Study on optimal aircraft types for China's main air route market: A model-based multi-scenario analysis at route scale

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DOI: https://doi.org/10.30212/JITI.202402.005

ABSTRACT

In the post-pandemic landscape, airlines must advance their fleet planning and strategy to tackle market volatility. Optimizing aircraft selection for specific routes can minimize costs and maximize profits. However, current research lacks route-level demand predictions considering both cost and aircraft attributes. Addressing this, we introduce a novel Aircraft Type-specific Demand Forecasting Model (ATDFM) that determines the best aircraft combinations per route, balancing costs and revenue. The ATDFM estimates demand for various aircraft on China's key routes, factoring in socio-economic and competitive elements. Initial scenarios show a high demand for Airbus's large single-aisle aircraft in China's main market, assuming their procurement cost doesn't exceed a 3% increase in operating costs, with Boeing's medium single-aisle jets following closely. Airbus performs well on international routes, while Boeing shines on regional and non-hub journeys. The study bridges gaps in the existing literature by focusing on route-level analysis and incorporating thorough assessments of operational costs and economic efficiency, while multi-scenario analysis yields insights into how different factors influence the selection of optimal aircraft types. The findings aid airlines in refining aircraft purchasing and flight operation strategies, while also assisting suppliers with strategic planning for product design and production line layouts.

Keywords: Chinese aviation market, Aircraft type-specific demand forecast, Bottom-up model, Scenario analysis, Route strategy.

1. Introduction

Guided by government policies such as the 14th Five-Year Plan for Civil Aviation Development and motivated by market competition, China's aviation transport market is continuously developing. At present, China's major domestic airlines have established a high-density, high-frequency aviation backbone network (Su et al., 2022) [1]. To further foster growth and effectively meet the challenges posed by high-speed rail development,, airlines are constantly innovating their product and service offerings. This enhances the efficiency of air travel, improves the travel experience, and strengthens passenger rights, thereby providing effective support for the establishment of a high-quality airline network (Shen et al., 2023; Ma et al., 2023) [2], [3]. However, the operation of the air passenger market must be based on a solid market foundation. Neglecting the market and making excessive investments can easily lead to resource waste and lower-than-expected input-output efficiency. Moreover, there are variations in the passenger demand across different routes and the development level of the economic hinterland they rely on. Especially in the post-pandemic era, the civil aviation industry faces two major challenges due to significant changes in the market: increased complexity and uncertainty in the market environment, requiring strategic preparation for various future scenarios, and significant changes in passenger air travel habits, leading to changes in travel scale and preferences, increased heterogeneity over time and region, and increased volatility (Su et al., 2022; To et al., 2024) [1], [4]."Scenario analysis" can help prevent overestimation or underestimation of future changes and their impacts in forecasts, thereby effectively diverging from traditional analysis constraints. It captures various emerging trends in the development of future air express market capacity and fleet demand, providing a more exhaustive reference for strategic management decision-making (hang et al., 2023; Cui et al., 2024; Lu et al., 2024) [5], [6], [7]. However, scant previous studies have employed scenario analysis to forecast air passenger market demand. Consequently, in the context of the current air passenger transport market, research should employ scenario analysis for multi-scenario forecasting, guiding airlines to devise operation strategies for a range of potential future scenarios, to manage escalating market risks and enhance their resilience.

Civil aircraft utilized by airlines for passenger routes typically have an average service life of 15 years (Liu et al., 2008) [8]. Considering the lengthy investment period and significant funds involved, aircraft procurement represents a long-term fixed asset investment decision for airlines that directly and significantly impacts business profitability. Determining the appropriate aircraft type is a major business decision that airlines need to consider (Schlesinger et al., 2021) [9]. Since the easing of the pandemic in 2023, China's air transport market has experienced sustained growth, albeit with increased uncertainty. Research focuses on accurately forecasting the demand for civil aircraft in China's passenger air travel market under various scenarios and on integrating the characteristics of different aircraft types to identify those that offer greater operational advantages. The outcomes of this research can guide companies in refining their aircraft procurement and flight operation strategies, thereby enhancing business efficiency and profitability.

Prior research focused on forecasting the demand for civil aircraft includes systematic studies conducted by Zhang et al. (2021) [10], Zhang et al. (2015) [11], and Liu et al. (2008) [8]. Zhang et al. (2021) [10] implemented newer computer models, such as machine learning, to forecast aircraft demand, thereby improving forecast accuracy. Liu et al. (2008) [8] presented a prediction path for fleet demand based on passenger traffic. However, both Zhang et al. (2021) [10] and Liu et al. (2008) [8] concentrated on a national level and did not differentiate between aircraft types, resulting in imprecise predictions. Zhang et al. (2015) [11] developed a model based on operational economics, considering multiple route constraints and aircraft types, which more effectively met actual needs, but they did not further analyze flight operation costs. Besides research institutions, aircraft manufacturers such as Boeing (2023) [12], Airbus (2023) [13], and the Commercial Aircraft Corporation of China (COMAC) (2021) [14] also prioritize forecasting air transport market demand to inform their management decisions and regularly publish reports. However, these forecasts are extensively commercialized, serve primarily corporate strategies, and may be subject to subjective bias. Additionally, these forecasts lack disclosure of their methods and details. To conclude, existing research on demand forecasting for civil aircraft lacks route-level analysis that encompasses both a dissection and a detailed examination of operational costs, which is the central focus of this study.

This study conducts a route-level analysis, focusing on optimizing aircraft types for specific routes, and projects the preferred aircraft model and demand volume for each routes, thus providing more precise and actionable insights. The contributions of this research are manifold: Firstly, it creates an ATDFM that integrates detailed operational costs with targeted route data to forecast the optimal aircraft types and their demand potential for China's main routes. Additionally, the study identifies advantageous aircraft models under varying route conditions and market circumstances, offering valuable guidance for airlines in optimizing aircraft procurement and flight operation strategies. Finally, forecasts across diverse scenarios improve understanding of how market factors influence the economic viability of operating various models, including the effects of high-speed rail development and competitive dynamics among major aircraft manufacturers on the demand for different aircraft types.

Following the introduction, the structure of the paper is as follows:

(1) Section 2, "Methods and Data": After calculating the operational costs for each aircraft type individually, we conduct a comparative economic analysis under various scenarios. This section describes the process and steps involved in developing the ATDFM. Furthermore, the data sources are detailed in this section.

(2) Section 3, "Results": The ATDFM is utilized to forecast the optimal aircraft models and the extent of their demand on China's principal routes. This method considers fluctuations in hub levels and market competition, thereby highlighting the impacts of different route levels and market competition on the demand for these models.

