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Near-Term Suitability Assessment of Deploying DAC System at Airport: A Case Study of 52 Large Airports in China

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Abstract: This study is the first to propose the deployment of direct air capture (DAC) systems at large airports to provide solutions for achieving carbon neutrality in aviation transportation. Here, an estimating model for carbon dioxide (CO_2) emissions in the landing and take-off (LTO) phase of large airports was developed, and the suitability of deploying DAC systems at airports was evaluated by the analytic hierarchy process (AHP). This study found that the annual CO_2 emissions of 52 large airports in the LTO phase are about 23 Mt, accounting for about 23% of the total CO_2 emissions of civil aviation in China. The four dimensions of airport transportation conditions, meteorological conditions, space resources, and security levels had a decreasing impact on the deployment of DAC systems in that order. The airports with suitable DAC systems are mainly located in the Yangtze River Delta, the Pearl River Delta, and the Chengdu-Chongqing Airport Cluster. This study provides a theoretical basis for the deployment of DAC systems at airports, which provides new CO_2 emission reduction solutions for the aviation transportation industry.

Keywords: carbon neutrality; CO_2 emissions; DAC; suitability evaluation; LTO

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1. Introduction

The growth of the civil aviation industry has been rapid due to the development of the global economy and the increase in people's living standards. However, this growth may have potential impacts on public health, the environment, and climate [1]. Of particular concern are the carbon emissions resulting from civil aviation, which have garnered increasing attention [2]. In recent years, carbon emissions from civil aviation have shown a trend of year-on-year growth. According to the International Air Transport Association (IATA), global civil aviation carbon emissions in 2019 (before the Corona Virus Disease 2019) were 990 million tons, accounting for 2.4% of total global carbon emissions. Civil aviation carbon emissions are expected to increase more than three times by 2050. Therefore, reducing carbon emissions from civil aviation has become an urgent issue.

According to the IATA, the total CO_2 emissions from global commercial aviation in 2019 reached 915 million tons, accounting for 2.4% of global CO_2 emissions. Additionally, 85% of the emissions come from passenger transport, reaching 778 million tons [3]. The aviation industry urgently needs to balance the demand for green development and improve industry competitiveness. The resolution of achieving net-zero carbon emissions by the global aviation industry by 2050 was approved at the 77th IATA Annual General Meeting. The commitment of this resolution is in line with the goals of the Paris Agreement, which is to limit global temperature rise to no more than 1.5 °C. To achieve the temperature control goal, the aviation industry in 2050 will need to reduce carbon emissions by 1.8 billion tons, and 65% of the emissions will be reduced through sustainable aviation fuels.

It is expected that new propulsion technologies, such as hydrogen, will reduce emissions by 13%. Efficiency improvements can contribute 3%. The remaining emissions will need to be addressed through carbon capture, utilization, and storage (11%) and offsetting (8%) [4].

In order to reduce carbon emissions from civil aviation, International Civil Aviation Organization (ICAO) has proposed a series of emission reduction measures, which include improving aircraft fuel efficiency, adopting Sustainable Aviation Fuels (SAFS) [5] biofuels, and improving air traffic control systems, but it cannot completely achieve carbon neutrality in the civil aviation industry [6,7]. In addition, some airlines have adopted their own emission reduction techniques, such as purchasing carbon offsets, adopting more environmentally friendly aircraft types, and promoting electronic passenger tickets. These measures can effectively reduce civil aviation carbon emissions, but the amount of emission reduction is relatively low.

Research shows now that the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program has a very limited incentive for major airlines to implement proactive mitigation measures [8]. As a result, airlines have explored and invested in carbon capture technologies. For example, United Airlines and Occidental Petroleum are investing in a large "direct air capture of CO_2 (DAC)" plant in Texas that will operate with fans and chemicals to remove CO_2 from the air and inject it underground. The plant will utilize fans and chemicals to remove CO_2 from the air and inject it into the ground. United Airlines' DAC technology research is driven by the company's vow to become carbon neutral by 2050 and its belief that technology, such as efficient aircraft and sustainable biofuels, are not enough.

It is predicted that China will surpass the United States as the world's largest civil aviation transportation market by 2030 [3]. The need to actively explore new emission reduction options for China's aviation transportation industry is equally important ahead of time. About 100 million tons of CO_2 were emitted in the civilian sector in China by 2020. Some studies indicate that China's aviation carbon emissions will increase significantly from 2020–2050, with CO_2 emissions likely to increase by 1.6 to 3.9 times [9]. As the potential for emission reduction from technology enhancement, equipment renewal, and operational optimization is approaching the "ceiling", it is extremely difficult to achieve carbon neutrality in the air transport industry by 2050, and China's air transport industry also needs to explore carbon capture technology to implement carbon reduction.

The DAC technology is a technology that recycles CO_2 emissions from distributed sources and is recognized as a key technology for climate change mitigation, comparable to solar, wind, batteries, and electrolyzers [10]. The DAC technology captures CO_2 in the air by means of adsorbent. After completing the trapping, the adsorbent is regenerated by changing heat, pressure, or temperature, and the regenerated adsorbent is applied again for CO_2 trapping while the pure CO_2 is stored. The advantage of DAC technology is that it can capture CO_2 from millions of small fossil fuel-burning units and hundreds of millions of distributed sources, such as vehicles. In the International Energy Agency (IEA) 2050 net-zero emissions scenario, more than 85 million tons of CO_2 would need to be captured by the DAC technologies in 2030, capturing about 9.8 million tons of CO_2 in 2050, requiring a significant acceleration from the current approximately 0.01 $MtCO_2$ [11]. There are currently 18 DAC facilities in Canada, Europe, and the United States. The first large-scale DAC unit with annual CO_2 emissions of up to one million tons is under construction with development in the US. In addition, the DAC plant has greater flexibility in terms of placement location than technologies, such as CCS or CCUS, which are primarily aimed at stationary source capture [12,13]. Under current technology, the levelized cost per ton of CO_2 captured from the atmosphere ranges from \$94 to \$232/ton of CO_2 [14], and all DAC technologies have the potential to operate at less than \$200/ton [15], with further decreases in capture costs expected in the future. Furthermore, DAC technologies can help to address unavoidable emissions and emissions from distributed sources, where 24% of transport emissions need to be reduced with the help of DAC [16]. At the same time, DAC technology can be combined with CCS technology to capture the CO_2 leaked from the CCS

technology storage [17]. The trend of increasing CO_2 emissions from the air transportation industry is inevitable, and the rational use of DAC technology may result in "negative carbon emissions" and greatly reduce atmospheric CO_2 concentration.

