Optimization of Flight Schedules at Tianjin Airport for Domestic Transfer Passengers

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DOI: https://doi.org/10.30209/IJMO.202604.008

Submitted: Apr. 18, 2026 Accepted: Jun. 16, 2026

ABSTRACT

Given Tianjin Airport's low proportion of international flights and dominance of domestic-to-domestic transfers, this paper proposes a schedule optimization method integrating flight connection quality grading. A connection quality assessment model is constructed from four dimensions: time matching, spatial detour coefficient, relative intensity, and service quality. The Jenks natural break method classifies connections into four tiers: Excellent, Good, Average, and Poor. A dual-objective optimization model is then established to maximize the proportion of Excellent and Good connections while minimizing schedule deviations, incorporating a Minimum Connecting Time (MCT) compression mechanism. Using Tianjin Airport as a case study and solved via an adaptive large neighborhood search algorithm, results show that with MCT=70 min, the numbers of Excellent and Good connections increase from 414 and 231 to 454 and 292 respectively, raising the combined Excellent+Good ratio from 70.49% to 71.05%. Further reducing MCT to 60 min increases this ratio to 71.54%. The optimized schedule yields a more rational spatiotemporal distribution, significantly improving connection quality and providing transfer passengers with more effective options.

Keywords: Flight schedule optimization, Domestic passenger transfers, Connection quality grading; Natural interruption method, MCT compression

1.Introduction

Airport transfer functions are central to the development of air transport networks, effectively enhancing network coverage and operational efficiency. The Civil Aviation Administration of China (CAAC) states in the Guidelines for Facilitating Civil Passenger Transfers that efforts should be focused on enhancing the convenience of passenger transfers[1] , comprehensively improving the passenger transfer service experience, and that airports should simplify transfer processes such as check-in, security screening, and baggage check-in as much as possible to stimulate the potential of aviation market demand, optimize airport MCT, and fully support the construction of a new development paradigm centered on the domestic economic cycle, with the domestic and international cycles reinforcing each other. As a key regional aviation hub for the coordinated development of the Beijing-Tianjin-Hebei region, Tianjin Airport has seen continuous expansion of its domestic route network and a steady increase in transfer passenger volume in recent years. However, the airport still faces challenges in providing transfer services. First, flight schedules are not sufficiently compact. Second, the convenience of transfer processes is low, and MCT times are excessively long, resulting in insufficient transfer convenience and hindering the development of significant hub competitiveness. Against the backdrop of continuously growing transfer demand, optimizing flight schedules and improving connection efficiency to enhance the effectiveness of transfer itineraries has become a critical issue that Tianjin Airport urgently needs to address.

Regarding the coordinated allocation of slot resources, Ribeiro [2] et al. pioneered a multi-objective optimization model based on IATA priority rules. By employing efficient computational methods, they improved the effectiveness of slot allocation at large airports. Empirical evidence confirmed that this model significantly enhances the match between airline demand and slot availability while quantitatively revealing the mechanisms of rule sensitivity; Ye Zhejiang [3] et al. focused on flight connection timeliness, constructing a dual-objective optimization model coupled with intelligent algorithms, and verified that it can simultaneously improve transfer connection efficiency and reduce the volume of slot adjustments. In the area of transfer efficiency evaluation, Ma Chenting et al. [4] demonstrated a strong correlation between spatio-temporal connectivity and transfer quality through flight wave structure analysis, proposing a rolling flight wave optimization approach; Huang Shihao [5] et al. established a quantitative relationship between slot offset tolerance and transfer quality using an adaptive hit window model. In the field of resource scheduling innovation, Song Yilu [6] et al. developed a flight wave optimization framework centered on passenger satisfaction, achieving a significant improvement in transfer experience; Li Yanhua [7] et al. constructed a multi-objective planning model for multi-terminal scenarios, whose hybrid algorithm effectively coordinates the demands of airlines, passengers, and airports while enhancing resource utilization.

Tianjin Airport’s current minimum connection time (MCT) for domestic-to-domestic transfers is 70 minutes. This paper focuses on the characteristics of domestic transfers at Tianjin Airport, integrating multi-dimensional connection quality assessment with the natural break method for classification. It constructs a dual-objective model that balances the proportion of high-quality connections with the minimization of schedule deviations, and introduces an MCT compression mechanism. The aim is to provide domestic transfer passengers with better transfer options and offer theoretical and practical references for transfer optimization at regional hub airports.

2. Current Status and Issues of Transfer Connections

2.1 Current Status of Transfer Connections

In 2024, Tianjin Airport’s aviation hub functions saw significant enhancement, with both the scale of its route network and service quality making simultaneous strides. Throughout the year, 48 airlines operated 193 routes, including 10 international and regional carriers; these routes covered 133 destinations, of which 116 were domestic and 17 were international or regional. The total number of registered routes reached 1,557, comprising 549 origin routes, 489 connecting routes, and 519 destination routes. Among these, 171 were domestic routes, accounting for 88.6% of the total 193 routes, demonstrating a pronounced passenger-oriented characteristic. Leveraging its strategic location as a gateway between Northeast and North China, the airport has established a preliminary transit network spanning Northeast, North, Central-South, East, Northwest, Southwest China, and Xinjiang. This has formed regional interconnection networks such as Northeast-Central-South and North-Central-South, continuously strengthening the hub’s capacity. In terms of service systems, the airport innovatively launched the “Jingjin Le Dao 2.0” brand. By coordinating operations between cross-regional transfer services and the transfer lounge in the domestic baggage claim area, paperless through-check-in services have reduced passenger procedures by more than 50%.Breakthroughs have been achieved in digital platform development, making it a pilot project for the Civil Aviation Administration of China’s through-check-in flight management and launching the “Transit Pass” mini-program; the service product portfolio has been expanded, with new specialized support services such as Express Transit, Caring Transit, and First-Time Traveler Assistance, comprehensively optimizing the transit experience for special groups.