(3) Section 4, "Discussion": Based on ATDFM forecasts under multiple scenarios, relevant managerial decisions are analyzed. The conclusions of this study may serve as references for airlines in fleet planning and assist in improving route operation quality and profitability.

(4) Section 5, "Conclusions": This section summarizes the core work and principal findings of the study while acknowledging its limitations and proposing directions for future research.

2. Methods and Data

Initially, we established an inventory of flight operation costs and an economic calculation list. Subsequently, based on these lists, we developed the ATDFM, which serves to quantify the operationally advantageous aircraft types and their potential demand for China's major routes in the future. Under a series of socio-economic and market competition scenarios, this model projects the demand scale for various types of passenger aircraft in the Chinese air passenger market from 2023 to 2037.

2.1. Flight Operation Cost Inventory

Prior research has underscored the significant impact of an airline's choice of aircraft type on the economic efficiency of flight operations. Drawing on the findings of Lee et al. (2019) [15], Camilleri et al. (2018) [16], Zuidberg (2014) [17], and Ryerson et al. (2013) [18], it can be deduced that the primary costs of flight operations encompass fuel, labor, aircraft maintenance, airport fees, en-route charges, in-flight services, and sales expenses. All these factors can be influenced by the aircraft type due to differences in operation efficiency, crew size, engine quantity, aircraft size, and flight speed, among others. The specific impacts are detailed in Table 1.

Table 1 Flight Operation Cost Inventory

Cost	The Impact of Aircraft Parameters on Operating Costs	Reference
Fuel Costs	①Various aircraft types, each possessing distinct propulsion efficiencies and fuel consumption traits, yield differing fuel expenses when operating on the same routes. ②The larger size of certain aircraft leads to lower fuel costs per unit.	(Ryerson et al., 2013; Camilleri et al., 2018; Lee et al., 2019) [15], [16], [18]
Labor Costs	①Long-range aircraft with a larger seating capacity necessitate increased crew and higher pilot wages. ②Owing to safety norms, crew sizes cannot be reduced below legal requirements, resulting in decreased per-unit wage costs for larger aircraft.	(Camilleri et al., 2018; Lee et al., 2019; Ezzinbi et al., 2014) [15], [16], [19]
Maintenance Costs	①Aircraft with a greater number of engines require more spare parts and mechanical upkeep, thereby escalating daily maintenance costs. ②Aircraft with higher speeds require more frequent maintenance due to higher utilization rates. ③Larger aircraft have lower per-unit costs for major spare parts' reserves due to fixed costs.	(Camilleri et al., 2018; Zuidberg, 2014; Lee et al., 2019) [15], [16], [17]
Landing Fees	Landing fees, levied by airport authorities for facility use, are based on aircraft weight and passenger load.	(Camilleri et al., 2018; Lee et al., 2019) [15], [16]
En-route Fees	En-route fees, which encompass air traffic control and navigation costs, are collected by the government, and largely determined by the aircraft size.	(Camilleri et al., 2018; Lee et al., 2019) [15], [16]

Source: By authors

2.2. Flight Operation Economics Checklist

In theoretical terms, the assessment of flight operation economics should be grounded on the principle of profit maximization. Nonetheless, given the multitude of uncertainties impacting airline revenues, this study provisionally omits income factors to maintain objectivity and comparability, focusing primarily on minimizing flight operation costs. An exhaustive examination of annual reports from publicly traded airlines in China reveals that the top four operating expenditures encompass fuel consumption, depreciation of engines and high-cycle parts, crew service costs, and airport takeoff and landing fees, typically accounting for more than 80% of total costs. Among these, the depreciation expenditures for engines and high-cycle parts differ significantly among airlines, which can be attributed to differences in aircraft acquisition strategies and depreciation techniques, and the associated data are challenging to procure. Consequently, this research focuses on utilizing fuel consumption, crew service expenditures, and airport takeoff and landing fees as components of flight operation costs.

2.2.1. Flight Operation Costs

$$
\begin{aligned}
&\mathit{Flight\ Operation\ Costs}\\
&= \mathit{Cost\ Per\ Flight} \times \mathit{Annual\ Number\ of\ Flights}\\
&= \begin{pmatrix} \mathit{Fuel\ Costs} + \mathit{Crew\ Expenses} \\ +\mathit{Takeoff\ and\ Landing\ Fees} \end{pmatrix} \times \frac{\mathit{Average\ Daily\ Aircraft\ Production\ Hours}}{\mathit{Flight\ Duration}} \times 365\\
&= \begin{pmatrix} \mathit{Fuel\ Costs} + \mathit{Crew\ Expenses} \\ +\mathit{Takeoff\ and\ Landing\ Fees} \end{pmatrix} \times \frac{\mathit{Number\ of\ Aircrafts} \times \mathit{Daily\ Utilization\ Rate}}{\mathit{Flight\ Distance} / \mathit{Aircraft\ Design\ Cruise\ Speed}} \times 365
\end{aligned}
$$

As the capacity of the aviation express passenger market is forecasted annually, it necessitates the corresponding computation of the total annual flight operating costs. Furthermore, due to variations in flight distances across diverse routes, the incorporating flight distance becomes essential when computing flight volume.

2.2.2. Flight Fuel Costs

$$
\begin{aligned}
&\mathit{Flight\ Fuel\ Costs}\\
&= \mathit{Flight\ Fuel\ Consumption} \times \mathit{Unit\ Fuel\ Price}\\
&= \mathit{Flight\ Duration} \times \mathit{Fuel\ Consumption\ per\ Operating\ Hour} \times \mathit{Unit\ Fuel\ Price}\\
&= \frac{\mathit{Flight\ Distance}}{\mathit{Aircraft\ Design\ Cruise\ Speed}} \times \mathit{Fuel\ Consumption\ per\ Operating\ Hour} \times \mathit{Unit\ Fuel\ Price}
\end{aligned}
$$

In practical operations, considering that the turnaround time is impacted by numerous uncertainties and the associated data are challenging to procure, flight time is utilized as a substitute. Moreover, as the fuel price is not influenced by the aircraft type or route, it is established as a uniform standard.

