33.28N)</td><td>(85.74E, 42.37N)</td></tr>
<tr><td>ROC6</td><td>(124.93E, 43.51N)</td><td>(117.85E, 35.35N)</td><td rowspan="2">Northeast-southwest</td><td rowspan="2">Heilongjiang province</td><td rowspan="2">Shandong province</td></tr>
<tr><td>ROC10</td><td>(119.97E, 35.60N)</td><td>(125.31E, 43.93N)</td></tr>
</table>

Source: Elaborated by the authors.

Results of air corridor establishment

Seven air corridors have been delineated within China's airspace based on the research route data, primarily located in the area to the east of the Hu Line (Fig. 6). The longest distance centerline was selected from the centerlines of the two overlapping ROC and the short line routes in the corridor were merged with the long line routes. Finally, seven ROC mid-lines, ROC0, ROC5, ROC7, ROC10, ROC12, ROC13, and ROC15, were identified as the basis for air corridor delineation and the approximate locations of the seven air corridors were determined. Afterward, extending the initial ROC centerline positions along great circle trajectories towards both ends until reaching the last airport with a route incorporated into the air corridor constitutes the establishment of the air corridor. It shall be named after the route within the ROC with the highest traffic volume.

The seven designated air corridors include the Harbin-Changsha, Harbin-Haikou, and Beijing-Chongqing corridors in the Northeast-Southwest, the Chongqing-Zhuhai, Urumqi-Hangzhou, and Beijing-Fuzhou corridors in the Northwest-Southeast, and the Shanghai-Chongqing corridor in the East-West. The Harbin-Changsha corridor is the highest frequency corridor among the seven corridors, averaging 131 flights per routes (Table 4), and Chongqing-Zhuhai is the lowest frequency corridor, averaging 39 flights per routes. The Urumqi-Hangzhou corridor is the longest average flying distance of the seven corridors, and the Chongqing-Zhuhai corridor is the shortest average flying distance.



Source: Elaborated by the authors.

Figure 6. Location of the seven air corridors and their including airports.

Table 4. List of airports included in each air corridor.

Air corridors	Number of flights	Average number of flights per air routes	Includes airports
Chongqing-Zhuhai	352	39	BHY, DZH, KOW, CAN, KWL, HAK, SWA, JGS, MXZ, NNG, HSC, XNN, ZHA, CKG, ZUH
Beijing-Fuzhou	749	62	PKX, PEK, FOC, HDG, HGH, HFE, HET, TNA, NKG, JUZ, SJW, TYN, WNZ, XUZ
Urumqi-Hangzhou	630	63	HGH, KRL, LHW, NKG, NNY, SHF, WUX, URC, WUH, XIY, YIN
Shanghai-Chongqing	1,888	76	BFJ, CTU, TFU, HGH, TXN, LZY, LZO, KHN, NGB JIQ, JUZ, PVG, HYN, WUH, XIC, YBP, YIW, YYA, CKG, CQW, WMT, ZYI
Harbin-Changsha	3,676	131	DLC, XUZ, LYG, JNZ, SHE, CGQ, DQA, EHU, YNT LYI, WEF, HRB, WUH, HNY, HFE, RIZ, TAO, LDS
Beijing-Chongqing	2,849	73	AKA, BSD, PKX, CTU, TFU, DZH, DLU, HRB, HDG TNA, KMG, LJG, LZO, NAO, SHE, WDS, SJW, YSQ TVS, TSN, XIC, YBP, CGQ, CIH, ZAT, CKG, WMT
Harbin-Haikou	6,041	93	AQG, JUH, DLC, FUO, KOW, CAN, HRB, HAK, HFE HIA, SWA, JGS, JDZ, LYG, LYI, LCX, KHN, NKG, TAO, BAR, JJN, RIZ, SYX, HSC, SZX, SHE, WEH WEF, WHA, XUZ, YNT, YNZ, CGQ, CSX, ZUH
Total	16,185	-	-

Source: Elaborated by the authors.