The above are the opportunities of DAC technology in the carbon-neutral background, meanwhile DAC technology development faces significant challenges in the future. Carbon capture technologies require high water resources [18], and DAC technology is no different. Assessed from a whole life cycle perspective, the DAC technology does not have advantages over renewable energy in terms of land use and material consumption, and the energy consumption will increase about five times [19]. In fact, the life cycle water consumption, material consumption, and land use of DAC systems are also of concern, and preliminary estimates of water consumption of DAC technologies range from 0 to 50 $Gt/GtCO_2$, and the utilization of renewable energy sources such as photovoltaic and wind power to drive DAC systems will lead to a significant increase in their life cycle land use area [20]. The current study concluded that DAC technology development could not be achieved without strong policy support [21].

The possibility of deploying DAC systems at airports is worthy of further study due to the relatively high carbon emissions from the LTO. The LTO cycle is a closed working process of aircraft landing from a high altitude at airport and taking off from an airport to a high altitude. It is defined as a height of 915 m from the surface to the top of the atmospheric boundary layer of airport aircraft. LTO cycle is a closed working process of aircraft landing from a high altitude to an airport and taking off from an airport to a high altitude. It is defined as a height of 915 m from the surface to the top of the atmospheric boundary layer [22]. The current research based on the LTO cycle focuses on the accounting and management of emissions around airports [23]. The emission is calculated with the type and number of aircraft, engine type, number of passengers, and using emission factors from the International Civil Aviation Organization engine exhaust emission database [24]. The main focus was on the study of pollutants such as nitrogen oxides, carbon monoxide, and hydrocarbons with aviation particles at airports during the LTO phase [25,26]. Moreover, studying more airport-specific LTO pollutant emissions, ref. [27] measured the total count concentration of 10 to 1000 nm particles, particle size distribution, and mass concentration of PM2.5 on the parking apron adjacent to the runway of Tianjin International Airport, China. Ref. [28] conducted an in-depth analysis of pollutant emissions during the aircraft take-off and landing cycle at Nanjing Lukou Airport (NKG). Ref. [29] presented ground-based, stratospheric aircraft engine emissions from flights departing at Los Angeles International Airport. Ref. [30] employed airline flight data to evaluate emissions from Turkish Airlines during the LTO phase. Studies related to CO_2 emissions during the LTO cycle of airports have been gradually paid attention to in recent years [31]. Aircraft emissions from the LTO cycles at Chania Airport (Crete), Greece, were estimated for the year 2016, adopting the International Civil Aviation Organization (ICAO) methodology and using daily data from air traffic [32]. Developed a methodology using flight data and Daily Aircraft Movement Records (DAMR) data to estimate CO_2 emission levels for different phases of flight within the LTO cycle [33]. An improved method is proposed to estimate aircraft emissions from LTO cycles [34]. However, the above studies are limited to accounting for pollutant and carbon emissions from airport LTO cycles and do not propose breakthrough emission reduction solutions.

However, the above studies are restricted to the accounting of pollutants and carbon emissions from LTO cycles in airports and do not propose breakthrough emission reduction solutions. In fact, the research on the deployment of DAC technology in civil aviation is only at the stage of a theoretical feasibility study, and there is a lack of research on the direct deployment of DAC technology in airports. This study will carry out a preliminary exploration of the deployment of DAC systems in airports, taking a large international airport in China as an example.

Based on the demand for carbon capture systems in the aviation industry and the advantages of DAC systems themselves, this study will explore the potential of deploying

DAC systems in airports. The following three main questions will be addressed: (1) What is the amount of CO_2 emissions in the LTO phase at major airports in China? (2) What are the factors influencing the deployment of DAC devices at airports? (3) Which airports are suitable for DAC deployment demonstration projects?

2. Data and Methodology

2.1. Data Sources

Large 4F and 4E international airports in China were selected for the study. In order to evaluate the airports, data on airport resources, production, weather, and safety levels were obtained. The data on airport resources and airport safety level were obtained from the Civil Aviation Administration of China (CAAC) Civil Airport Encyclopedia database [35]. Airport production data, such as passenger throughput, cargo throughput, take-offs, and landings, were obtained from the "Civil Aviation Airport Production Statistics Bulletin" [36] and "Civil Aviation Industry Development Statistics Bulletin" [37]. Airport climate data were obtained from China Meteorological Data Network and China Weather [38] (see Appendix A, Table A1). The types and numbers of aircraft in service for the major Chinese aviation groups are shown in Table 1. Fuel burn and emissions data for different aircraft types in the LTO phase were obtained from the European Environment Agency [39,40].

Table 1. Statistics of aircraft types and numbers of major aviation groups in service in China.

Aircraft Type	ACG	CEAG	CSAH	HAG	Total
Airbus A319-100	36	34	17	14	101
Airbus A319neo	0	0	4	0	4
Airbus A320-200	120	165	113	111	509
Airbus A320neo	75	91	47	33	246
Airbus A321-200	68	73	96	23	260
Airbus A321neo	36	0	58	3	97
Airbus A330-200	19	29	10	22	80
Airbus A330-300	34	24	25	35	118
Airbus A350-900	23	16	16	0	55
Boeing 737-700	30	47	31	10	118
Boeing 737-800	321	212	312	207	1052
Boeing 737 MAX 8	7	0	11	8	26
Boeing 747-400	5	2	0	3	10
Boeing 747-8	4	0	0	0	4
Boeing 777-300ER	20	20	15	0	55
Boeing 777F	9	13	15	0	37
Boeing 787-8 Dreamliner	0	0	16	7	23
Boeing 787-9 Dreamliner	10	10	23	27	70
Embraer ERJ-135	0	2	0	0	2
Embraer ERJ-190	0	0	5	34	39
Embraer ERJ-195	0	0	0	20	20
COMAC ARJ21	14	16	19	0	49
Total	831	754	833	557	2975

ACG = Air China Group; CEAG = China Eastern Airlines Group; CSAH = China Southern Airlines Holding; HAG = Hainan Airlines Group; https://www.planespotters.net/search?q=Air+China (accessed on 20 March 2023).

2.2. CO_2 Emissions Estimation Methods in the LTO Cycle

Figure 1 shows the flowchart of the study. In the first step, four categories of 13 types of data were obtained for 52 airports, in addition to the percentage of aircraft types that LTO at the airports. In the second step, a model was developed to assess the CO_2 emissions of airports in the LTO phase and a model based on the AHP method to evaluate the suitability of DAC system deployment. Finally, the evaluation model was applied to evaluate the CO_2 emissions and suitability of 52 airports and identify the airports suitable for DAC system deployment in China.