2.2.3. Crew Express

$$
\begin{aligned}
&\mathit{Crew\ Expenses}\\
&= \mathit{Flight\ Crew\ Pay} + \mathit{Cabin\ Crew\ Pay}\\
&= \mathit{Unit\ Wage\ per\ Hour\ for\ Flight\ Crew} \times \mathit{Number\ of\ Flight\ Crew} + \mathit{Unit\ Wage\ per\ Hour\ for\ Cabin}\\
&\quad \mathit{Crew} \times \mathit{Number\ of\ Cabin\ Crew}
\end{aligned}
$$

Firstly, the count of cabin crew members for each flight is determined based on the document titled "*Operating Qualification Rules for Large Aircraft Carriers in Public Air Transport*". Secondly, given that the forecast is solely applicable to domestic routes and the flight duration for domestic flights does not surpass the upper limit stipulated in the document, the majority of domestic flights are staffed with two pilots. Consequently, the wage disparity between pilots is not taken into consideration at present. Lastly, due to the challenge in quantifying the impact of aircraft models on the cabin crew unit hourly wage, the cabin crew unit hourly wage is established as a uniform standard.

2.2.4. Flight Takeoff and Landing Fees

The calculation of flight takeoff and landing fees is based on the formula stipulated in the document titled "*Notice on Issuing the Adjustment Plan for Civil Airport Charge Standards*". This formula is influenced by both the nature of the airport and the maximum takeoff weight of the aircraft.

2.3. Scenario Setting

Throughout the scenario analysis process, considering multiple factors and enhancing the precision of scenario settings can improve the accuracy of forecast outcomes (Andros et al., 2021) [20]. Building upon the research conducted by Li et al. (2022) [21], scenarios A1, A2, and A3 have been developed to depict the economic development profiles of the two cities at either end of the flight route, as illustrated i in Table 2. Taking into account factors such as the future trajectory of high-speed rail and aviation competition and cooperation, as well as shifts in the passenger consumption market, scenarios B_1, B_2, and B_3 have been formulated to represent the annual passenger market capacity, as detailed in Source: By authors.

Table 3. Regarding the competitiveness of aircraft brands in the market, potential shifts in international relations may impact China's procurement costs of foreign aircraft from various brands, thus influencing the market competitiveness of Boeing and Airbus aircraft. As a result, scenarios C1, C2, and C3 have been established, as depicted in Table 4..

2.3.1. GDP growth rate

The GDP growth rate spanning the years 2009-2019 is derived from the annual city statistical yearbooks. According to the study by Chen et al. (2024) [22], China's anticipated annual GDP growth rate is projected to fall between 4% and 6%, with a potential fluctuation margin of 2%. Consequently, the forecast value in this study is taken as the median, with the low forecast value reflecting a 1% reduction, and the high forecast value reflecting 1% increase.

2.3.2. Annual passenger traffic growth rate

The passenger traffic volume for the routes spanning 2009-2019 is sourced from the *China Civil Aviation Statistical Yearbook*. According to Yuan et al. (2023)[23] the operation of High-Speed Rail (HSR) is expected to significantly replace aviation, potentially leading to a variance of approximately 10% in the growth rate of aviation passenger traffic in cities where HSR is present.. Consequently, the forecast value for the annual passenger traffic growth rate in this study is set as the median, with the low forecast value reflecting 5% reduction, and the high forecast value reflecting 5% increase.

2.3.3. Boeing and airbus aircraft procurement costs

Given the complex and dynamic nature of the international relations landscape that China is navigating in this new era (Jiang et al., 2023) [24], the bilateral competition between China and the United States injects uncertainty into the future market prospects of Boeing products in China. Consequently, the unpredictable future international relations landscape could potentially inflate the supplementary procurement costs of either Boeing or Airbus aircraft. In light of this, the optimization outcome achieved without additional procurement costs for both Boeing and Airbus aircraft is considered as the median forecast value. The scenario where Boeing aircraft bear additional procurement costs is regarded as the forecast scenario where Airbus holds a competitive advantage, and vice versa. Initial calculations suggest that the procurement cost of each model constitutes approximately 5% of the total operating cost over 15 years. Therefore the additional procurement cost of each model is set at 5% of the 15-year operating cost.
Source: By authors.

Table 5 displays the combinations of various scenarios. The forecast for the ideal aircraft model and its demand size on China's primary routes encompasses the complete combination of three scenarios, resulting in a total of 27 scenarios. Among all scenarios, scenario $A_2B_2C_2$ represents the situation where all driving factors sustain their current developmental level without external influences. Therefore, it is established as the benchmark scenario.

Table 2 Future Scenarios for Economic Conditions of Cities at Both Ends of the Route

Scenario		Description
A_1	Low growth	Undergo slow growth, with the annual GDP growth rate at the lower boundary of the forecasted range
A_2	Moderate growth	Undergo moderate growth, with the annual GDP growth rate at the midpoint of the forecast range
A_3	High growth	Undergo rapid growth, with the annual GDP growth rate at the upper boundary of the forecasted range

Source: By authors.

Table 3 Future Scenarios for HSR and Civil Aviation Competition and Cooperation

Scenario		Description
B_1	Low growth rate in air passenger traffic	HSR development quickens while aviation takes no collaborative measures in response, amplifying the substitution effect of HSR on aviation
B_2	Moderate growth rate in air passenger traffic	HSR development sustains its current pace, while aviation implements some collaborative measures in response, maintaining the substitution effect of HSR on aviation at its present level

B_3	High growth rate in air passenger traffic	HSR development decelerates, while aviation implements very proactive collaborative measures in response, diminishing the substitution effect of HSR on aviation

Source: By authors.

Table 4 Future Scenarios for Competition of Boeing and Airbus in Chinese Market

Scenario		**Description**
C_1	Airbus is in a dominant position	Amidst persistent tensions in Sino-US relations and more relaxed Sino-European relations, Boeing's competitiveness in the Chinese market experiences a significant decline
C_2	Airbus and Boeing are evenly matched	With a slight relaxation in Sino-US relations and stable Sino-European relations, Boeing and Airbus find themselves on equal footing in the Chinese market
C_3	Boeing is in a dominant position	With improved Sino-US relations and heightened tensions in Sino-European relations, Airbus's competitiveness in the Chinese market experiences a significant decline

Source: By authors.