Air corridor structure and element characterization

The seven designated air corridors exhibit a "diamond-shaped three-dimensional structure," with the Beijing-Tianjin-Hebei Airport Cluster, Yangtze River Delta Airport Cluster, Guangdong-Hong Kong-Macao Greater Bay Area Airport Cluster, and Chengdu-Chongqing Airport Cluster forming the apex. Among them, the edges that form the diamond-shaped structure are Beijing-Fuzhou, Beijing-Chongqing, Chongqing-Zhuhai, and Harbin-Haikou, with Shanghai-Chongqing serving as its central line. The five corridors are all located east and south of the Hu Line, encompassing 158 routes and 12,706 flights, which account for 80.6% of the total routes and 78.5% of the total flights among the seven corridors. This indicates that China's aviation network layout is closely tied to population and urban distribution, reflecting the national air traffic control capability of core airport clusters (Wang and Fengjun 2019). However, in terms of airport coverage, the Western region boasts the highest number of airports, followed by the Eastern, Central, and Northeastern regions of China. This can largely be attributed to the remarkable growth in airport numbers in the West from 2000 to 2019. According to Shuyan *et al.* (2023), the number of airports in these regions experienced growth rates of 118.2, 19.6, 50, and 107.7%, respectively. Specifically, the pace of airport construction in the West accelerated significantly after 2005, resulting in more than 50% of the country's airports being located in this region by 2019. This surge in airport infrastructure not only enhances connectivity within the Western region but also strengthens ties between the West and other regions, thereby further promoting the development of the regional aviation industry. Urumqi Diwopu Airport, playing a central role in the Western region, hosts a multitude of linear airports offering a diverse array of air services. The region has fostered a dispersed aviation layout radiating outward from a single core, thereby facilitating the establishment of the Urumqi-Hangzhou air corridor.

The seven corridors exhibit variations in the number of airports they encompass (Table 2). The Beijing-Fuzhou corridor connects 14 airports spanning North and East China. The Chongqing-Zhuhai corridor links 15 airports across the Southwest, Northwest, Central-South, and East China regions. The Urumqi-Hangzhou corridor links 12 airports in Xinjiang, the Northwest, South-Central, and East China regions. The Harbin-Changsha corridor connects 20 airports in the Northeast, East China, and South-Central regions. The Beijing-Chongqing corridor interconnects 28 airports across the Northeast, North, Northwest, and Southwest regions. The Shanghai-Chongqing corridor serves 23 airports in the Southwest, Central-South, and East China. Finally, the Harbin-Haikou corridor interlinks 35 airports in the Northeast, North, East, and South-Central regions. Notably, the Harbin-Haikou corridor boasts the highest number of airports and flights among the corridors, traversing much of Eastern China.

The seven air corridors exhibit significant disparities in the number of participating routes. Specifically, the Harbin-Haikou corridor boasts the highest number of participating routes, with 65 routes (Tables 3 and 4), and the largest total flight volume, totaling 6,041 flights. Within this corridor, there are 12 routes with flight volumes exceeding 100 flights (bi-directional), namely HRB-HAK, CAN-SHE, CAN-YNT, CAN-TAO, HAK-NNG, SYX-SHE, SYX-NNG, SZX-SHE, SZX-TAO, SHE-ZUH, CGQ-ZUH, and CGQ-SYX. Among these, the Harbin-Haikou corridor stands out as the corridor with the widest latitude span within Chinese airspace. Its participants primarily operate medium-haul routes, with an average distance of 1,828 km. Long-haul routes are favored by routes due to their higher profitability (Shuyan *et al.* 2023), and air travel is increasingly preferred by passengers due to its high efficiency and minimal susceptibility to ground conditions. With the growing prevalence of the "migratory bird" retirement model and the exacerbation of aging populations in Northeast China, the proportion of individuals aged 60 and above in the three Northeastern provinces exceeded 20% in 2021 (National Bureau of Statistics of China 2021). Consequently, more elderly individuals are opting for retirement destinations with superior climates and environments, such as Sanya and Haikou in Hainan, Guilin and Nanning in Guangxi, and Zhuhai and Shenzhen in Guangdong (IIR-SJTU 2022). Additionally, the organization of regional tourism events influences aviation transport layouts (Wang and Jingjuan 2016). For instance, in January 2023, the Harbin International Ice and Snow Festival attracted 23,394 million visitors, resulting in an 18.2% increase in total flight operations and a 49.4% increase in completed passenger throughput at Harbin Taiping International Airport compared to the previous year (Shuyan *et al.* 2023).