2.2 Issues with Transfer Connections

Hub airports serve as critical nodes in air transport networks, and their operational efficiency is primarily reflected in the volume of transfers and the quality of connections. As a regional hub, Tianjin Airport faces certain challenges regarding transfers. (1) Tianjin Airport has a relatively sparse route network, with few international routes and a significant gap in domestic flights compared to the two airports in Beijing. Therefore, improving flight connectivity and enhancing the connectivity of the route network is particularly important. (2) Flight schedules lack sufficient density, and slot resources are not efficiently allocated, resulting in poor connection efficiency. For some flights, the layover time is excessively long, causing transfer passengers to be stranded for extended periods; for others, the connection time is too short, increasing the risk of missed connections and directly impacting the travel experience and airport service quality. (3) Regarding transfer service processes, there is a lack of efficient coordination among different airlines and ground handling units. This is particularly evident in cross-carrier transfer operations, where information barriers and discrepancies in service standards are prominent. This not only forces passengers with non-through baggage to spend extra time completing complex procedures but also makes it difficult to adjust itineraries promptly during special circumstances, such as flight delays, due to inadequate emergency response mechanisms. (4) At the infrastructure level, the capacity of existing transfer facilities is struggling to keep pace with the continuously growing passenger throughput. Issues such as congestion in transfer corridors, a shortage of seating in waiting areas, and declining efficiency of baggage handling systems are becoming increasingly prominent during peak hours. During peak periods such as the tourist season, these problems are further exacerbated, resulting in significantly longer transfer times for passengers and frequent baggage delays, which directly undermine the airport's overall service quality and hub competitiveness.

3. Flight Schedule Optimization Model

3.1 Assumptions and Decision Variables of the Model

To construct a scientifically sound flight schedule optimization model that accurately describes the operational logic of Tianjin Airport, this section makes the following assumptions regarding the practical problem:

(1) Time Interval Attributes of Flight Schedules: Flight schedules are not precise time points but are divided into "time slots" through fixed time intervals. In this process, the minimum time granularity serves as the basic time unit for airport operations, typically set at 15 minutes. The specific duration can be adjusted based on the airport's actual needs; busy airports typically set it at 5 minutes [8], while Tianjin Airport, as a regional hub, is set at 15 minutes in this study. Airport slot capacity refers to the maximum number of flights that can theoretically take off and land within a given time slot, subject to constraints such as runways, air traffic control, and taxiways. This paper examines airport capacities of 15 minutes and 60 minutes.

(2) Flight Type Restrictions: When optimizing the flight schedule, this study does not consider additional flights, charter flights, flight cancellations, or resumptions; it focuses solely on the airport's scheduled flights to ensure the research concentrates on the schedule optimization of scheduled flights.

(3) Passenger Connecting Time Assumptions: Passenger connecting time refers to the time interval between a transfer passenger's arrival at the airport and the departure of their subsequent flight. This must meet the minimum and maximum connecting time requirements for the corresponding transfer type. This study assumes that passenger layover time is solely related to the transfer type, disregarding time variations caused by individual differences such as special service requests or baggage transfer, and primarily focuses on domestic passenger transfers at Tianjin Airport.

(4) Assumptions regarding transfer time compression: The compressed MCT must be less than both the transfer time and the MACT, with the upper limit for MCT compression set at 20% and not falling below the safety threshold of 40 minutes [1].

(5) Airline Slot Shift Acceptance Assumption: The baseline slot is based on the initially approved slot at the start of the scheduling season. During optimization, adjustments must be made within the shift range acceptable to the airline, and the adjusted slot must satisfy the airport's overall operational constraints.

(6) Flight Priority Assumption: All study flights are treated as having equal priority; no

distinction is made regarding slot competition differences between base carrier flights, foreign carrier flights, boutique routes, etc.

For the flight schedule optimization problem at a hub airport, a 0–1 decision variable is used:

$$Q_{ij}=\begin{cases}1\\0\end{cases} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{[Formular 1]}$$

$$W_{kl}=\begin{cases}1\\0\end{cases} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{[Formular 2]}$$

$$Z_{ijkl}=\begin{cases}1\\0\end{cases} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{[Formular 3]}$$

i: represents a certain arriving flight.

j: represents an available arrival time, numbered sequentially as 1, 2, …, J.

k: represents a certain departing flight.

l: represents an available departure time, numbered sequentially as 1, 2, …, l.

Qij: is used to indicate whether an arriving flight is assigned to a certain arrival time. If an arriving flight is assigned to a certain time, the corresponding value is“1”; otherwise, it is“0”.

Wkl: is used to indicate whether a departing flight is assigned to a certain departure time. If a departing flight is assigned to a certain time, the corresponding value is “1”; otherwise, it is “0”.[8]

Z_{ijkl} : is used to determine whether a given pair consisting of an arriving flight and a departing flight can form a valid connection. Specifically, if an arriving flight arrives at its assigned arrival time and can form a connection with a departing flight at its assigned departure time, the corresponding value is “1”; otherwise, it is “0”.