Table 5 Setting of scenario combinations for ATDFM

Scenarios	A_1			A_2			A_3		
	B_1	B_2	B_3	B_1	B_2	B_3	B_1	B_2	B_3
C_1	$A_1B_1C_1$	$A_1B_2C_1$	$A_1B_3C_1$	$A_2B_1C_1$	$A_2B_2C_1$	$A_2B_3C_1$	$A_3B_1C_1$	$A_3B_2C_1$	$A_3B_3C_1$
C_2	$A_1B_1C_2$	$A_1B_2C_2$	$A_1B_3C_2$	$A_2B_1C_2$	$A_2B_2C_2$	$A_2B_3C_2$	$A_3B_1C_2$	$A_3B_2C_2$	$A_3B_3C_2$
C_3	$A_1B_1C_3$	$A_1B_2C_3$	$A_1B_3C_3$	$A_2B_1C_3$	$A_2B_2C_3$	$A_2B_3C_3$	$A_3B_1C_3$	$A_3B_2C_3$	$A_3B_3C_3$

Source: By authors

2.4. Structure of ATDFM

The ATDFM utilizes a bottom-up approach to predict the primary aircraft types and their demand volume on China's major air routes in the future. This model computes operational costs for each aircraft type across different routes, referencing flight operation cost sheets and economic calculation sheets, with its optimization objective being cost minimization. Inputs for ATDFM encompass:

(1) Economic efficiency of flight operations

(2) Constraints on capacity demand

(3) Airspace capacity constraints.

Outputs from ATDFM comprise:

(1) A combined memory of demand volume for different aircraft types

(2) Fluctuations in demand volume for each aircraft type under various scenarios

(3) Aircraft types with competitive advantages in operational economics. Scenario configurations are based on three socioeconomic variables, forming 27 scenarios. Fig. 1 illustrates a schematic diagram of the ATDFM structure.

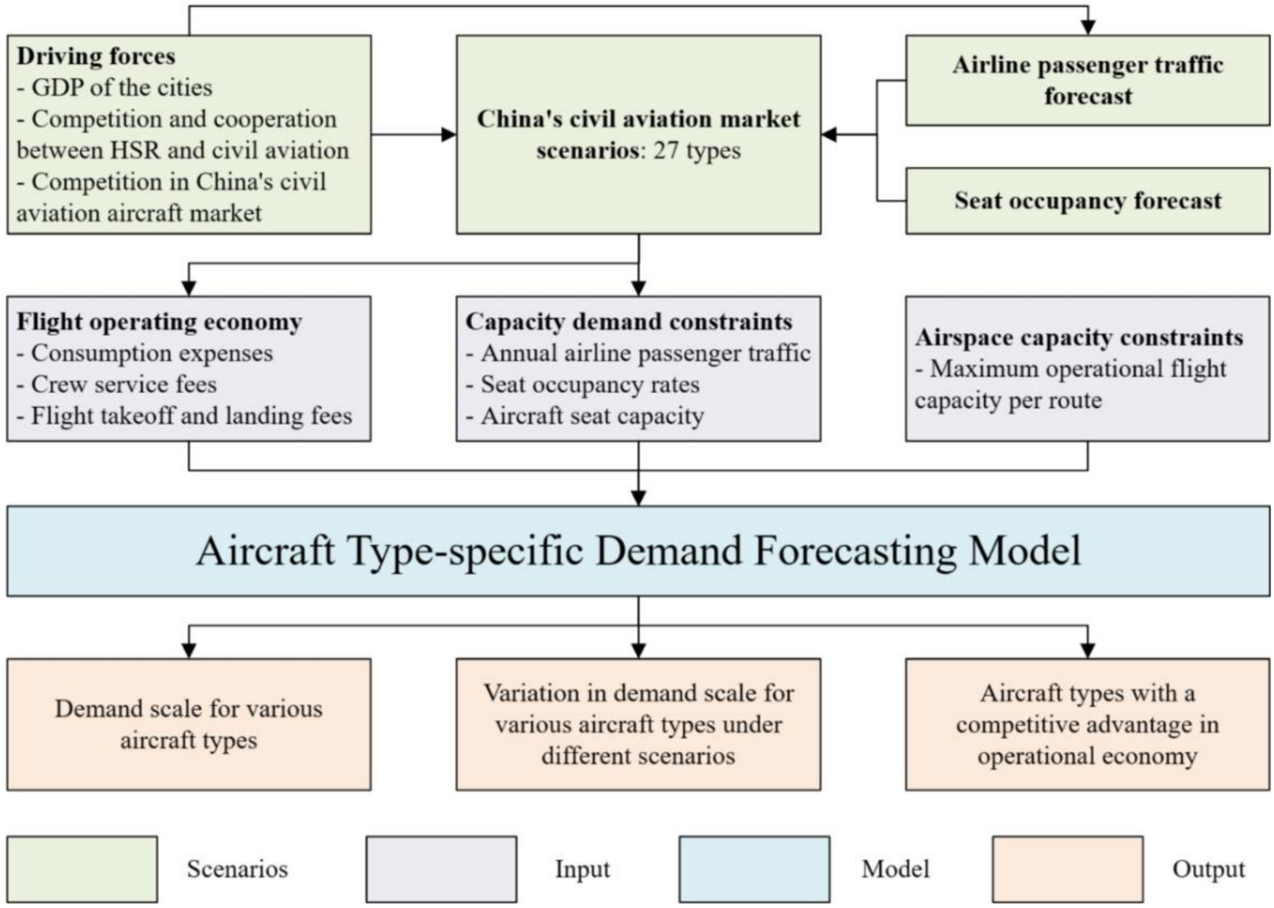


Fig. 1. Schematic structure of ATDFM

Source: By authors.

When comparing the operational costs of various aircraft types, it's crucial to consider factors beyond just minimizing flight operation costs. The distinctiveness of different route markets, such as passenger demand and airspace capacity, must also be taken into account. Key factors include:

1. The annual total capacity provided on the route must fulfill the seat demand of the route market for that respective year. To calculate the annual total capacity provided, it's necessary to have a reliable measure of retiring capacity. Based on the research by Liu et al. (2008) [8], assuming an aircraft lifespan of 15 years and an average yearly retirement rate, the current capacity will be fully retired after 15 years, with 1/15 of the current capacity retiring annually. This analysis allows for the computation of the total capacity per annum.
2. The number of flights on the route must not exceed the limit of airspace capacity, particularly the hub airport airspace capacity.

Based on the preceding analysis, this study focuses on a single route as the research subject and aims to minimize flight operation costs. To address this, an integer programming model is formulated to articulate the optimization problem of aircraft type and route matching. The model includes constraints ensuring effective capacity supply meeting passenger demand constraints and flight volume complying with time capacity constraints.

Equation (1) represents the minimum flight operation cost, while equation (2) defines the flight operation cost calculation formula. Equation (3) stipulates that the annual flight volume of each route must not exceed the time capacity limit and equation (4) signifies that the added capacity should not be less than the added seat demand.