The Chongqing-Zhuhai corridor has the fewest participating routes and the lowest flight volume. Among these, only the Chongqing-Zhuhai route has a flight volume exceeding 100 flights (bi-directional), while the flight volumes of other routes are all less than 50 flights. This is primarily due to the corridor's participants operating short-haul routes, with an average length of 963 km, such as BHY-CAN (485 km), SWA-HAK (857 km), MXZ-ZHA (763 km), KOW-NNG (941 km), NNG-HSC (679 km), etc. The expansion of the high-speed rail network has exerted pressure on the aviation network, with high-speed rail gradually becoming the dominant mode of transportation within a 1,500 km range (Yang *et al.* 2022). Consequently, passengers have a greater number of cost-effective alternative transportation options such as high-speed rail, trains, and buses, leading to a lower frequency of air transportation for short-distance journeys.

After the establishment, the flight density of individual routes within the corridors increased, accommodating more flights than before the establishment. The average flight density of single routes within the Harbin-Haikou corridor increased by 1.44% after the establishment, with an average increase of 17 flights per route. Similarly, the Harbin-Changsha corridor saw increases of 3.40% and 80 flights respectively. The Beijing-Chongqing corridor witnessed increases of 2.41% and 30 flights respectively. The Shanghai-Chongqing corridor saw an increase of 2.90%. The Beijing-Fuzhou corridor saw increases of 8.22% and 17 flights respectively. The Urumqi-Hangzhou corridor saw increases of 9.55% and 15 flights respectively. The Chongqing-Zhuhai corridor saw the highest increase in flight density after the establishment, with a growth rate of 10.95%. Among these, the Chongqing-Zhuhai corridor experienced the highest growth rate in flight density of individual routes after the establishment, while the Harbin-Changsha corridor witnessed the largest increase in the average number of flights per route. This is mainly attributed to the relatively low number of participating routes and higher flight volumes within these corridors, resulting in increased flight density and growth rates of both percentage and absolute numbers after the establishment.

Results of carbon emission measurement for air corridors

Air corridor carbon emissions analysis

During the study period, aviation carbon emissions in the seven air corridors totaled 619,431 metric tons. The Harbin-Haikou corridor recorded the highest emissions, while the Chongqing-Zhuhai corridor reported the lowest, with a 17-fold difference between the two (Table 5). Strong correlations exist between emissions and the number of route participants, flights, and types of aircraft in each corridor. The average carbon emissions across the seven air corridors were 88,490 tons. The Harbin-Haikou, Harbin-Changsha, and Beijing-Chongqing corridors exceeded the average carbon emissions by 138, 77, and 13%, respectively. Conversely, the Chongqing-Zhuhai, Urumqi-Hangzhou, Beijing-Fuzhou, and Shanghai-Chongqing corridors fell below 86, 72, 67, and 1% of the corridor's average carbon emissions, respectively.

Table 5. CO_2 emissions from seven air corridors.

Air corridors	Total CO_2 emissions/t	LTO phase CO_2 emission s/t	CCD phase CO_2 mission s/t	Average flight distance of route participants/km	Average cruise time of route participants/s
Harbin-Haikou	209,540	17,340	192,200	1,828	7,451
Harbin-Changsha	156,697	10,581	145,748	1,467	8,517
Beijing-Chongqing	99,921	9,127	90,790	1,936	7,332
Shanghai-Chongqing	87,520	5,617	81,843	1,581	7,867
Beijing-Fuzhou	29,067	2,032	27,035	1,345	7,143
Urumqi-Hangzhou	24,650	2,417	22,234	2,971	8,129
Chongqing-Zhuhai	12,257	992	11,257	963	7,271
Total	619,431	48,106	571,107	-	-

Source: Elaborated by the authors.