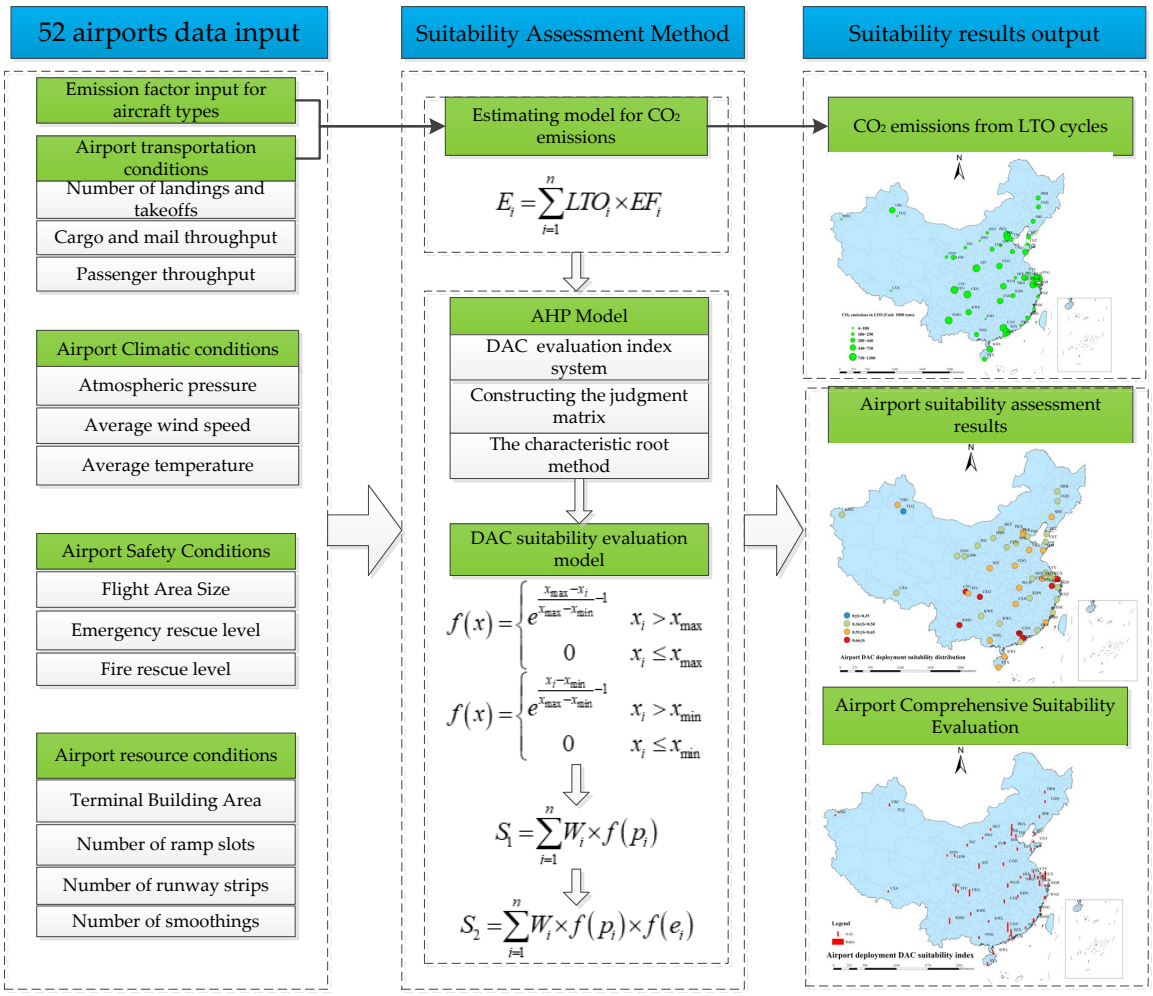


Figure 1. Flow chart of this study.

2.3. CO_2 Emissions Estimation Methods in the LTO Cycle

The LTO cycle consists of taxiing, take-off, and climb at take-off and landing, approach, and taxiing at the end of the aircraft, see Figure 2. The fuel rate of the aircraft in this cycle is different in each phase, while the fuel efficiency required to bring the aircraft up (and land again) is different, and the fuel required to bring the aircraft up (and land again) is independent of the flight time and can be considered constant.

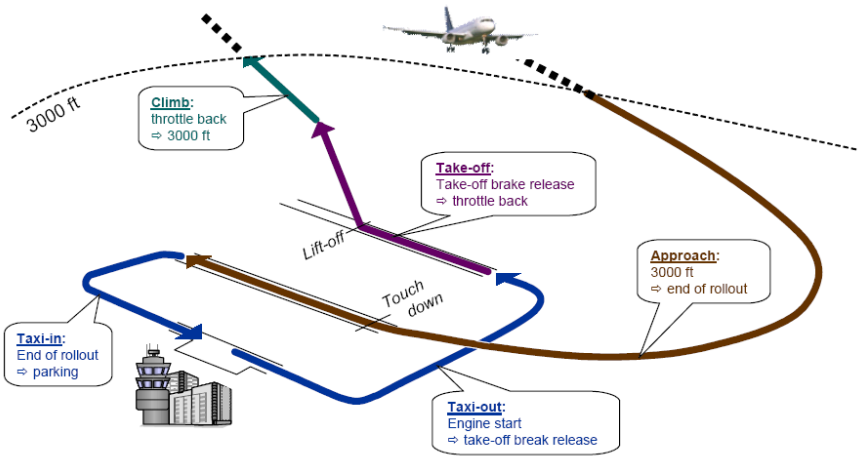


Figure 2. LTO cycle [40].

For the calculation of aviation carbon emissions for the LTO cycle, the calculation can usually be based on the total activity data multiplied by the corresponding cycle average emissions [41], as shown in Formula (1):

$$E_i = \sum_{i=1}^{n} LTO_i \times EF_i \quad (1)$$

where E_i denotes the annual LTO phase aviation carbon emissions of the i airport, LTO_i denotes the total number of LTO cycles of the i airport, and EF_i is the average carbon emissions per LTO cycle (kg/LTO) of the i airport throughout the year.

2.4. Airport Suitability Evaluation

The hierarchical analysis method has the advantages of being systematic, simple, and practical and requiring less quantitative data information. It solves the problem of systematic analysis of different levels of data in assessing the suitability of airport deployment DAC and solves the difficulty of not having detailed data in the initial assessment of airport suitability because of the relatively less data required. This method is very suitable for the assessment of the airport deployment DAC system, which is a system without structural characteristics.

The AHP, as a multi-objective analysis and decision-making method, decomposes a complex multi-objective problem into several factors and groups them into a hierarchy according to their relationships, and calculates the single ranking (weights) and total ranking of the hierarchy through the fuzzy quantification method of qualitative indicators to determine the relative importance of each factor in the hierarchy. The suitability of airport deployment of the DAC system is a complex problem covering many influencing factors, so it is reasonable for the hierarchical analysis method to be used to evaluate the suitability of the airport.

2.4.1. Evaluation Index System

In this paper, we combine the conditions of airport safety, weather, resources, and production, consider the impact of the DAC system operation on airport production, follow the principles of objectivity, relevance, and operability, and select airport climate, airport safety, airport resources, and airport production as the criterion layer based on the analytical idea of AHP, and select 13 indicators under the criterion layer as the indicator layer to establish the evaluation system of the suitability of DAC system deployment in major national airports in China, as shown in Figure 3.