3.2 Evaluation and Classification of Flight Connection Quality

3.2.1 Multi-dimensional evaluation model

To enhance the travel experience for transfer passengers and optimize itinerary planning to better meet their needs, this paper comprehensively analyzes the key factors affecting passenger transfers and constructs a comprehensive connection quality evaluation model based on four dimensions: time matching, spatial indicators, relative intensity, and service quality. [9]

The temporal indicator considers the type of transfer and uses a piecewise evaluation function with intermediate thresholds—which is then smoothed—to assess the feasibility of a transfer within a specific time window; the spatial indicator is represented by the detour coefficient of the connecting flight, with thresholds set to reflect its impact on passenger acceptance; the relative strength indicator reflects the attractiveness relationship between connecting flights and direct flights[10], particularly when direct flight frequencies are low, making the connection quality of connecting flights even more critical; the service quality indicator reflects the convenience level of the connecting services provided by airlines. Flight connection quality is calculated through weighted averaging across these four dimensions to comprehensively evaluate flight connections.

（1） Time Matching（T）

$$\Delta t = W_{kl} - Q_{ij} \quad \cdots\cdots\cdots\cdots \text{[Formular 4]}$$

$$T_{ijkl} = \begin{cases} 1 & t_c^{mct} \leq \Delta t \leq t_c^{mt} \\ 1 - \frac{\Delta t - t_c^{mt}}{t_c^{mact} - t_c^{mt}} & t_c^{mt} < \Delta t \leq t_c^{mact} \\ 0 & \text{Other} \end{cases} \quad \cdots\cdots\cdots\cdots \text{[Formular 5]}$$

Δt : is the time interval between an arriving flight and a departing flight.

C: is the type of connecting flight formed by arriving flight i and departing flight k, including domestic-domestic, domestic-international, international-domestic, and international-international.

t_c^{mct} :is the minimum layover time for passengers in connection type C.

t_c^{mact}:is the maximum acceptable time for passengers in connection type C.

t_c^{mt}: represents the layover time for Class C passengers, calculated as the average of the minimum layover time and the maximum acceptable time.

（2） Spatial Indicator（D）

$$R = \frac{k_1 + k_2}{k_{Straight}} \quad \cdots\cdots\cdots\cdots \text{[Formular 6]}$$

$$D_{ijkl} = \begin{cases} 1 & R \leq 1.2 \\ \frac{1.4 - R}{0.2} & 1.2 < R \leq 1.4 \\ 0 & \text{Other} \end{cases} \quad \cdots\cdots\cdots\cdots \text{[Formular 7]}$$

R :is the detour coefficient.

k_1: the distance from the departure airport of flight i to its destination airport.

k_2: the distance from the departure airport of connecting flight k to its arrival airport.

K_{direct}: the distance between the departure airport of flight i and the arrival airport of flight k.

（3） Relative Strength（P）

$$P_{ijkl} = \begin{cases} 1 - \frac{f}{8} & f \leq 8 \\ 0 & \text{Other} \end{cases} \quad \cdots\cdots\cdots\cdots \text{[Formular 8]}$$

f :is the frequency of direct flights from the departure airport of flight i to the arrival airport of subsequent flight k

（4）Service Quality (F)

$$F_{ijkl} = \begin{cases} 1 & S_1 \in S' \\ 0.9 & S_2 \in S'' \\ 0.3 & S_3 \in S''' \\ 0.1 & \text{Other} \end{cases} \quad \cdots\cdots\cdots\cdots \text{[Formular 9]}$$

S’: both flights are operated by the same full-service airline.

S’’: the two flights are operated by different full-serviceairlines within the same alliance.

S’’’: flights are operated by full-service airlines from different alliances or by a single low-cost carrier.

（5）Overall Connection Quality （W）

$$W_{ijklC}=\frac{\gamma_1\ T_{ijkl}+\gamma_2\ D_{ijkl}+\gamma_3 P_{ijkl}+\gamma_4 F_{ijkl}}{\gamma_1+\gamma_2+\gamma_3+\gamma_4} \cdots\cdots\cdots \text{[Formular 10]}$$

γ_1: time weighting coefficient.

γ_2: spatial weighting coefficient.

γ_3: relative strength weighting factor.

γ_4: service Quality Weighting Factor. [4]

3.2.2 Classification using the natural discontinuity method

The natural break method [11], also known as the Jenks optimization method, is a data classification technique based on the statistical characteristics of the data itself. It aims to optimize data classification by identifying natural groupings or “breakpoints” within the data. Its core objective is to divide the data into several categories by identifying natural turning points, ensuring that the variation within each category is minimized while maximizing the difference between categories. Calculating flight connection quality based on the arrival and departure schedules at Tianjin Airport, and determining classification thresholds using the Natural Break Method:

Excellent: $W\in(0.81319972541433，1]$.

Good: $W\in(0.6759710964979356，0.81319972541433]$.

Average: $W\in(0.5140770760055055，0.6759710964979356]$.

Poor: $W\in(0.1823024283759868，0.5140770760055055]$.

Specifically: In the Natural Break Method’s evaluation of flight transfer services, “Excellent” and “Good” grade flights demonstrate the best time alignment, with tight connections that minimize wasted time for passengers during transfers; they have a low detour coefficient, saving both passenger time and unnecessary costs for airlines resulting from detours; direct flight frequencies between the departure and destination airports are relatively low, making transfers within the same airline’s network relatively convenient, and passengers are more likely to choose a connecting flight. IN contrast, “Average” and “Poor” rated flights are significantly affected by time constraints; passengers face excessively long layover wait times, which negatively impacts their initial experience; they have high detour coefficients and frequent direct flight options, leading passengers to prefer direct flights; and since most connecting flights are operated by different airlines, service continuity is disrupted, resulting in a poorer service experience and an overall transfer evaluation that falls far short of “Excellent” and “Good” rated flights.