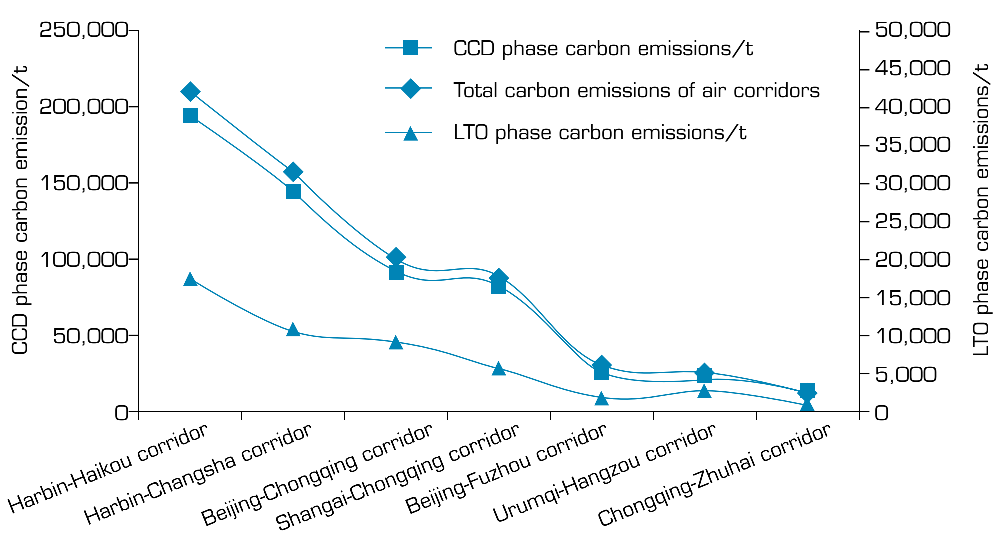
The Harbin-Haikou corridor exhibits the highest aviation carbon emissions. This is primarily attributed to its highest number of route participants and flights. Additionally, the average distance of routes operated by participants in this corridor is 1,828 km, ranking third among the seven corridors. During the CCD phase, the average aircraft's cruise time is 7,451 s, resulting in an average carbon emission rate of 26 tons per second. Furthermore, 59% of the routes in this corridor utilize medium-sized aircraft suitable for medium to long-haul flights (Table 6), such as the Airbus A320 series (including Airbus A318, Airbus A319, and Airbus A320) and the Boeing 737 series (including Boeing 737-700, Boeing 737-800, and Boeing 737-900), with 4,228 and 1,929 flights respectively. The average CO_2 emission factor for medium-sized aircraft operating within their route intervals during the study period reached 27.1 kg CO_2·km. Some medium-haul routes exceeding 2,000 km in length utilize large-sized aircraft such as the Airbus A330 series (including Airbus A330-200 and Airbus A330-300) used for 98 flights, and the Boeing 787 series (including Boeing 787-8 Dreamliner and Boeing 787-9 Dreamliner) utilized for 24 flights. During the study period, large-sized aircraft exhibited an average CO_2 emission factor of 32.7 kg CO_2·km within their route intervals. Large-sized aircraft, due to their longer range, heavier weight, and higher passenger capacity, have relatively higher engine fuel consumption rates, resulting in significantly higher CO_2 emission factors compared to medium and small-sized aircraft. The Airbus series and Boeing series of large-sized aircraft recorded average CO_2 emission factors of 41 kg CO_2·km and 34 kg CO_2·km within their route intervals, respectively, representing 1.28 and 1.42 times the CO_2 emission factors of medium-sized aircraft within the same series. The aviation carbon emissions in the Chongqing-Zhuhai corridor totaled only 12,099 tons, primarily due to its minimal number of route participants and flights. The average route length for participants in this corridor was 963 km, and the aircraft cruise time and distance were relatively short. The corridor predominantly utilized medium and small-sized aircraft, such as the A320 series with 228 flights and the B737 series with 109 flights, along with a few other small-sized aircraft totaling four flights.