2.4.2. Constructing the Judgment Matrix

In this paper, we employ the 1–9 scale method to analyze the above hierarchical index system, compare the elements in each level by 2 based on experts' scores, and then construct a judgment matrix based on the relative importance of each level using the exponential scale method to reduce the difficulty of comparing different indicators and the influence of human factors, improve the accuracy, and finally calculate the weight of each indicator.

2.4.3. Checking the Consistency of the Judgment Matrix

The characteristic root method is used to determine the relative importance ranking of all factors at the same level relative to the corresponding elements at the previous level, and then the maximum characteristic root is solved, and then the consistency test is performed. In this paper, based on the engineering background of practical application and with reference to the index weights in the existing research results, the average random consistency index value is used for the consistency test of the exponential scale judgment matrix (Table 2). The test Formula (2) is:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

where n is the latitude of the matrix, CI 0, also complete consistency, CI close to 0, there is satisfactory consistency, the larger the CI, the more serious the inconsistency. In order to measure the size of CI, the random consistency index RI is introduced. The method for randomly constructing 500 promissory comparison matrices defines the consistency ratio, as shown in Formula (3):

$$CR = \frac{CI}{RI} \tag{3}$$

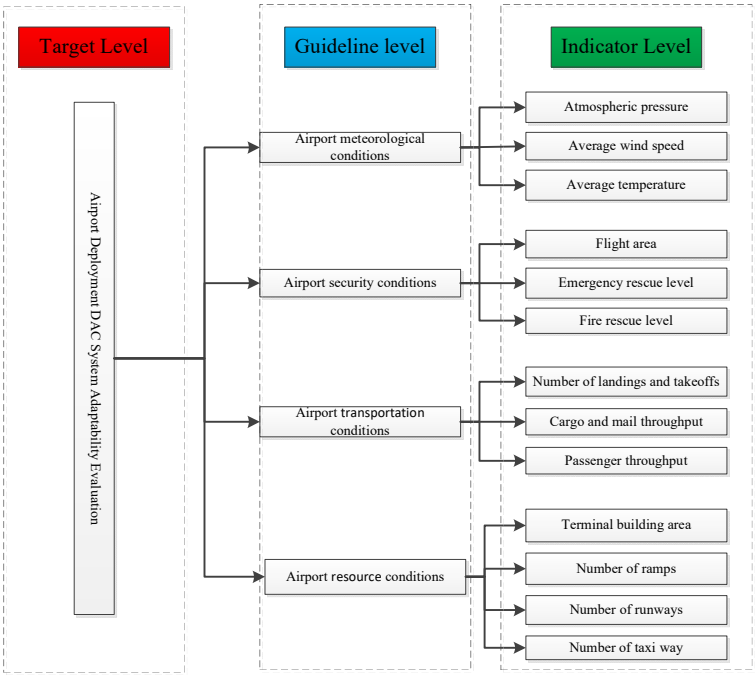


Figure 3. Airport Deployment DAC System Suitability Evaluation System.

Table 2. The RI factors.

Matrix Order	3	4	5	6	7	8	9
RI	0.5149	0.8031	1.1185	1.2494	1.3450	1.4200	1.4646

Generally, when the consistency ratio $CR < 0.1$, the degree of inconsistency of the judgment matrix is considered to be within the permissible range, and there is satisfactory consistency, which passes the consistency test, and its normalized feature vector can be used as the weight vector, otherwise it should be reconstructed into a pairwise comparison judgment matrix and adjusted.

2.4.4. Suitability Evaluation Model

In order to determine the scores of the evaluation indicators, this study selected the dimensionless fuzzification process to calculate the scores of each indicator for each airport and the Formula (4) at the dimensionless fuzzification process of the data of the said positive indicator class parameters is:

$$f(x) = \begin{cases} e^{\frac{x_i - x_{min}}{x_{max} - x_{min}} - 1} & x_i > x_{min} \\ 0 & x_i \leq x_{min} \end{cases} \tag{4}$$

where $f(x)$ is the quantized value of the parameter to be treated after eliminating the effect of the magnitude, x_i is the parameter value of the parameter to be treated, x_{max} is the maximum value of the parameter of the influence factor in the candidate airport, x_{min} is the minimum value of the influence factor in the candidate airport.

The Formula (5) at the data dimensionless fuzzification of the inverse indicator class parameters described is:

$$f(x) = \begin{cases} e^{\frac{x_{max}-x_i}{x_{max}-x_{min}}-1} & x_i < x_{max} \\ 0 & x_i \geq x_{max} \end{cases} \quad (5)$$

where $f(x)$ is the quantified value of the parameter to be treated after eliminating the effect of the magnitude, x_i is the parameter value of the parameter to be treated, x_{max} is the maximum value of the parameter of the influence factor among the candidate airports, x_{min} is the minimum value of the parameter of the influence factor among the candidate airports.

In the study of suitability evaluation, most scholars have adopted evaluation models, such as the comprehensive index method, fuzzy comprehensive judgment method, multi-objective linear weighting method, etc., of which, comprehensive index method is the common method for suitability evaluation at present, and this paper selects the comprehensive index method to carry out the suitability evaluation of DAC of China International Airport with the following Formulas (6) and (7):

$$S_1 = \sum_{i=1}^{n} W_i \times f(P_i) \quad (6)$$

where, S_1 is the suitability evaluation result, W_i is the weight of the ith evaluation index, $f(P_i)$ is the score of the ith evaluation index.

$$S_2 = \sum_{i=1}^{n} W_i \times f(P_i) \times f(e_i) \quad (7)$$

where, S_2 is the result of comprehensive suitability evaluation after the introduction of carbon emission, W_i is the weight of the ith evaluation index, $f(P_i)$ is the quantified value of the ith index after eliminating the influence of the scale, $f(e_i)$ is the quantified value of the ith airport carbon emission after eliminating the influence of the scale.

Based on the quantitative criteria of suitability evaluation and assigned to the evaluation unit, the suitability evaluation results of DAC system deployment at China International Airport were obtained by superimposing the index scores according to Formulas (5) and (6). According to the classification of the suitability evaluation results and the dimensionless quantified values of the indicators, the airport evaluation results are classified into four levels: Suitability, sub-suitability, general suitability, and poor suitability, as shown in Table 3.

Table 3. Classification of suitability evaluation results.