3.2.3 Process for calculating flight connection quality

(1) Based on flight arrival and departure schedules, time metrics are set according to transfer types to preliminarily screen eligible flight combinations and calculate transfer time metrics [4], such as:

Table 1. MCT and MACT for different transfer types

Transfer Type	MCT/min	MACT/min
Domestic-Domestic	50	180
Domestic-International	120	360
International-Domestic	120	360
International-International	160	480

Source: By authors.

(2) Combining data on the geographical distances between airports nationwide, further screening is performed within the time-matched combinations. Routes with excessively high detour coefficients are eliminated using the detour coefficient formula, and spatial indicators are calculated to generate spatially optimized flight pair combinations.

(3) For pairs that meet the spatial criteria, flight frequency is treated as a constraint. Further calculations are performed based on the frequency of direct flights between routes; flights with a frequency greater than 8 are filtered out, and their relative strength indicators are calculated.

(4) Collect relevant airline information and calculate service quality indicators based on time, space, and relative strength.

(5) Finally, based on the comprehensive connection quality model, the total connection quality for each flight is calculated to provide data support for the next step of the analysis.

(6) Using the natural break method, classify flight connection quality into four categories: excellent, good, average, and poor.

3.3 Optimization Objectives

(1) Maximizing the Proportion of High-Quality Connections

Most current studies aim to “maximize the number of transfer opportunities” but do not consider the effectiveness of transfer itineraries, such as detour coefficients, direct flight frequencies, and service quality [12]. This paper proposes simultaneously improving both the quantity and quality of transfers by using a multidimensional evaluation to identify the proportion of “Excellent” and “Good” connections. The weights are set at 0.6 and 0.4, respectively, reflecting a priority on the transition to the “Excellent” grade, as determined by the Analytic Hierarchy Process. The formula is as follows:

$$\text{a}\, MAXZ_1 = \frac{N_{\text{Excellent}}+N_{\text{Good}}}{N_{\text{Total}}} \times 100\% \quad \cdots \text{[Formular 11]}$$

$N_{\text{Excellent}}$: represent the number of valid connections rated as "Excellent".

N_{Good} : represent the number of valid connections rated as "Good".

(2) Minimizing Flight Slot Adjustments to Maximize Offset

An airline's acceptance of schedule adjustments is inversely proportional to the offset amount [13]. To balance airport operational efficiency and airline satisfaction, the maximum schedule offset for individual flights must be controlled to avoid excessive adjustments that disrupt airline scheduling plans. The formula is as follows:

$$MINZ_2 = max(\,|\Delta t_i|,\ |\Delta t_k|) \cdots\cdots\cdots\cdots \text{[Formular 12]}$$

Δt_i : represent the schedule adjustment amounts for domestic arrival flight i .

Δt_k: represent the schedule adjustment amounts for domestic departure flight k.

$(\,|\Delta t_i|,\ |\Delta t_k|) \leq 30$ mins (Maximum offset acceptable to the airline).

3.4 Constraints

To ensure that the optimized flight schedule complies with actual airport operating rules and airline operational requirements while improving the effectiveness of connecting flights, this paper considers the following six types of constraints when constructing the model: flight slot allocation uniqueness constraint, connecting flight effectiveness constraint, airport capacity constraint, flight slot offset constraint, MCT compression constraint, and variable value constraint[12,14].Together, these constraints ensure that the optimized solution increases the proportion of high-level connections while maintaining operational feasibility and airline acceptability.

(1) Uniqueness Constraint for Flight Slots

Each flight (arriving or departing) must be assigned exactly one slot:

$$\sum_{j \in Sa} Q_{ij} = 1 \quad \forall i \in Fa \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{[Formular 13]}$$

$$\sum_{l \in Sd} W_{kl} = 1 \ \forall k \in Fd \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{[Formular 14]}$$

Sa: the sets of arrival times,

SD: the sets of departure times,

Fa: the sets of arriving flights,

Fd: the sets of departing flights,

(2) Valid Connection Constraint

To ensure that flights i and k form a valid connection, the following conditions must be satisfied simultaneously:[16]

①Time window constraint: The layover time must fall between MCT and MACT;

②Consistent connection type: All are domestic-to-domestic transfers;

③The connection variable Z_{ijkl} is logically consistent with the schedule variable.

$$Z_{ijkl} \le \theta_{jlc} \quad \forall\ i,j,k,l,c \cdots\cdots\cdots \text{[Formular 15]}$$

$$Q_{ij} + W_{kl} \ge 2\, Z_{ijkl} \quad \forall\ i,j,k,l \cdots\cdots\cdots \text{[Formular 16]}$$

$$Z_{ijkl} = 0 \quad \text{if } \Delta t \notin \left[\, t_c^{mct},\ t_c^{mact} \right] \cdots\cdots\cdots \text{[Formular 17]}$$

θ_{jlc} : indicates whether time slot j and l meet the Class C transfer time requirement.

(3) Airport Capacity Constraints

Limit the number of takeoffs and landings within any 15-minute or 60-minute time window:

$$\sum_{i \in Fa} \sum_{j=s}^{s+L_c-1} Q_{ij} \le R_a^c \quad \forall\ s, c \in C \cdots\cdots\cdots \text{[Formular 18]}$$

$$\sum_{k \in Fd} \sum_{l=s}^{s+L_c-1} W_{kl} \le R_d^c \quad \forall\ s, c \in C \cdots\cdots\cdots \text{[Formular 19]}$$

$$\alpha_c \sum_i \sum_j Q_{ij} + \mu_c \sum_k \sum_l W_{ij} \le R_{total}^c \ \forall\ s, c \in C \cdots\cdots\cdots \text{[Formular 20]}$$

R_a^c : represent the upper limits for arrival.