By minimizing flight operation costs, ATDFM applies the following optimization algorithm: under conditions where the total flight volume does not exceed the maximum operational flight capacity and the supplied effective seat number satisfies the route passenger flow demand, it selects the optimal combination of aircraft types and computes the demand volume for the selected types. The meanings of the variables involved are demonstrated in Table 6.

$$\min\ C_j = \sum_{i \in I} C_{ij},\quad \forall j \in J \tag{1}$$

$$\begin{aligned} C_{ij} &= \left(Fu_{ij} + W_{ij} + Fe_{ij}\right) \times F_{ij} \times Y \\ Fu_{ij} &= Fuh_i \times Tb_{ij} \times Fp \\ W_{ij} &= Wq_i \times Wp \times Tb_{ij} \\ F_{ij} &= \frac{X_{ij} \times U_i}{Tb_{ij}} \times 365 \\ Tb_{ij} &= \frac{Dis_j}{V_i} \end{aligned} \tag{2}$$

s.t.

$$\sum_{i \in I} F_{ij} \le Fmax_j,\quad \forall j \in J \tag{3}$$

$$\begin{aligned} Su_j &\ge Dn_{jk},\quad \forall k \in K;\quad \forall j \in J \\ Su_j &= \sum_{i=1}^{m} \left(S_i \times F_{ij}\right) \\ Dn_{jk} &= \left[D_{jk} - Dn_{jk-1} - D_j^{-1} \times \left(1 - \frac{k}{Y}\right)\right] \div L_{jk} \end{aligned} \tag{4}$$

$$X_{ij} \text{ is integer},\quad \forall i \in I;\quad \forall j \in J \tag{5}$$

Table 6 Variables List

Variable	Meaning	Variable	Meaning
C_{ij}	The total annual operating cost for aircraft type i on route j	Wp	The unit wage per hour for cabin crew
S_i	The seating capacity of aircraft type i	Fe_{ij}	The takeoff and landing fee for a single flight of aircraft type i on route j
L_{jk}	The load factor for route j in year k	$Fmax_j$	The maximum operational flight capacity for route j

F_{ij}	The total annual number of flights for aircraft type *i* on route *j*	Su_{jk}	The additional capacity for route *j* in year *k*
X_{ij}	The number of aircraft of type *i* on route *j*	Dn_{jk}	The additional seat demand after maintaining the capacity for route *j* in year *k*
U_i	The daily utilization rate of aircraft type *i*	D_{jk}	The total passenger demand for route *j* in year *k*
Tb_{ij}	The flight time of aircraft type *i* on route *j*	D_j^{-1}	The passenger demand for route *j* in the year before the forecast year
Dis_j	The distance of route *j*	Y	The average aircraft service life
V_i	The flying speed of aircraft type *i*	i	The sequence number of aircraft type
Fu_{ij}	The fuel cost for a single flight of aircraft type *i* on route *j*	j	The sequence number of route
Fuh_i	The fuel consumption per flight hour for aircraft type *i*	k	The sequence number of forecast year.
Fp	The unit price of fuel	I	The total number of aircraft types.
W_{ij}	The labor cost for a single flight of aircraft type *i* on route *j*	J	The total number of routes.
Wq_i	The number of cabin crew for a single flight of aircraft type *i*	K	The total number of years.

Source: By authors.

2.5. Data Sources

2.5.1. Aircraft data

Aircraft are categorized into turbofan regional jets, single-aisle jetliners, and twin-aisle jetliners, further divided by large, medium, and small dimensions (COMAC, 2021)[14]. This study selects representative models from Boeing, Airbus, and COMAC as sources for aircraft parameters. The chosen models are displayed in

Table 7. Data regarding fuel consumption per flight hour and daily utilization rates are obtained from the *Statistical Data on Civil Aviation of China 2020*.The information on seating capacity, flight speed, and maximum takeoff weight are derived from the Wikipedia entries for each model.

Table 7 Typical aircraft models for each type under each brand

Classification of aircraft types		**Brand**	**Aircraft model**
Turbofan regional jets	Large	Embraer	EMB-190
		COMAC	ARJ21-700
Single-aisle jetliners	Small	Airbus	A319
		Boeing	B737-700

	Middle	Airbus	A320
		Boeing	B737MAX8
		COMAC	C919
	Large	Airbus	A321NEO
		Boeing	B737-900ER
Twin-aisle jetliners	Small	Airbus	A350-900
		Boeing	B787-9
	Middle	Airbus	A350-1000
		Boeing	B777-300ER

Note: The aforementioned aircraft manufacturers lack a substantial commercial presence in the small and medium-sized turbofan regional jet market; Operational data for the C919 is currently not accessible and will not be factored into subsequent calculations.

2.5.2. Route data

The focus of the prediction is on the major air route market in China. The selection criteria include routes with a minimum of 10 daily operations in China in 2019, totaling 163 routes, primarily spanning the network between international and regional hubs.

The approach for forecasting passenger flow on China's major routes refers to the research conducted by Li et al. (2023)[25], utilizing a variable weight combination model constructed by Partial Least Squares (PLS) and a Vector Autoregressive Model (GA-SVR) optimized by a genetic algorithm.

The technique for predicting the load factor on routes employs the Support Vector Regression (SVR) model. The airspace capacity is computed using the average daily hourly flow rates and capacity utilization data of the coordinated primary airports as indicated in the *National Civil Aviation Flight Operations Efficiency Report 2022*. Macroeconomic historical data of cities are derived from city statistical yearbooks spanning from 2000 to 2020. Historical data of passenger transport volume and load factor on routes are obtained from the *China Civil Aviation Statistical Yearbook* from 2000 to 2020. Flight distance data for the routes are sourced from the OAG database.

3. Results

3.1 Operational Advantage Aircraft Types on Major Chinese Routes

Firstly, this study successfully predicts the passenger flow on major Chinese routes under various scenarios. By forecasting each route individually, we derive nine development trends of passenger flow on major Chinese routes under combinations of three different scenarios of slow (A_1), medium (A_2), and fast (A_3) GDP growth in the cities at both ends of the routes, and three different scenarios of low (B_1), medium (B_2), and high (B_3) annual growth rates of passenger market capacity in the context of high-speed rail and aviation cooperation. When GDP growth is slow (A_1), the passenger flow on major Chinese routes is anticipated to be within the range of 4.3-4.5 billion person-times over the next 15 years; with medium growth (A_2), the passenger flow is projected to be within the range of 4.6-4.8 billion person-times; with fast growth (A_3), it is estimated to be within the range of 4.9-5.2 billion person-times.