Evaluation Result Intervals	**0 ≤ S < 0.35**	**0.36 ≤ S < 0.5**	**0.51 ≤ S < 0.65**	**0.66 ≤ S**
Evaluation Levels	Poor suitability	General suitability	Sub-suitability	Suitability

3. Results and Discussion

3.1. CO_2 Emissions from LTO Cycles

In order to better locate airports suitable for the deployment of DAC systems, the annual LTO cycle CO_2 emissions of major 4E and 4F airports were accounted for in this study in China. The distribution of LTO cycle CO_2 emissions for 52 airports in China is shown in Figure 4. The annual CO_2 emissions from LTO cycle at the 52 airports are about 23 Mt, of which the top five airports are Guangzhou Baiyun International Airport (CAN), Shanghai Pudong International Airport (PVG), Shenzhen Baoan International Airport (SZX), Chengdu Shuangliu International Airport (PKX) and Beijing Capital International Airport (CTU). The annual CO_2 emissions of aircraft landing and taking off from these five airports in LTO phase are 1.24, 1.19, 1.09, 1.03, and 1.02 Mt, respectively, and the total emissions of these 5 airports account for about 24% of the annual emissions of 52 airports,

which is the most suitable for the deployment of DAC system only from the perspective of CO_2 emissions.

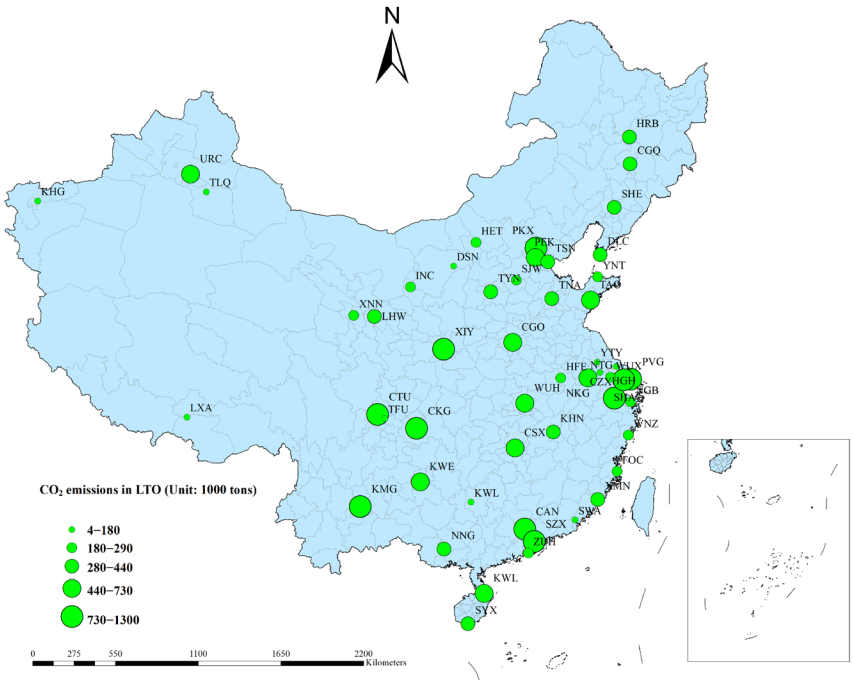


Figure 4. CO_2 emissions in the LTO cycle phase at major airports.

From a sub-regional perspective, see Figure 3, the suitable airport clusters are mainly located in four regions: North China, East China, South China, and Southwest China. Among the clusters, North China is the cluster area of Beijing and Tianjin city airports, with LTO cycle CO_2 emissions of about 2.4 million tons/year. East China is the cluster area of airports in Shanghai, Nanjing, Changzhou, and other cities, with LTO cycle CO_2 emissions of about 4.5 million tons/year. South China is the cluster area of airports in Guangzhou, Shenzhen and other cities, with LTO cycle CO_2 emissions of about 2.7 million tons/year. Southwest China is the cluster area of Chengdu and Chongqing, with LTO cycle CO_2 emissions of about 2.1 million tons/year. In Southwest China, Chengdu and Chongqing are the clusters of CO_2 emissions, with LTO cycle CO_2 emissions of about 2.1 million tons/year. From the perspective of the number of flights and CO_2 emissions, these regions are suitable for the deployment of DAC systems.

3.2. Airport Suitability Evaluation

It is not sufficient to evaluate the suitability of airports to deploy DAC systems only in terms of CO_2 emissions. Therefore, four dimensions were selected by considering the airport meteorological, airport security, airport resource, and airport transportation conditions. From the results of expert scoring (see Table 4), the four decision-level indicators were ranked in descending order of importance for airport DAC deployment: Airport meteorological, airport security, airport resource, and airport transportation conditions.

Table 4. Decision matrix determination of guideline level.

Guideline Level	Airport Meteorological	Airport Security	Airport Resource	Airport Transportation
Airport meteorological	1	1/5	1/7	1/9
Airport security	5	1	1/2	1/5
Airport resource	7	2	1	1/3
Airport transportation	9	5	3	1

In airport meteorological conditions, the importance of DAC system deployment is in order of atmospheric pressure, average temperature, and average wind speed (see Table 5), where average wind speed is the most critical factor affecting DAC system deployment, which will directly affect the diffusion rate of CO_2 and consequently the capture efficiency of DAC system.

Table 5. Determination of airport meteorological judgment matrix.

Airport Meteorological	Atmospheric Pressure	Average Temperature	Average Wind Speed
Atmospheric pressure	1	1/5	1/9
Average temperature	5	1	1/2
Average wind speed	9	2	1

The deployment of the DAC system should reduce the impact on airport safety, which requires high-security measures at the airport. Therefore, at the level of airport security, from the expert scoring results (see Table 6), the impact of flight area, emergency rescue level, and fire rescue level on the deployment of the DAC system at the airport increases step by step.

Table 6. Airport security judgment matrix determination.

Airport Security	Flight Area	Emergency Rescue Level	Fire Rescue Level
Flight area	1	1/3	1/5
Emergency rescue level	3	1	1/3
Fire rescue level	5	3	1

For the impact of airport production influencing factors on DAC system deployment, experts scored mainly considering the magnitude of total carbon emissions (see Table 7) so that the degree of influence of passenger throughput, cargo and mail throughput, and number of take-offs, and landings decreases gradually.

Table 7. Airport transportation judgment matrix determination.

Airport Transportation	Number of Landings and Take-Offs	Cargo and Mail Throughput	Passenger Throughput
Number of landings and take-offs	1	1/3	1/5
Cargo and mail throughput	3	1	1/2
Passenger throughput	5	2	1

The amount of airport resources is directly related to whether the airport has sufficient space to deploy a DAC system. Therefore, the airport terminal building area, ramps, number of runways and taxiways quantity will affect the deployment space. The expert scoring takes into account that the DAC system is most suitable to be deployed near the runway and taxiway too, therefore, these four airport resource factors have an increasing influence on the DAC system deployment in order (see Table 8).