The trend of total air corridor carbon emissions aligns with aircraft CCD phase carbon emissions (Fig. 7). Despite operating in the stratosphere where encountering low drag, slow airflow, and complex weather is more challenging, the maximum engine thrust has been reduced to 34%, resulting in relatively low CO_2 output per kilometer. The LTO phase entails more complex operating conditions compared to the CCD phase, characterized by the engine operating at maximum thrust and higher fuel consumption rates. Fuel consumption rates during take-off and climb processes were approximately 2.6 to 3.4 times and 2.0 to 2.8 times higher than those during the CCD phase were. However, due to the short flight duration of the LTO phase, its impact on overall air corridor carbon emissions is not significant. Additionally, the CO_2 emission factor for a single type of aircraft decreases as the distance flown increases (Fig. 8). The CO_2 emission factor for an aircraft operating at maximum range is reduced by 40.52 to 88.57% compared to that at minimum range. This reduction can be attributed to the fact that long-distance flights typically operate at higher cruising altitudes and speeds, where air density is lower, resulting in reduced drag and increased flight efficiency.

Table 6. CO_2 emission factors for different aircraft types.

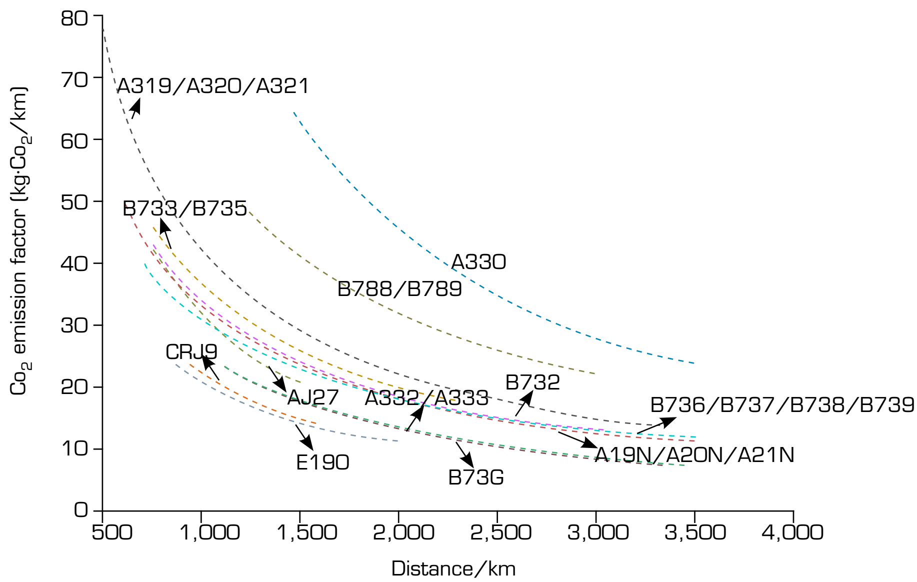
Aircraft category	Aircraft type	Minimum flight range/km	CO_2 emission factor / kg·CO_2/km	Maximum flight range /km	CO_2 emission factor / kg·CO_2/km	Average CO_2 emissions during the flight/CO_2·km
Large	A330	1,470	50	3,489	21	41
	A332/A333	1,234	20	3,441	9	13
	B788/B789	1,215	41	3,039	16	34
Medium	A19N/A20N/A21N	619	48	3,489	17	23
	A319/A320/A321	485	67	3,319	12	37
	B736/B737/B738/B739	702	34	3,435	10	23
	B73G	1,106	25	3,395	8	16
	B732	752	34	3,039	10	23
	B733/B735	752	43	2,309	14	27
Small	E190	857	24	1,989	11	16
	CRJ9	935	24	1,572	14	19
	AJ27	752	42	1,526	19	28

Source: Elaborated by the authors.



Source: Elaborated by the authors.

Figure 7. Comparison of carbon emissions in LTO and CCD phases.