R_d^c: represent the upper limits for departure.

R_{total}^c: represent the upper limits for total capacity.

L_c: represents the capacity window length (15 min/60 min).

α_c: capacity envelope parameters.

μ_c: capacity envelope parameters.

(4) Flight Schedule Offset Constraints

Control the schedule adjustment for each flight within the airline's acceptable range:

$$|\Delta t_i| \le \mu_{max} \quad \forall i \in Fa \cdots\cdots\cdots \text{[Formular 21]}$$

$$|\Delta t_k| \le \mu_{max} \quad \forall k \in Fd \cdots\cdots\cdots \text{[Formular 22]}$$

μ_{max}: represents the maximum deviation acceptable to the airline, with a value of 30 minutes

(5) MCT Compression Constraints

The compressed MCT must meet safety and operational minimums:

$$t_c^{mact} \ge \Delta t \ge \dot{t}_c^{mct^*} \ge 40 \cdots\cdots\cdots \text{[Formular 23]}$$

$\dot{t}_c^{mct^*}$: is the compressed minimum transfer time,

(6) Constraints on Variable Values

All decision variables are 0-1 variables or integer variables:

$$Q_{ij},\ W_{kl},\ Z_{ijkl} \in \{0,1\}\ ;\ \ \Delta t_i, \Delta t_k \in Z^+ \cdots\cdots\cdots \text{[Formular 24]}$$

3.5 Model Solution

This paper presents a large-scale integer programming model aimed at maximizing the proportion of high-level connections and minimizing the maximum deviation of flight schedules. [17] Due to the large scale of the model variables, traditional exact algorithms struggle to solve the problem within a reasonable timeframe. Therefore, based on the research of Birolini [15]and others, this paper designs an Adaptive Large Neighborhood Search (ALNS) algorithm for solution.

3.5.1 Algorithm flow and step description

Step 1: Initial Solution Generation and Parameter Setting. Input the original flight schedule data and verify whether the schedule satisfies the capacity constraints. For time slots that do not satisfy the constraints, flights are randomly selected for schedule adjustments, with the absolute value of the adjustment not exceeding 30 minutes. [18] This process is repeated iteratively until an initial solution S that satisfies the capacity constraints is generated. The initial solution is simultaneously set as the global optimal solution S_*,and the counters are initialize$p=0$。 Parameter settings include: initial operator weights$w_j=[0.25,0.25,0.25,0.25]$, initial simulated annealing temperature$T_0=100$, maximum number of iterations $I_{max}=1000$, weight update coefficient $\rho=0.15$, and cooling coefficient $\varepsilon=0.95$.

Step2: Solution degradation operation. Determine whether the termination conditions are met (number of iterations$i\geq I_{max}$or number of consecutive non-improvements$P\geq 30$).If the termination conditions are met, proceed to Step 6 to output the optimal solution; otherwise, use a random perturbation operator to perturb the current solution: randomly select 15% of the flights, set the arrival times of the perturbed flights to the maximum value, and set the departure times to the minimum value, ensuring that the perturbed flights cannot connect with other flights, resulting in the perturbed solutionS_{ip} .

Step3: Selection and execution of the repair operator**.** A roulette wheel selection mechanism is used to choose a repair operator from the library, which includes two types: greedy repair and random repair. The greedy repair operator traverses the ±30-minute candidate time window, calculates the flight connection quality increment$\Delta G=0.6\left(N_{优}^{new}-N_{优}^{old}\right)+0.4\left(N_{良}^{new}-N_{良}^{old}\right)$ for each time slot, and selects the time slot with the highest connection qualityΔG for repair; the random repair operator randomly selects a time slot within the feasible range for repair. During the repair process, capacity constraints and MCT constraints must be continuously verified until all disrupted flights have been rescheduled, yielding the repaired solutionS_{new} .

Step 4: Decision on whether to accept the new solution. Determine whether to accept the new solution based on the Metropolis rule of the simulated annealing algorithm. When the objective function value of the new solution is $f(S_{new})\leq f(S)$, the new solution is accepted; the current solution$S=S_{new}$ is updated, and the operator scores are updated. When the objective function value of the new solution is $f(S_{new})>f(S)$, the suboptimal solution is accepted with probability$P=e^{-(f(S_{new})-f(S))/T}$. If the new solution is better than the global optimal solutionS_* , the global optimal solution$S_*=S_{new}$ is updated, and the consecutive non-improvement counter is reset to$p=0$; if the new solution does not improve upon the global optimal solution, the counter $p=p+1$.

Step 5: Adaptive update of operator weights. Update the weights after each iteration based on operator performance. Operator scores are assigned according to the following four scenarios: 15 points if the new solution updates the global optimal solution, 12 points if it updates a local optimal solution, 8 points if it is accepted but does not update the optimal solution, and 0 points if it is rejected. The weight update formula is:

$$w_j=(1-\rho)w_j+\rho\frac{c_j}{\sum c_j},c_j>0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{[Formular 25]}$$

c_j: the number of times operator j is used. After the update, the probability of selecting an operator is the normalized result of each operator’s weight, ensuring that operators with higher weights have a greater probability of being selected.

Step 6: Iterative parameter updates and termination check

Update the iteration count $i=i+1$and update the simulated annealing temperature according to $T=\sigma T$. Check again whether the termination conditions are met ($i\geq I_{max}$ or $P\geq 30$). If the termination conditions are met, output the global optimal solution S_*; otherwise, return to Step 2 to continue the iteration.