The factors influencing the deployment of DAC systems at airports were weighted using hierarchical analysis in this study. The weighting of each influencing factor is calculated, and from the 13 factors, it is found that (see Table 9), the most critical indicator table affecting the deployment of DAC system at airports is passenger throughput (39.2% weighting), followed by cargo and mail throughput and average wind speed both at 15.4%, and these three factors directly determine the CO_2 emissions in the LTO cycle phase at airports, which affects the airport CO_2 concentration and thus the DAC system These three factors directly determine the CO_2 emissions during the LTO cycle and affect the airport CO_2 concentration, thus affecting the efficiency and CO_2 capture cost of the DAC system. Atmospheric pressure, with a weight of 6.2%, mainly affects the CO_2 diffusion rate and has

a greater impact on CO_2 capture by the DAC system. The number of smoothing and the number of runs are also relatively high because the DAC system needs a certain amount of space for deployment. The other influence factors also have some influence on DAC, but the degree of influence is relatively low.

Table 8. Airport resource judgment matrix determination.

Airport Resource	Terminal Building Area	Number of Ramps	Number of Runways	Number of Taxiways
Terminal building area	1	1/4	1/5	1/7
Number of ramps	4	1	1/3	1/5
Number of runways	5	3	1	1/3
Number of taxiways	7	5	3	1

Table 9. The weighting of factors influencing the deployment of DAC systems at airports.

Target Level	Guideline Level Weight	Indicator Level	Indicator Level Weight	Combined Weights
Suitable for deployment of DAC systems at airports	Airport security (0.039)	Flight area	0.072	0.003
		Emergency rescue level	0.279	0.011
		Fire rescue level	0.649	0.025
	Airport resource (0.137)	Terminal building area	0.051	0.007
		Number of ramps	0.126	0.017
		Number of runways	0.262	0.036
		Number of taxiway	0.561	0.077
	Airport meteorological (0.241)	Atmospheric pressure	0.105	0.025
		Average temperature	0.258	0.062
		Average wind speed	0.637	0.154
	Airport transportation (0.583)	Number of landings and take-offs	0.063	0.037
		Cargo and mail throughput	0.265	0.154
		Passenger throughput	0.672	0.392

3.3. Airport Suitability Assessment Results

Based on the AHP, the suitability of 52 large airports in China for the deployment of DAC systems was evaluated. From Figure 5, we can find that there are seven airports with the suitability index over 0.65, namely, Guangzhou Baiyun International Airport (CAN), Shanghai Pudong International Airport (PVG), Shenzhen Baoan International Airport (SZX), Chongqing Jiangbei International Airport (CKG), Chengdu Shuangliu International Airport (CTU), Kunming Changshui International Airport (KMG) and Hangzhou Xiaoshan International Airport (HGH). These seven airports are among the top 52 airports in terms of emergency response level, airport resources, and airport production capacity, which provide safe and sufficient space for the deployment of DAC systems, while having a large carbon footprint. In addition, these seven airports are located south of the Yangtze River in China, where the temperature and wind speed are ideal for DAC systems, and the climate diffusion conditions are poor for direct CO_2 capture from the air.

From the geographical distribution of suitability, it is easy to see in Figure 4 that the distribution of airports that are more suitable and generally suitable for DAC system deployment is balanced. The suitability airports are mainly concentrated in the airport cluster areas of Beijing, Tianjin, Hebei and Yangtze River, and Hainan Island, while the generally suitable airports are more distributed in the northeast and northwest regions. In terms of the suitability ratio, the percentage of suitable airports is 13.5%. The highest percentage of generally suitable airports is about 51%, followed by more suitable airports with about 36%. There is only one international airport with poor suitability for the Turpan Jiaotonghe Airport (TLQ) distributed in Xinjiang, which is mainly due to low CO_2 emissions in the LTO phase, the poor safety emergency level, and high average wind speed all year round.

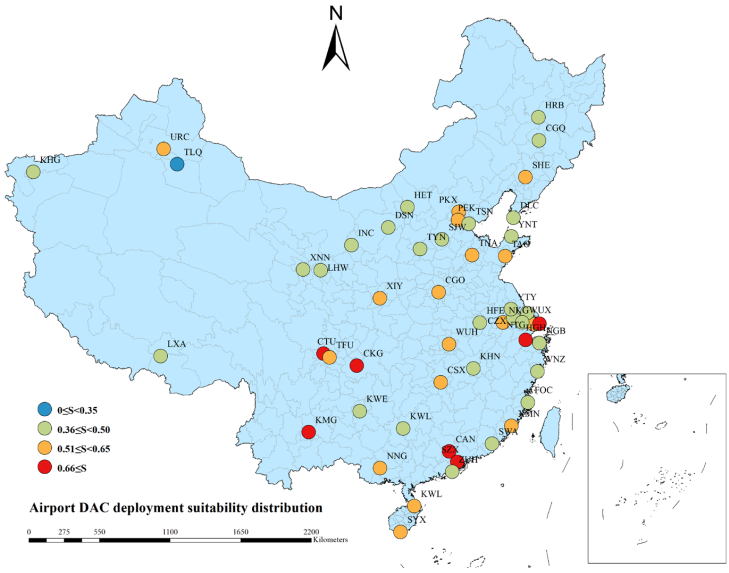


Figure 5. Airport deployment DAC suitability distribution.

3.4. Airport Comprehensive Suitability Evaluation

The airport LTO phase CO_2 emissions were introduced into the airport suitability evaluation, and the results of the comprehensive airport suitability evaluation were obtained. The suitability index of the evaluated airports was evaluated based on the weights of the influencing factors of the airport DAC system deployment, the dimensionless data of each influencing factor, and its carbon emission of each airport. The higher the suitability index of an airport, the more suitable it is for the deployment of the DAC system.

From Figure 6, the top five airports in the suitability index are Guangzhou Baiyun International Airport (CAN), Shanghai Pudong International Airport (PVG), Shenzhen Baoan International Airport (SZX), Chongqing Jiangbei International Airport (CKG), and Chengdu Shuangliu International Airport (CTU). Compared with not introducing CO_2 emissions to evaluate airport suitability, the names of the top five airports have not changed, the difference is that the ranking of these five airports has changed. Because Shanghai Pudong and Shenzhen Baoan airports have higher CO_2 emissions in the LTO phase, their rankings have improved.

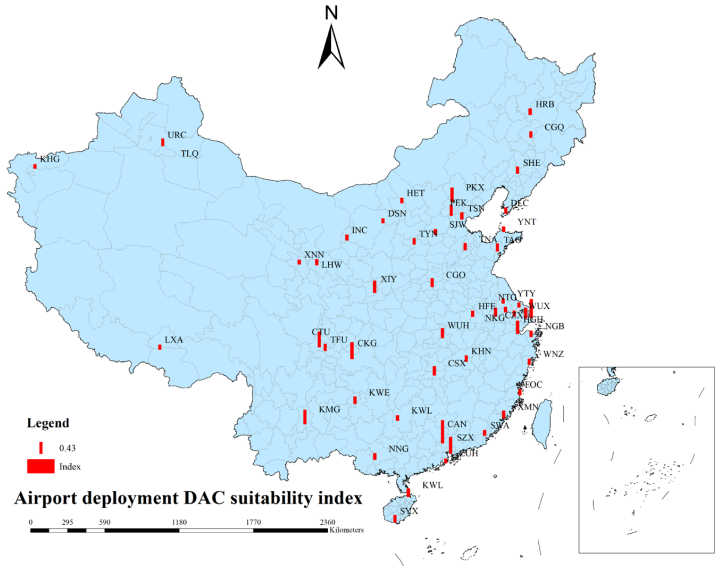


Figure 6. Geographical distribution of suitable DAC system deployment.