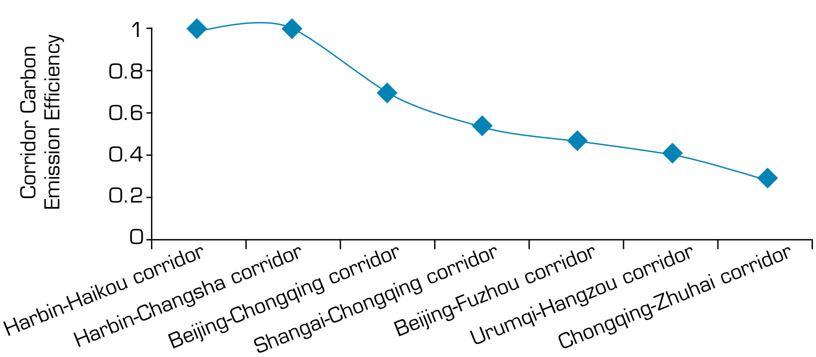


Source: Elaborated by the authors.

Figure 8. The variation of the CO_2 emission factor with mileage for different aircraft types is shown.

Comparison and analysis of carbon emission efficiency in established air corridors

- Two air corridors are operating at high-efficiency levels, namely the Harbin-Haikou corridor and the Harbin-Changsha corridor (Fig. 9), both with efficiency values of 1. This is primarily due to the long average distances flown by participants in these corridors (1,828 km for the Harbin-Haikou corridor and 1,476 km for the Harbin-Changsha corridor), as well as the extended cruise times (7,451 s for the Harbin-Haikou corridor and 8,517 s for the Harbin-Changsha corridor). Based on the results of calculating CO_2 emission factors for different aircraft types (Table 4), it is evident that longer flight distances result in lower CO_2 emissions per unit distance flown. However, the overall carbon emission efficiency of the participants within these corridors remains high. After the establishment of the Harbin-Haikou corridor and the Harbin-Changsha corridor, the average distances flown by participants increased by 453 km and 207 km respectively compared to before the establishment. The average cruise times of aircraft decreased by 125 s and 1,125 s respectively, indicating that after establishment, the average flight speeds of aircraft within these corridors have increased compared to before establishment, which is the main reason for maintaining high carbon emission efficiency.



Source: Elaborated by the authors.

Figure 9. Corridor carbon emission efficiency.

- Two air corridors, the Beijing-Chongqing corridor and the Shanghai-Chongqing corridor, are operating at a moderate efficient level, with efficiency values of 0.701 and 0.531 respectively. Post-establishment, the average distances flown by participants in these corridors increased by 585 km and 88 km, respectively, compared to before establishment. However, the average cruise times of aircraft decreased by 330 s and 251 s, respectively. This indicates that post-establishment, aircraft within these corridors are flying at faster speeds compared to pre-establishment levels, resulting in lower carbon emissions per unit of time and higher carbon emission efficiency.
- Two air corridors, the Beijing-Fuzhou corridor and the Urumqi-Hangzhou corridor, are operating at low-efficiency levels, with efficiency values of 0.464 and 0.406, respectively. This is primarily due to the increased average distances flown by participants in these corridors post-establishment. The Beijing-Fuzhou corridor saw an increase of 290 km, while the Urumqi-Hangzhou corridor saw an increase of 341 km. When the average cruise time of aircraft within a corridor remains constant, longer flight distances result in higher carbon emissions, leading to decreased carbon emission efficiency.
- The Chongqing-Zhuhai corridor stands out for its exceptionally very low efficiency, registering at 0.289, making it the least efficient corridor among the seven. This inefficiency primarily stems from the post-establishment increase in the average cruise time of aircraft within the corridor, which rose by 733 s compared to pre-establishment levels. With prolonged cruise times, aircraft emit more carbon, resulting in a notable decline in the corridor's carbon emission efficiency.