3.5.2 Design of key operators

(1) Disruption Operators

① Low-quality removal: Prioritize removing flight pairs with lower connection quality; the removal rate is 15%.[19]

② Capacity-Sensitive Deletion: For 15-minute time slots exceeding capacity limits, randomly remove one flight schedule.

(2) Repair Operators

① Greedy Repair: Iterate through the ±30-minute candidate time window and select the slot that maximizes the connection quality increment (ΔG).[20]

② Random Repair: Randomly select a time slot within the feasible range, ensuring compliance with the MCT constraint.

3.5.3 Algorithm parameter settings

Table 2. Algorithm parameter values

Parameter	**Value**	**Description**
Maximum Iterations	1000	Based on convergence results from similar studies [x]

Parameter	Value	Description
Initial temperatureT_0	100	Simulated annealing parameters, set based on problem scale
Cooling coefficientε	0.95	Controls the rate of temperature decrease
Weight update coefficientρ	0.15	Value in Equation (25)
Maximum number of unimproved iterations	30	Termination condition threshold

Source: By authors.

3.5.4 Convergence analysis

(1) Convergence Criteria

A dual termination condition is used:

① The maximum number of iterations is set to 1,000;

② The process automatically terminates when the rate of change in the proportion of high-order connections over 50 consecutive iterations is less than 0.1%.

(2) Stability Verification Method

Conduct 10 independent experiments and calculate the meanμ and standard deviation μ ,of the final solutions. The formula is:

$$\mu=\frac{1}{n}\sum_{i=1}^{n} x_i \cdots\cdots\cdots\cdots \text{[Formular 26]}$$

$$\sigma=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\mu)^2} \cdots\cdots\cdots\cdots \text{[Formular 27]}$$

When $\sigma\leq 1.2\%$, the algorithm is deemed to have good stability.

4.Case Analysis

4.1 Case Background and Relevant Parameters

This paper takes Tianjin Binhai International Airport as the research subject, aiming to optimize and adjust the airport’s flight schedule. By reducing flight transfer times and improving the quality of connections between flights, the overall flight operation efficiency is enhanced. The data used in this study is sourced from the OAG database, specifically the flight schedule data for Tianjin Binhai International Airport on March 15, 2025. This dataset contains a total of 424 flight segments, including 211 inbound flights and 213 outbound flights. The data includes flight numbers, operating airlines, departure and arrival airports, and departure and arrival times. The model parameters are set as follows:

(1) As Tianjin Airport handles few international flights, they are excluded from this study. This paper focuses primarily on domestic flight transfers at Tianjin Airport. The minimum connection time (MCT) for domestic-to-domestic transfers is set at 70 minutes, with 60 minutes used for subsequent optimization.

(2) Parameter settings for the flight connection quality assessment model. More than 80% of the effective connections of Tianjin Airport are domestic-domestic types. For such passengers, the length of transit time directly determines whether they choose to transfer, and it is also the core factor affecting the transfer experience. At the same time, the current domestic-domestic minimum transit time (MCT) of Tianjin Airport is 70 minutes, and the number of effective connections can be significantly reduced to 60 minutes, indicating that the time dimension is sexual. Tianjin Airport is a regional hub connecting Northeast, North China, Central South and other regions. Connections with excessive deviation coefficients will greatly increase passenger acceptance, and spatial indicators have medium binding force on transit. According to the statistics of direct flights departing from-destination at Tianjin Airport, the proportion of routes with a daily frequency of more than 8 flights is about 28%. The relative intensity index can effectively distinguish the connection between "strong direct flight substitution" and "scarce direct flight". Moderate importance. Although cross-company connection still accounts for a certain proportion, in recent years, measures such as "Beijing-Tianjin Ledao 2.0" through service and paperless through boarding have greatly simplified the transit process, and the impact of service on passenger decision-making is lower than time factors, so its importance is relatively low. Based on the AHP method, the importance order of each dimension is obtained: time > space > relative intensity > service, which is consistent with the general perception of passengers' travel. Based on the above analysis, passengers have a higher degree of transit time and a lower degree of convenience of transit services, so this paper assumes that γ_1=2.4，γ_2=1，γ_3=0.87，γ_4= 0.76. [4,21-23],whereγ_4= is The average value of the convenience coefficient of the service in the literature [23].

4.2 Optimization Results and Analysis

4.2.1 Changes in quality grade distribution

To evaluate the effectiveness of the MCT compression strategy and the flight schedule optimization model, this study compares the distribution of flight connection quality grades for 70-minute and 60-minute MCTs before and after optimization, as shown in Table 3. It also compares the distribution of flight connection quality grades for 70-minute and 60-minute flight schedules after optimization, as shown in Table 4.

Table 3. Comparison of flight connection quality grade distributions for MCT compression strategies

Scenario	MCT (minutes)	Optimal Count	Good	Average	Number of Poor Connections	Total number of effective connections	Percentage of Excellent and Good
Before Optimization	70	414	231	177	93	915	70.49%
	60	495	261	180	124	1,060	71.43%
After optimization	70	454	292	170	134	1,050	71.05%
	60	485	337	190	137	1,149	71.54%

Source: By authors.

The data in Table 3 shows that reducing MCT helps improve flight connection quality.Before schedule optimization, reducing the MCT from 70 minutes to 60 minutes increased the total number of effective connections by 145 and raised the proportion of "Excellent" and "Good" connections by 0.94%. After schedule optimization, reducing the MCT from 70 minutes to 60 minutes further increased the total number of effective connections by 99 and raised the proportion of "Excellent" and "Good" connections by 0.49%.