From Figure 6, it is found that the airports with high suitability index are mainly concentrated in cities south of the Yangtze River. In the southeast, Shanghai, Hangzhou, and Nanjing are represented by the Yangtze River Delta airports. In the southwest, Chongqing, Chengdu, and Kunming are suitable airports. In the south, Guangzhou, Shenzhen, and Sanya have higher airport suitability. Compared to the south of the Yangtze River, where more airports are suitable for DAC deployment, only Beijing and Xi'an in the north have outstanding suitability indices for international airports. After the introduction of CO_2 emissions, the overall suitability of the DAC system for airports shifts south.

4. Conclusions and Policy Recommendations

(1) In the LTO phase, the annual CO_2 emissions of 52 international airports in China are about 23 Mt, accounting for 23% of the total emissions of civil aviation in China, of which the top five airports in terms of emissions are Guangzhou Baiyun International Airport, Shanghai Pudong International Airport, Shenzhen Baoan International Airport, Chengdu Shuangliu International Airport, and Beijing Capital International Airport. The annual CO_2 emissions from these five airports during the LTO phase are 1.24, 1.19, 1.09, 1.03, and 1.02 Mt, respectively, and the total emissions from these five airports account for about 24% of the annual emissions from the LTO cycle of 52 airports.

(2) The evaluation indicators of the suitability of airport deployment of DAC system can be divided into four categories and 13 indicators, in which the airport production capacity and airport climate conditions have a greater influence on the suitability of development, while the influence of airport safety level and airport resource conditions is relatively small.

(3) Without involving LTO cycle CO_2 emissions, the results of the suitability evaluation of the airport deployment DAC system are that the airports with suitable and relatively suitable airports are mainly concentrated in the Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing, and Beijing-Tianjin-Hebei airport clusters, and the generally suitable areas are mainly distributed in the northeast and most of the northwest airport clusters.

(4) With the introduction of CO_2 emissions in the LTO cycle into the suitability evaluation index, the suitability evaluation of the airport deployment DAC system shows that the suitable airports are mainly concentrated in the Yangtze River Delta, the Pearl River Delta, and the Chengdu-Chongqing airport group, the relatively suitable and generally suitable airports are mainly distributed in the Beijing-Tianjin-Hebei and Hainan airport groups, and the less suitable areas are mainly distributed in the northeast and northwest airports.

(5) The results of the suitability evaluation of airport DAC system deployment have the highest correlation with the CO_2 emissions in the LTO phase of the airport. When evaluating the suitability of the airport DAC, the weather conditions related to the total CO_2 emissions and CO_2 dispersion rate in the LTO phase of the airport should be emphasized.

5. Policy Recommendations

Based on the above findings, the policy recommendations of this study are proposed: Considering the special nature of carbon emission reduction in the aviation sector, it is not very realistic to achieve carbon neutrality only from civil aviation itself, and it is necessary to actively explore other ways to reduce emissions. The deployment of DAC systems in airports can effectively reduce CO_2 emissions in the LTO phase, and relevant government departments should provide active policy support to explore the deployment of carbon capture systems in airports where DAC systems are suitable. Airports should reserve sufficient space and resources for the deployment of DAC systems without affecting normal airport production and cooperate with major airlines to promote the deployment of DAC systems in airports to achieve the carbon emission reduction goals of airports and

airlines. In addition, DAC system deployment plans should be initiated in the Yangtze River Delta, Pearl River Delta, and Beijing-Tianjin-Hebei airport clusters to further discuss the engineering feasibility of DAC system deployment.

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Abbreviations

ACG	Air China Group
AHP	Analytic hierarchy process
CAAC	Civil Aviation Administration of China
CAN	Guangzhou Baiyun International Airport
CCS	Carbon capture and storage
CCUS	Carbon Capture, Utilization and Storage
CEAG	China Eastern Airlines Group
CKG	Chongqing Jiangbei International Airport
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSAH	China Southern Airlines Holding
CTU	Beijing Capital International Airport
DAC	Direct air capture
DAMR	Daily Aircraft Movement Records
HAG	Hainan Airlines Group
HGH	Hangzhou Xiaoshan International Airport
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
KMG	Kunming Changshui International Airport
LTO	Landing and take off
PKX	Chengdu Shuangliu International Airport
PVG	Shanghai Pudong International Airport
SZX	Shenzhen Baoan International Airport
TLQ	Turpan Jiaotonghe Airport

Appendix A

In the first row of the table, 1 = Abbreviations; 2 = Flight area; 3 = Fire rescue level; 4 = Emergency rescue level; 5 = Flight area (10,000 sqm); 6 = Terminal building area (10,000 sqm); 7 = Number of ramps; 8 = Number of runways; 9 = Number of taxiways; 10 = Average temperature; 11 = Meteorological horizontal atmospheric pressure (mmHg); 12 = Average wind speed; 13 = Passenger throughput (10,000 people); 14 = Cargo and mail throughput (tons); 15 = Number of landings and take-offs.

Table A1. Basic data information of 52 airports.