DISCUSSION

The increasing air traffic flow has led to issues regarding airspace resource utilization and aviation carbon emissions, which remain major challenges for China's aviation industry. These issues not only affect civil aviation operational safety but also relate to the industry's green development (Yinuo *et al.* 2019). In terms of airspace utilization, air traffic demand in China is primarily concentrated in the eastern and southern regions, which together account for 31% of the country's total area but 74% of the population and approximately 75% of the aviation demand. Although a dense network of flight routes has been established in these areas, the total available airspace is limited, leading to excessively high flight density in corresponding airspace and flight routes, especially during peak periods. This has increased the probability of flight delays and put pressure on air traffic control, particularly in major hub cities and economically developed regions. In areas such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Greater Bay Area, where airport clusters are located, frequent flight take-offs and landings result in a supply-demand mismatch in airspace resources, and their usage mutually impacts one another.

In addition to the increased demand during holidays, the summer period is also often affected by severe convective weather, which tends to cause delays in major flight routes (Ran *et al.* 2024). For example, on August 16, 2024, due to heavy rain in Guangzhou, flights could not land, resulting in varying degrees of take-off delays across the entire Beijing-Guangzhou air corridor. Some flights were delayed by up to 3 hours, affecting the normal utilization of airspace in at least eight provinces in China. Meanwhile, airspace in Central and Western regions remained largely unused. Regarding aviation carbon emissions, China has been the world's second-largest civil aviation market since 2005, following the United States. As the national economy continues to grow steadily, aviation demand is expected to rise, leading to a corresponding rigid increase in aviation carbon emissions. On a global scale, there is no significant difference between countries in terms of single-aircraft emission reductions. The long update cycle for aviation engine technology and the high cost of sustainable aviation fuels make it difficult to achieve significant emission reductions in the short term. As a responsible major country committed to sustainable development, China pledged at the 75th United Nations General Assembly in 2020 to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Therefore, carbon reduction in the aviation sector is a key issue in achieving the national dual-carbon goals.

The Chinese government and civil aviation authorities have proposed a series of relevant policies to address the current airspace issues and mitigate the challenges faced. The 2017 Government Work Report specifically mentioned the need to further optimize the national airspace resource allocation, improve airspace resource utilization, expand civil aviation usage areas, and promote airspace reform. In 2021, the Civil Aviation Administration of China (CAAC) released the 14th Five-Year Plan for Civil Aviation

Development, which proposed improvements to the airspace management system and modernization of the air traffic management system, including optimizing flight route networks and enhancing air traffic control service capacity. This plan set the general direction and objectives for efficient air corridor operations and airspace optimization. To address the existing aviation carbon emission pressures, the CAAC released the 14th Five-Year Plan for Green Development of Civil Aviation in 2022. The overall goal for civil aviation development is to achieve phased results in green transformation by 2025 and establish a green, low-carbon, and circular development system by 2035. By then, the aviation industry aims to achieve carbon-neutral growth in air transport and become a global leader in sustainable civil aviation development. Therefore, given the growing demand potential of China's civil aviation market, achieving green transformation and full decarbonization within a tight timeframe will be a challenging and complex task.

This study integrates airspace resource optimization with the issue of aviation carbon emissions. By identifying the structure of China's aviation network, it delineates air corridors and validates the delineation results from the perspective of carbon emissions. Unlike previous studies, which have focused largely on technical aspects of aviation carbon reduction, this research explores carbon reduction from the perspective of airspace resource management. Finding the optimal decarbonization path through non-technical means is a key innovation and contributes to the theoretical exploration of green development in the civil aviation industry. Furthermore, while past research has predominantly approached the issue from the perspective of airport terminals, focusing on congestion in the terminal areas and carbon emissions during the LTO phase, this study expands the research to include the optimization of airspace linear network structures and carbon emissions throughout the entire flight phase. By validating the research's content from the angle of carbon emissions, it aligns more closely with societal development expectations.