Table 4. Comparison of the distribution of connection quality ratings for optimized flight schedules

Time	Optimized	Excellent Connections	Good Connections	Average	Poor	Total Number of Effective Connections	Percentage of Excellent and Good
70 minutes	Before Optimization	414	231	177	93	915	70.49%
	After optimization	454	292	170	134	1,050	71.05%
60 minutes	Before optimization	495	261	180	124	1,060	71.43%
	After optimization	485	337	190	137	1,149	71.54%

Source: By authors.

As shown in Table 4, flight schedule optimization improves connection quality under all MCT conditions. When the MCT is 70 minutes, optimization increases the total number of effective connections from 915 to 1,050, an increase of 135, and the proportion of "Excellent" and "Good" connections rises by 0.56%; when the MCT is 60 minutes, the total number of effective connections increases from 1,060 to 1,149, an increase of 89, and the proportion of "Excellent" and "Good" connections rises slightly by 0.11%.

4.2.2 Effects of improved transfer efficiency

(1) Increase in Effective Connections: Through the MCT compression strategy, the number of effective transfer opportunities corresponding to "Excellent" and "Good" connections increased from 645 to 756 before optimization, representing a 17.2% increase; after optimization, the number increased from 746 to 822, representing a 10.18% increase. Through the optimization of flight schedule strategies, the number of effective transfer opportunities for connections between "Excellent" and "Good" grades increased from 645 to 746, representing a 15.66% increase; the number of effective transfer opportunities for connections between "Good" and "Excellent" grades increased from 756 to 822, representing an 8.73% increase.

(2) Network Accessibility: The structure of Tianjin Airport's connecting route network has been significantly strengthened, forming a multi-directional, wide-coverage hub radiation pattern. Specifically: Passengers from the Northeast can conveniently transfer through Tianjin to destinations in Central-South, Southwest, East China, North China, Northwest China, and Xinjiang; passengers from East China can connect through Tianjin to Northwest China and Xinjiang. This network structure exhibits cross-regional and high-connectivity characteristics, significantly enhancing the breadth of route coverage and accessibility efficiency of Tianjin Airport as a regional hub. As shown in Figure 1:

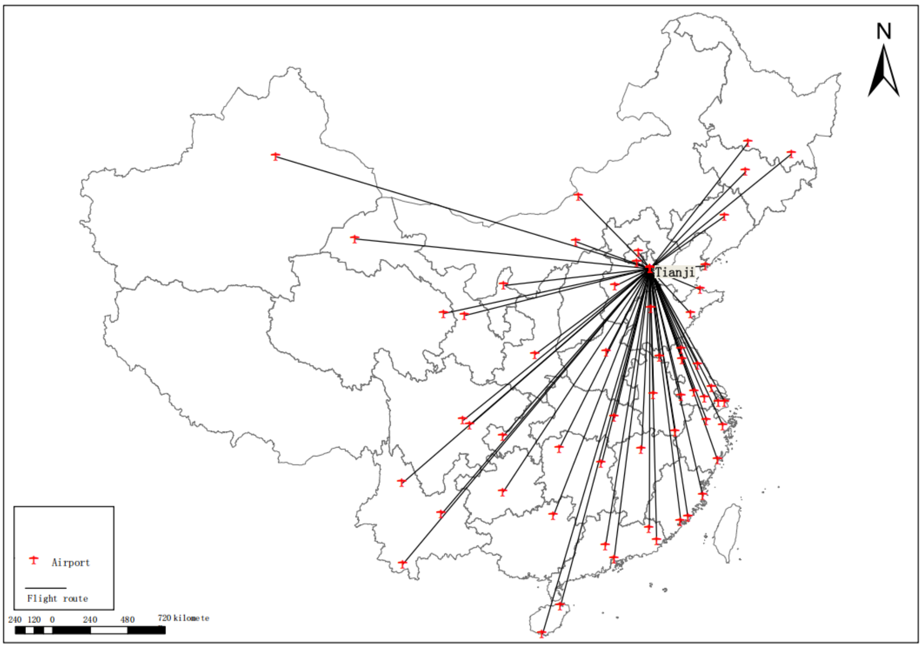

Figure 1 Diagram of Tianjin Airport's transfer route network structure

Source: By authors.