Airport Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Beijing Capital International Airport	PKX	4F	10	10	1639	143.8	380	3	7	13.1	758.6	2.8	1270.33	98.87	15.76
Beijing Daxing International Airport	PEK	4F	10	10	1853.2	78	243	4	14	13.1	758.6	2.8	1027.76	12.75	10.59
Tianjin Binhai International Airport	TSN	4E	9	8	800	36.4	146	2	4	13.9	762.1	3.2	584.17	13.15	6.02
Shijiazhuang Zhengding International Airport	SJW	4E	8	8	222.5	20.9	78	1	2	13.9	755.6	2.2	556.28	4.34	5.33
Taiyuan Wusu International Airport	TYN	4E	9	8	40.7	8.1	59	1	1	11.9	695.3	2.1	552.70	4.01	5.50
Huhehaote Baita International Airport	HET	4E	8	8	313	10.3	64	1	1	7.8	664.6	3.4	453.99	3.01	4.96
Erdos Ijinholo International Airport	DSN	4E	8	8	224.3	10.5	19	1	1	7.8	664.6	3	72.14	0.44	1.92
Shenyang Taoxian International Airport	SHE	4E	9	8	290.7	33.2	81	1	2	9.2	757.5	2.1	938.73	13.25	8.33
Dalian Zhoushuizi International Airport	DLC	4E	8	8	261	15.2	80	1	1	12.3	754.1	2.7	636.85	12.65	6.65
Changchun Longjia International Airport	CGQ	4E	8	8	374.6	20.4	58	1	2	7.2	739.9	2.7	721.31	6.05	6.20
Harbin Taiping International Airport	HRB	4E	9	8	350	13.3	83	1	1	5.6	750	2.7	949.65	9.68	8.22
Shanghai Hongqiao International Airport	SHA	4E	9	9	630	44.6	161	2	4	18.1	761.8	3.9	1471.16	18.45	12.27
Shanghai Pudong International Airport	PVG	4F	10	10	202000	145.6	340	4	8	18.1	761.8	3.9	1417.84	311.72	20.44
Nanjing Lukou International Airport	NKG	4F	9	9	723	39.2	141	2	3	17.5	760.6	2.7	1214.05	37.79	12.59
Changzhou Benniu International Airport	CZX	4E	8	8	298.7	3.8	21	1	1	17.5	760.6	2.7	194.73	3.06	3.21
Nantong Xingdong International Airport	NTG	4E	9	8	195.6	6.7	32	1	1	17.5	760.6	2.7	171.86	5.43	2.29
Wuxi Shuofang International Airport	WUX	4E	8	8	251	10.5	32	1	1	17.5	760.6	2.7	376.89	9.80	3.78
Yangzhou Taizhou International Airport	YTY	4E	8	8	154	3.1	14	1	0	17.5	760.6	2.9	139.44	0.88	4.16
Hangzhou Xiaoshan International Airport	HGH	4F	9	9	672.8	37	183	2	4	19	757.7	2.9	2003.81	82.98	19.04
Ningbo Lishe International Airport	NGB	4E	8	8	251.1	15.6	56	1	2	18.8	761.4	2.8	616.56	8.53	5.61
Wenzhou Longwan International Airport	WNZ	4E	8	8	53.4	15.3	59	1	1	18.8	761.4	2.8	560.79	6.19	5.30
Hefei Xinqiao International Airport	HFE	4E	8	8	482.8	10.9	29	1	2	17	756.9	2.5	571.27	7.66	5.69
Fuzhou Changle International Airport	FOC	4E	9	9	322.4	21.6	62	1	2	21.2	760.5	4.5	573.94	9.18	5.82
Xiamen Gaoqi International Airport	XMN	4E	9	9	248	14.9	96	1	2	23.4	759.7	3.4	1012.56	26.21	9.98
Nanchang Changbei International Airport	KHN	4E	8	8	256.3	12.4	51	1	2	18	759.5	2	472.46	4.02	4.93
Jinan Yaowang International Airport	TNA	4E	9	8	291	16	56	1	2	15.6	747.1	2.3	824.23	13.77	7.88
Qingdao Jiaodong International Airport	TAO	4F	10	10	949	54	184	2	2	14.3	755.7	3.3	972.01	22.00	9.59
Yantai Penglai International Airport	YNT	4E	8	8	250	9	48	1	1	14.3	755.7	2.2	310.24	6.22	3.74
Zhengzhou Xinzheng International Airport	CGO	4F	9	9	688	1.5	120	2	3	17	752.3	2	922.17	62.47	9.44
Wuhan Tianhe International Airport	WUH	4F	9	9	675	64.5	117	2	3	18	759.5	1.5	1160.64	29.87	11.51
Changsha Huanghua International Airport	CSX	4E	9	9	376.2	26.6	81	2	3	16.5	751.8	2.5	1250.88	15.58	11.41
Guangzhou Baiyun International Airport	CAN	4F	10	10	1430	118.2	279	3	8	23.1	753.7	2.2	2610.50	188.41	26.66
Shenzhen Baoan International Airport	SZX	4F	9	9	794	59.7	243	2	3	23.1	753.7	4.1	2156.34	150.70	23.57
Jieyang Chaoshan International Airport	SWA	4E	7	7	263	5.7	42	1	1	23.7	759.3	2.5	573.40	3.10	5.00
Zhuhai Jinwan Airport	ZUH	4E	8	8	261.4	9.2	33	1	1	23.7	756.4	4.9	400.57	2.85	3.95
Nanning Wuxu International Airport	NNG	4E	8	8	384.4	21.5	106	1	3	22.7	746.1	2.7	665.95	15.19	6.66

Table A1. *Cont.*

Airport Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Guilin Liangjiang International Airport	KWL	4E	8	8	393.8	15	48	1	1	20.4	745.5	1.9	173.62	0.71	2.03
Haikou Meilan International Airport	KWL	4E	9	9	821	44.6	137	2	3	25.2	753.1	2.8	1116.22	12.44	10.57
Sanya Phoenix International Airport	SYX	4E	9	9	250.5	9.4	83	1	1	26	757.7	3.4	951.43	6.33	7.65
Xi'an Xianyang International Airport	XIY	4E	9	9	669.5	45.4	165	2	4	15.6	726.5	2.2	1355.84	20.63	12.59
Lanzhou Zhongchuan International Airport	LHW	4E	8	8	136.5	8.7	77	1	1	6.8	569.6	2.8	594.24	5.55	5.80
Xining Caojiabao International Airport	XNN	4E	8	8	352.8	5.5	34	1	1	6.8	569.6	3.6	260.94	1.59	2.86
Yinchuan Hedong International Airport	INC	4E	8	8	327.7	12.9	45	1	1	11.5	667.8	1.5	378.58	2.61	3.74
Chongqing Jiangbei International Airport	CKG	4F	10	9	1046	73.8	174	3	9	19.5	737.4	1.1	2167.35	41.48	18.86
Chengdu Shuangliu International Airport	CTU	4F	10	9	825.2	48.8	228	2	5	16.9	713.4	1.4	1781.74	52.99	15.98
Chengdu Tianfu International Airport	TFU	4F	10	10	1330	71	210	3	7	16.9	713.4	1.4	1327.59	8.17	12.03
Guiyang Longdongbao International Airport	KWE	4E	8	8	350	21.5	50	1	2	15.9	659.8	2.9	979.78	8.11	8.45
Kunming Changshui International Airport	KMG	4F	9	9	900	54.83	191	2	4	17	608.3	2.4	2123.75	31.01	19.38
Lhasa Gongga International Airport	LXA	4E	8	8	238.8	2.6	18	1	1	10.5	489.5	2	258.36	2.90	2.73
Urumqi Diwobao International Airport	URC	4E	9	9	270	18.5	118	1	2	8.5	684.1	2.4	1003.54	9.37	8.97
Kashgar Airport	KHG	4E	8	8	382.5	2.4	6	1	1	13.8	654.7	3.4	155.11	0.86	1.41
Turpan Jiaotonghe Airport	TLQ	4E	8	8	128.7	0.5	16	1	0	17	759.2	2.2	3.96	0.01	0.12

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