CONCLUSION

The research findings are divided into two main parts:

- Based on the assessment of China's airspace structure, this study aims to optimize airspace resource utilization. Seven air corridors are delineated across China based on the positions of flight ROC, incorporating a total of 196 routes and 16,185 flights. The seven corridors are as follows: Chongqing-Zhuhai corridor, Beijing-Fuzhou corridor, Urumqi-Hangzhou corridor, Harbin-Changsha corridor, Beijing-Chongqing corridor, Shanghai-Chongqing corridor, and Harbin-Haikou corridor. Among these, the Harbin-Haikou corridor has the most route participants and flight volumes, while the Chongqing-Zhuhai corridor has the fewest. The Harbin-Haikou corridor also has the highest flight frequency, and the Urumqi-Hangzhou corridor has the longest average flight distance for participants. The seven delineated air corridors collectively form a "diamond-shaped three-dimensional structure," with the Beijing-Tianjin-Hebei airport cluster, Yangtze River Delta airport cluster, Guangdong-Hong Kong-Macau Greater Bay Area airport cluster, and Chengdu-Chongqing region airport cluster at the vertices. The Beijing-Fuzhou corridor, Beijing-Chongqing corridor, Chongqing-Zhuhai corridor, and Harbin-Haikou corridor constitute the four edges of this structure, with the Shanghai-Chongqing corridor serving as the central axis. All five corridors are distributed in the region east and south of the Hu Huanyong Line, indicating a high correlation between China's aviation network layout and population and urban distribution. It also reflects the overall control capacity of core airport clusters over air transport.
- A comparative analysis of carbon emissions before and after the delineation of the air corridors was conducted. The seven air corridors emitted a total of 619,431 tons of carbon, with the overall carbon emission trend aligning with the carbon emissions during the aircraft's CCD phase. Among these, the Harbin-Haikou corridor had the highest emissions, while the Chongqing-Zhuhai corridor had the lowest. The emissions were closely related to the number of route participants, flight volumes, and aircraft types in each corridor. Large aircraft do not have flight environment advantages and are primarily affected by the CO_2 emission factor. The corridors in a high carbon emission efficiency state are the Harbin-Haikou corridor and Harbin-Changsha corridor, those in a medium carbon emission efficiency state are the Beijing-Chongqing corridor and Shanghai-Chongqing corridor, those in a low carbon emission efficiency state are the Beijing-Fuzhou corridor and Urumqi-Hangzhou corridor, and the corridor in an extremely low carbon emission efficiency state is the Chongqing-Zhuhai corridor. Compared

to the pre-corridor delineation, the average carbon emission per second generated by all aircraft in the seven corridors after delineation decreased by 79.75%, and the carbon emission per kilometer decreased by 93%, indicating that the carbon emission efficiency of aircraft improved after the corridors were delineated. This improvement is mainly due to the reduction in the average distance of ROC and the corresponding reduction in carbon emissions from flight routes.

Compared to existing studies (Yaqing *et al.* 2018), although this research divides only seven air corridors, the coverage is extensive, and the airspace structure is more prominent. The study found that the seven air corridors of different scales varied in terms of carbon emissions and emission efficiency, strongly confirming the uneven development of China's aviation industry in terms of regions, time periods, and other factors. Approaching the optimization of airspace resource utilization from the perspective of air corridor planning not only helps optimize the structural layout of airspace resources and improve airspace utilization efficiency but also provides a solid theoretical foundation for China's civil aviation industry to advance toward green development, offering valuable reference directions. However, the current study has certain limitations. Due to data collection difficulties, the analysis is based on only 1-month's flight data to identify and delineate China's air corridors and route network structure, resulting in a small sample size that may not fully reflect the complex and dynamic real-world situation. Therefore, future research should focus on expanding the data sample, incorporating long-term and multidimensional data, and conducting comprehensive analysis from a dynamic perspective. This will be a key focus for advancing research in this field in the future.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Funding Acquisition: Han R; **Resources, Supervision:** Han R; **Writing - Review & Editing:** Han R; **Conceptualization:** Ran X; **Methodology:** Ran X; **Software:** Ran X; **Investigation:** Ran X and Li H; **Formal Analysis:** Ran X; **Writing - Original Draft:** Ran X; **Data Curation:** Ran X and Han R; **Visualization:** Li H; **Resources:** Li H and Han R; **Supervision:** Li H; **Validation:** Li H and Han R; **Final approval:** Ran X.

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