Delving further into the ATDFM results, Fig. 2 illustrates the operationally advantageous aircraft types and their demand scale on major Chinese routes under 27 scenarios from 2023 to 2037. These scenarios encompass combinations of three distinct GDP growth rates in the cities at both ends of the routes, three different scenarios of annual growth rates of passenger market capacity in the context of high-speed rail and aviation cooperation, and three different scenarios of Airbus and Boeing competition in the Chinese market, namely Airbus dominance (C_1), balance (C_2), and Boeing dominance (C_3). The outcomes represent the forecasted demand scale for the aviation express fleet under these scenarios.

When comparing the forecast results under three scenarios of city economic development (A_1, A_2, A_3), the market share of each aircraft type remains similar. In the $A_1B_2C_2$, $A_2B_2C_2$, and $A_3B_2C_2$ scenarios, the operationally advantageous aircraft type is the Airbus large single-aisle aircraft, with shares of 68.6%, 69.08%, and 68.46% respectively, followed by Boeing's medium single-aisle jet aircraft, with shares of 28.5%, 28.01%, and 28.63% respectively. The absolute demand for each aircraft type escalates with the growth rate of city GDP. Hence, as the economic growth rate of the cities at both ends of the route amplifies, the demand scale for the aviation express fleet will expand, yet the difference in the proportion of demand for each aircraft type is not substantial.

When comparing the forecast results across three scenarios of aviation and high-speed rail cooperation (B_1, B_2, B_3), the market share of each aircraft type remains consistent. In scenarios $A_2B_1C_2$, $A_2B_2C_2$, and $A_2B_3C_2$, the operationally advantageous aircraft type is the Airbus large single-aisle aircraft, with shares of 63.45%, 69.08%, and 68.32% respectively, followed by Boeing's medium single-aisle jet aircraft, with shares of 33.9%, 28.01%, and 28.85% respectively. The absolute demand for each aircraft type increases with the growth rate of passenger flow on the route. Therefore, as the substitution rate of high-speed rail for aviation decreases, the demand scale for aircraft on China's major routes will expand, yet the difference in the proportion of demand for each aircraft type is not substantial.

When comparing the forecast results under three scenarios of Boeing and Airbus competition in the Chinese market (C_1, C_2, C_3), the market share of each aircraft type exhibits a significant difference. In the $A_2B_2C_1$ and $A_2B_2C_2$ scenarios, the Airbus large single-aisle jet aircraft maintains a competitive advantage, with shares of 71.37% and 69.08% respectively, followed by Boeing's medium single-aisle jet aircraft, with shares of 25.30% and 28.01% respectively. In the $A_2B_2C_3$ scenario, Boeing's medium single-aisle jet aircraft secures a competitive advantage, with a demand share of 92.84%, followed by Airbus large single-aisle jet aircraft, with a share of merely 4.42%. Consequently, it can be inferred that the competition between Boeing and Airbus in the Chinese market is the primary factor influencing the operationally advantageous aircraft type on China's major routes, with the Boeing medium single-aisle jet aircraft and the Airbus large single-aisle jet aircraft being the two directly competing models.

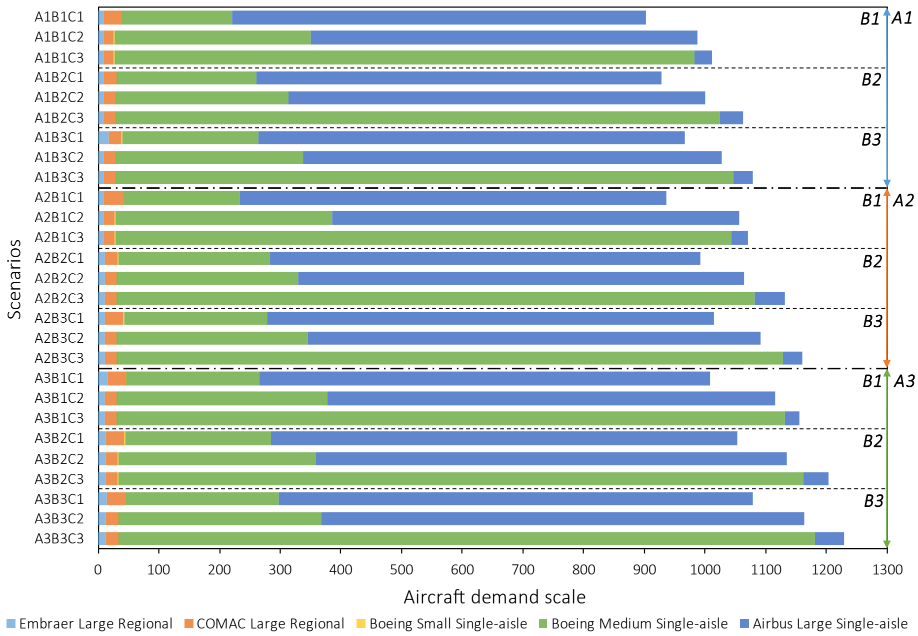


Fig. 2. Operational Advantage Aircraft Types and Their Demand Scale on Major Chinese Routes from 2023 to 2037

3.2 Operationally Advantageous Aircraft Types: Variations in Hub Grades

To further analyze the performance of each aircraft type on different major Chinese routes, this study divides major Chinese routes based on the grades of the aviation hubs at both ends of the route. This division draws upon the ratings outlined in China's aviation hub grades in *the 14th Five-Year Plan for Civil Aviation Development*. Aviation hub grades are categorized into international aviation hubs, regional aviation hubs, and non-hubs, resulting five types of routes. Figure 3 illustrates the proportion of demand (Figure 3a) and demand scale (Figure 3b) of operationally advantageous aircraft types on major Chinese routes of each category under the baseline scenario, specifically, the $A_2B_2C_2$ scenario, spanning from 2023 to 2037.

3.2.1. Routes connecting international aviation hubs constitute the principal commercial application scenarios for all aircraft types

In summary, the market for major routes in China necessitates a total of 1064 aircraft of diverse types. Among them, the fleet size for International-International routes is 469, International-Regional routes is 486, and International-Non-Hub routes are 57. Consequently, the total fleet size for routes connecting international aviation hubs is 1012, accounting for 95.11% of the total fleet size. Additionally, the fleet size for Regional-Regional hub routes is 45, and Regional-Non-Hub routes are 7.