5. Recommendations for Optimizing Tianjin Airport's Route Network

Based on the flight schedule optimization model and empirical analysis results presented earlier, and to continuously improve the efficiency of Tianjin Airport's domestic transfer services and strengthen its regional hub functions, this paper proposes the following optimization recommendations across four dimensions: operational mechanisms, network layout, service experience, and system support. First, deepen the coordination of flight schedules and the dynamic management mechanism for Minimum Connecting Time (MCT).Integrate the flight connection quality grading system and the dual-objective optimization model into the schedule coordination process, and regularly conduct simulation evaluations using adaptive large-neighborhood search algorithms to achieve the coordinated optimization of “maximizing the proportion of high-quality connections” and “minimizing flight schedule deviations. “Advance the implementation of MCT compression strategies; while ensuring operational safety, gradually reduce the MCT for domestic-to-domestic transfers from 70 minutes to 60 minutes to unlock more effective transfer opportunities. Establish a dynamic slot negotiation mechanism with airlines; within an acceptable deviation range (±30 minutes), prioritize adjusting flight schedules with “moderate” or “poor” connection quality to promote the concentration of slot resources toward high-efficiency transfer combinations. Second, build a multi-tiered, high-coverage transfer route network. Leveraging optimized cross-regional transfer corridors such as “Northeast–Central and South” and “East China–Northwest,” further expand transfer links for high-potential routes such as Northeast to Southwest and North China to Xinjiang. For routes with low direct flight frequencies, prioritize the deployment of transfer products to enhance route attractiveness by improving the “relative strength” indicator. Addressing shortcomings in the airport network structure, we will collaborate with hub airlines to launch or increase frequencies on domestic routes that align with the hub’s transit functions, thereby strengthening network connectivity and access efficiency. Third, we will promote the standardization and digitization of transit service processes. We will comprehensively promote the “Jingjin LeDao 2.0” service brand and further advance convenience measures such as cross-carrier through-check-in, paperless through-ticketing, and fast-track transfers to reduce the time passengers spend on procedures. Establish a coordination mechanism for service standards among airlines, particularly in cross-carrier transfer scenarios, to promote information sharing and emergency response coordination, thereby reducing the risk of passengers missing connecting flights. Improve the functionality of transfer facilities, optimize the layout of passageways and waiting areas during peak hours, and explore the establishment of “joint service counters” to provide one-stop guidance and support for transfer passengers. Fourth, we will strengthen data-driven and brand-oriented marketing strategies. Based on the results of connection quality grading, we will collaborate with airlines to launch competitively priced, differentiated transfer products for “Excellent” and “Good” rated transfer combinations, attracting time- and cost-sensitive passenger segments. Utilizing digital platforms such as “Transfer Pass,” we will proactively recommend transfer itineraries with high connection quality and short transit times to passengers, enhancing the experience and satisfaction of those who independently plan their travel. Regularly publish reports on the connectivity of the transfer route network to communicate Tianjin Airport’s network advantages and service capabilities as a regional hub, thereby shaping the airport’s brand image as a “convenient transfer hub.”

6. Conclusion

This paper addresses the current operational situation at Tianjin Airport, which is characterized by a focus on domestic-to-domestic transfers and a relatively low proportion of international flights. It constructs a schedule optimization system that integrates flight connection quality grading. Through theoretical modeling and empirical analysis, the main conclusions are as follows:

(1) The multi-dimensional connection quality assessment model, based on four core dimensions—time match, spatial detour coefficient, relative intensity, and service quality—combines an evaluation system constructed using the natural break method to classify flight connection quality into four levels: “Excellent,” “Good,” “Average,” and “Poor,” thereby establishing clear quantitative standards for connections of different grades. This model overcomes the limitations of traditional single-time-dimension assessments, enabling the precise identification of high-value transfer combinations and providing a scientific basis for subsequent optimization. In particular, it effectively identifies high-quality transfer solutions characterized by “tight time connections, low detour costs, and strong airline service synergy.”

(2) Dual-Objective Optimization Model and MCT Compression Mechanism Significantly Enhance Transfer Efficiency The optimization model, which aims to “maximize the proportion of high-grade connections” and “minimize flight schedule deviation,” combined with an adaptive large-neighborhood search algorithm, demonstrated significant results in a pilot study at Tianjin Airport: When MCT was set to 70 minutes, the number of “Excellent” and “Good” connections increased by 9.66% and 26.41%, respectively, compared to pre-optimization levels, and the combined proportion of “Excellent” and “Good” connections rose from 70.49% to 71.05%;When the MCT was reduced to 60 minutes and combined with schedule optimization, the proportion of "Excellent" and "Good" connections further increased to 71.54%, and the total number of effective transfer itineraries rose by 25.57%. Meanwhile, the schedule deviation was strictly controlled within the 30-minute range acceptable to airlines, balancing optimization effectiveness with operational feasibility.

(3) Dual Upgrades in Transfer Network Accessibility and Service Experience Following optimization, Tianjin Airport has established a cross-regional, highly connected hub radiation pattern: passengers from Northeast China can conveniently transfer through Tianjin to six major regions including Central-South and Southwest China, while those from East China can efficiently connect to Northwest China and Xinjiang. The coverage breadth of the route network and transfer efficiency have been significantly enhanced. Furthermore, in conjunction with the “Jingjin Le Dao 2.0” service brand and the development of a digital platform, the passenger transfer process has been simplified by more than 50%. Pain points such as handling of non-directly checked baggage and cross-carrier information coordination have been alleviated, effectively reducing the risk of missed connections and passenger dwell time. The transfer service experience has shifted from “accessibility” to “quality.”

(4) The optimization approach provides replicable insights for domestic transfer-oriented hubs. The optimization plan for Tianjin Airport outlines a comprehensive pathway of “quality classification—model construction—algorithmic solution—mechanism implementation”: unlocking

transfer potential through MCT compression (from 70 to 60 minutes), enhancing connection efficiency through refined schedule adjustments, and strengthening service guarantees through standardized service protocols. This approach is particularly suitable for regional hub airports with weak international routes but strong domestic transfer demand, providing a theoretical framework and practical model for such airports to overcome the challenges of “insufficient transfer traffic and weak hub competitiveness.”

Acknowledgements

We are grateful for the financial support from the National Natural Science Foundation of China(U2333206); the Major Project of Key Research Base of Humanities and Social Sciences of the Ministry of Education of China (22JJD630006); the Civil Aviation Safety Capacity Building Project of 2024 "Domestic Air Shuttle Safety Supervision"; and the Major Project of Social Sciences of Tianjin Municipal Commission of Education (2018JWZD52); Civil Aviation University of China Graduate Student Research Innovation Program (No. [2024YJSKC080013]); Civil Aviation University of China Graduate Student Research Innovation Program (No. [2024YJSKC07001]).Tianjin Medical University Research Project on Hospital Management Innovation(No. [2024YG22]).

Conflicts of Interest

The authors confirm that there are no conflicts of interest.

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