3.2.2. Airbus large single-aisle jets exhibit the most competitive advantage

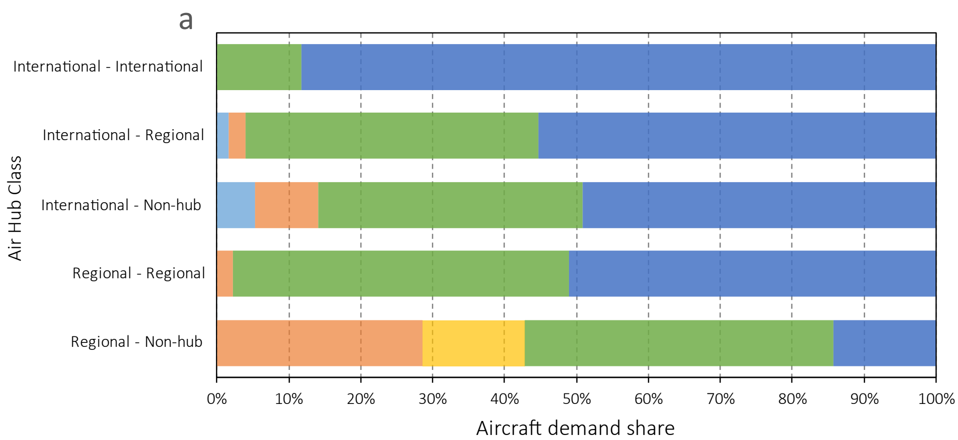
Considering all types of routes, large single-aisle jets are highly competitive. Based on the forecast for the Chinese major route market from 2023 to 2037, the demand for all types of aircraft will amount to 1064 units, among which large single-aisle jets will represent 1033 units, nearly 69.08%

of the total. Medium single-aisle jets are next with a demand of 298 units, nearly 28.01% of the total. Moreover, ARJ21-700, EMB-190, and other turbofan regional jets, also have a presence in the Chinese major route market, with the future operation market primarily concentrated on the International-Regional route market. In terms of brands, Airbus exhibits stronger competitiveness, followed by Boeing.

3.2.3. Different types of routes correspond to different optimal operation aircraft

On international routes, Airbus's large single-aisle jets hold a significant competitive advantage, with a demand for 414 units, which accounts for 88.27% of the 469 units operating on these routes. Boeing's medium single-aisle jets follow, with a demand share of 11.73%. On international-regional, international-non-hub, and regional-regional routes, Airbus's large single-aisle jets continue to hold a competitive advantage, with a demand share ranging from approximately 49% to 55%. Following this, the competitiveness of Boeing's medium single-aisle jets has improved, with their demand share increasing from approximately 36% to 46%. Overall, both Airbus and Boeing have distinct comparative advantages. On regional-non-hub routes, the competitive advantage of Boeing's medium single-aisle jets has further increased, followed by COMAC's large turbofan regional jets, which have demand shares of 42.86% and 28.57%, respectively.

Among all types of routes, the domestically produced COMAC ARJ21 primarily holds a comparative economic advantage on regional-non-hub routes. As the accessibility and quantity of non-hub airports in China continue to rise in the future, new routes will emerge in the regional-non-hub route network that connects hub and non-hub airports, gradually forming an important niche market. The demand for the ARJ21 is also expected to continue to rise.



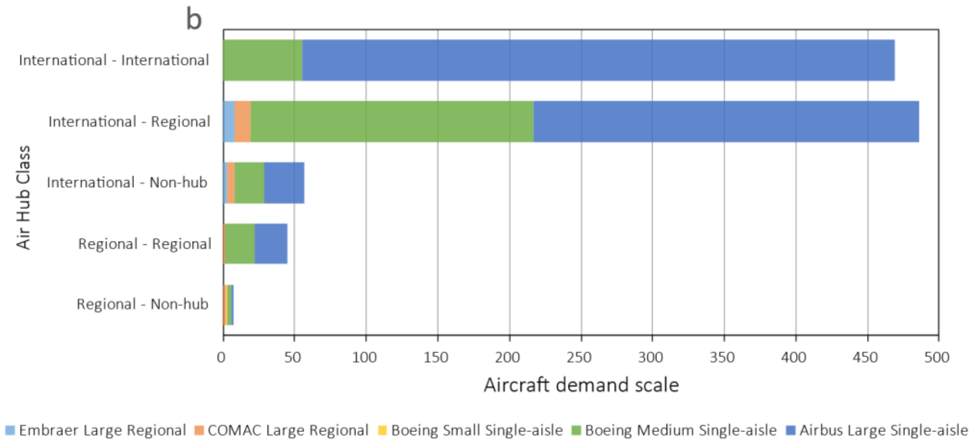


Fig. 3. The demand proportion (a) and demand volume (b) of operationally advantageous aircraft types on major Chinese routes of each category under the $A_2B_2C_2$ scenario from 2023 to 2037

3.3 Operationally advantageous aircraft types: an analysis of market competition

To investigate the influence of the competitive dynamics between Boeing and Airbus in the Chinese passenger aircraft market on operationally advantageous aircraft types and their demand volume, this study computes the projected fleet demand volume considering adjustments in the Airbus purchase cost growth rate. This is conducted under the relatively stable premise of the economic development scenarios of cities at both ends of the route and the civil aviation high-speed rail competition and cooperation scenarios (both under the A_2B_2 scenario).

Fig. 4 illustrates the impact of changes in Airbus' purchase cost growth rate under the A_2B_2 scenario from 2023 to 2037 on the demand share of operationally advantageous aircraft types on primary Chinese routes. If shifts in international relations augment Airbus' purchase costs in the Chinese market to within 3% of operational costs, Airbus' large single-aisle jet aircraft consistently maintain an advantage. When this rises to 4% of operational costs, the advantageous aircraft type becomes Boeing's medium single-aisle jet aircraft, with its demand volume representing approximately 65%. When this climbs to 5% of operational costs, the demand volume for Boeing's medium single-aisle jet aircraft further increases to around 93%. It is evident that when the additional purchase cost of Airbus aircraft, due to shifts in international relations, is within 3% of its operational costs, Airbus' large single-aisle jet aircraft consistently hold a competitive edge in the air express market.

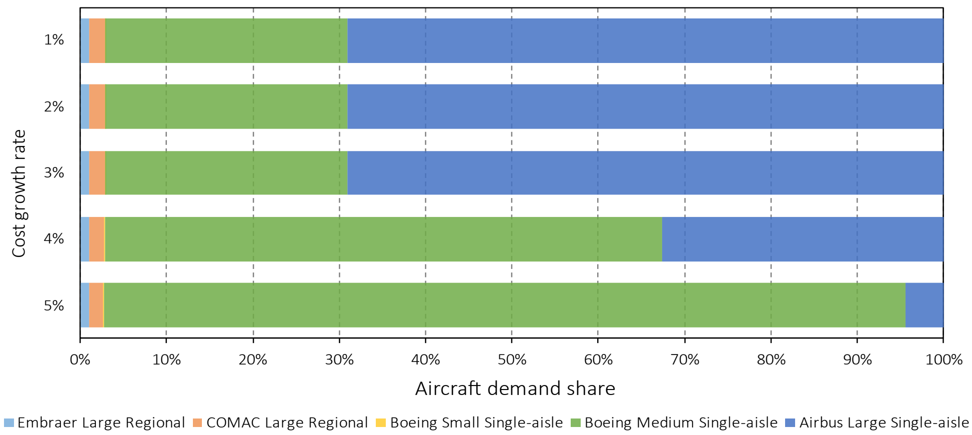


Fig. 4. Effect of Changes in Airbus' Purchase Cost Growth Rate from 2023-2037 on the Demand Share of Operationally Favorable Aircraft Types on Primary Chinese Routes

4. Discussion

This research formulates an integer programming model to delineate the optimization problem of aircraft type and route alignment, gauged by flight operating costs. It projects the fleet demand magnitude in the primary Chinese route market and encapsulates the operationally favorable aircraft types for various route classifications. According to the projections, generally, Airbus' large single-aisle jet aircraft, exemplified by the A321NEO model, possess a comparative edge in the Chinese primary route market, followed by Boeing's medium single-aisle jet aircraft, represented by the B737MAX8 model. Moreover, the A321NEO maintains a distinct economic superiority over the B737MAX8 on international-to-international, international-to-regional, and international-to-non-hub routes. On regional-to-regional routes, both models present equivalent competitiveness. The COMAC ARJ21-700, a domestic regional jet, concentrates on certain international-to-regional, international-to-non-hub, regional-to-regional, and regional-to-non-hub routes, leveraging its economic efficiency. Consequently, Chinese airlines can reference the advantageous aircraft types for assorted route types to strategize their fleet composition, nurture future long-term route markets, and orchestrate aircraft procurement strategies accordingly.

This study extends the forecast results of the operationally advantageous aircraft types and their demand scale on the main Chinese routes, constructing 27 development scenarios for the Chinese air passenger market. These scenarios are driven by factors such as the economic development of cities at both ends of the route, the interplay between high-speed rail and civil aviation, and the competitive dynamics of Boeing and Airbus in the Chinese market. Our research suggests that the economic development of cities at both ends of the route and the interplay between high-speed rail and civil aviation primarily influence the passenger flow and fleet demand scale of the route market. However, they have a minimal impact on the demand proportion of each aircraft type, thus their influence on the operationally advantageous aircraft type is marginal. The competitive dynamics of Boeing and Airbus in the Chinese market exert a minor influence on the fleet demand scale, but significantly affects the demand proportion of each aircraft type, thus becoming a key factor influencing the operationally advantageous aircraft type. Consequently, airlines and airports can modify their anticipated route passenger flow scale and fleet demand scale by future trends in city economic development and the interplay between high-speed rail and civil aviation, when strategizing resource investments. Airlines can modify their expectations of the competitive dynamics between Boeing and Airbus in the Chinese market, and the corresponding operationally advantageous aircraft type for air express, in line with international relations trends when strategizing their fleet.

Based on our calculations, under the scenario of subdued GDP growth in cities at both ends of the route, the passenger flow scale on the main Chinese routes from 2023 to 2037 is projected to range between 4.3 and 4.5 billion. Under a moderate growth scenario, the passenger flow scale is projected to be between 4.6 and 4.8 billion. In an accelerated growth scenario, the passenger flow scale is projected to be between 4.9 and 5.2 billion. When the supplementary purchase cost of Airbus aircraft, resulting from shifts in international relations, is within 3% of its operating costs, Airbus' large single-aisle jet aircraft consistently maintain a competitive edge in the air express market. Airlines and airports can modify their expectations of air express passenger market capacity and fleet demand scale in line with forecast results under diverse scenarios when strategizing resource investments.

5. Conclusions

This study conducts a route-level analysis, concentrating on aircraft type optimization for particular routes. Accurately forecasting the demand for preferred operational aircraft types on China's major routes under various scenarios is essential for airlines in the face of escalating market risks. This contributes to improving aircraft procurement and flight operation strategies, thereby enhancing business efficiency and profitability, as well as the quality and profitability of route operations. The main findings of this study are as follows:

1. Employing a bottom-up Model (ATDFM), our study indicates that Airbus's large single-aisle jets exhibit the highest theoretical demand potential in the Chinese mainline market, followed by Boeing's medium single-aisle jets.
2. The competitive edge of Airbus's large single-aisle jets is striking on routes connected to international aviation hubs, whereas Boeing's medium single-aisle jets show a significant advantage on routes linked to regional aviation hubs and non-hubs.
3. Airbus's large single-aisle jets sustain their competitive advantage in the express airline market provided that the additional procurement costs attributed to international relations do not exceed 3% of their operational costs.
4. The rivalry between Boeing and Airbus in the Chinese market profoundly affects the demand distribution for various models, emerging as a significant factor in influencing the choice of preferred operational aircraft for a route.

These insights provide significant implications for both airlines and aircraft suppliers, facilitating the continuous optimization of aircraft procurement and flight operation strategies, along with strategic planning for long-term product design and production line layouts.

This study is subject to several limitations. Firstly, uncertainty exists within the parameter settings of driving factors in the constructed scenarios, which could benefit from an expanded dataset for more comprehensive analysis to better align with real-world conditions. Secondly, in the calculation of flight operational costs, variations in engine and high-cycle parts depreciation—influenced by factors such as aircraft acquisition methods and depreciation approaches—show significant differences across airlines and are challenging to obtain, hence this variability was not included in the analysis. Future research may address this element by refining the model and securing reliable data sources. Lastly, owing to restricted data access, some pertinent aircraft models were excluded from the stock (

Table 7), necessitating further field research to assemble a more comprehensive list.

Acknowledgments

This work was supported by the National Natural Science Foundation of China "Research and validation of key technologies for air-ground security integration of small and medium-sized airport clusters" (Grant No.U2333206). MOE Project of Key Research Institute of Humanities and Social Sciences at Universities "Research on Strategic Transformation and Sustainable Development of State-owned Enterprises under the Perspective of Green Governance" (Grant No.22JJD630006). Tianjin Research Innovation Project for Postgraduate Students " Theoretical Mechanism and Empirical Study on the Influence of Air Transport Network on Regional Coordinated Development" (Grant No.2022SKY168).

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