

## Article

# Research on Collaborative Optimization of Airport Taxiing Paths and Runway Capacity Based on Rapid Exit Taxiway Departure Mode

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**Abstract:** To address the increasingly prominent issue of inefficient utilization of runway resources, which is primarily caused by the excessive occupancy of runway infrastructure by small aircraft during peak operational periods, this paper proposes an innovative approach utilizing rapid exit taxiways for aircraft takeoff procedures. In order to systematically evaluate and implement this strategy, we develop a comprehensive two-stage collaborative optimization model that seamlessly integrates taxiing path optimization with dynamic runway departure scheduling. By thoroughly considering complex airport surface operation rules and safety constraints, a joint optimization framework for both taxiing paths and takeoff entrance allocation is rigorously formulated. The primary objective functions of this mathematical model are designed to minimize overall taxiing time and significantly reduce runway occupancy time. To effectively solve the proposed model and handle its computational complexity, an advanced hybrid approach combining a genetic algorithm and mixed-integer programming is employed. Extensive case study simulations are conducted to validate the performance of the proposed methodology. The empirical results demonstrate substantial improvements across key performance indicators: the total taxiing time is reduced by 13.41%, the average runway occupancy time is decreased by 6.82%, and the overall runway capacity is increased by 6.93% following the optimization process. Ultimately, these findings clearly indicate that the proposed rapid exit taxiway takeoff mode can effectively alleviate severe runway-end queuing bottlenecks by strategically increasing the number of available takeoff entrances. This approach thereby improves surface taxiing efficiency and substantially enhances overall runway capacity when compared with conventional airport operation modes.

**Keywords:** airport planning; rapid exit taxiway; runway capacity; path optimization; occupancy time

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## 1. Introduction

With the rapid development of civil aviation in China, both airport passenger throughput and aircraft movements have steadily increased, making runway capacity an increasingly critical factor constraining airport development. According to the Statistical Bulletin on the Production of Civil Transport Airports in China (2025) issued by the Civil Aviation Administration of China (CAAC), by the end of 2025, there were 270 transport airports in operation nationwide, handling 1,529.046 million passengers, 21.864 million tons of cargo and mail, and 12.448 million aircraft movements, representing year-on-year increases of 4.8%, 9.0%, and 0.4%, respectively [1]. Meanwhile, the number of transport airports with an annual passenger throughput exceeding 10 million reached 41. Runway capacity has thus become a key constraint on the rapid and efficient development of airports, leading to a series of issues such as severe delays, increased fuel consumption, and reduced operational efficiency, which threaten the sustainable development of the

aviation industry. Direct approaches to increasing runway capacity through physical means, such as constructing new runways or expanding existing ones, are often restricted by practical constraints and are difficult to implement. Therefore, improving airport operational modes provides a feasible approach to enhancing runway capacity.

In existing studies on runway capacity optimization, the research focus has gradually shifted from traditional empirical analysis to simulation-based approaches, data-driven methods, and integrated optimization frameworks [2]. Models have been developed to analyze the impact of operational strategies and key parameters on runway capacity. Investigations into runway operations under different separation constraints and operational configurations have provided quantitative evaluations of runway capacity in complex scenarios. Delay propagation mechanisms have been analyzed, and quantitative approaches to evaluate delay costs have been proposed, improving overall airport operational efficiency through optimization models. From a system perspective, airport capacity formation has been analyzed considering multiple interacting factors, revealing the coupled effects of operational conditions and environmental influences. Studies on Rapid Exit Taxiways (RET) from both operational and geometric perspectives have demonstrated that optimizing RET layout can effectively reduce runway occupancy time (ROT) and improve runway capacity. Integrated optimization models combining runway allocation and aircraft trajectory optimization have shown that coordinated optimization can significantly enhance airport efficiency and capacity.

Taxiway path planning, as a major research direction in airport surface operation optimization, has achieved significant progress in model development, algorithm design, and integrated optimization [1]. Existing studies mainly focus on objectives such as shortest path length, minimum taxiing time, and optimal fuel consumption. Taxi path optimization models have been developed based on the dynamic characteristics of airport surface operations and solved using optimization techniques to improve taxi efficiency. Operational constraints have been incorporated into taxi path optimization, and efficient algorithms have been proposed to improve taxi scheduling performance. Integrated optimization frameworks combining gate assignment, taxi scheduling, and pushback operations have been proposed to enhance airport surface efficiency. The coupling relationship between gate assignment and taxi routing has been addressed by developing integrated models based on space-time networks and solving them using advanced optimization techniques.

At present, improvements in runway capacity and taxi route optimization are mainly achieved by adjusting airport operational modes or by re-planning taxi routes using multi-objective optimization methods. This paper innovatively proposes that rapid exit taxiways (RET) can be used as available take-off entries for small aircraft, with the taxiway holding position serving as the take-off starting point. In this way, aircraft can complete part of the acceleration process before entering the runway, thereby reducing runway occupancy time (ROT) and improving runway capacity. Meanwhile, the increase in available take-off entries enables the reconfiguration of taxi routes, which can shorten taxi distance and reduce taxiing conflicts, thus improving taxiing efficiency. Therefore, this paper considers the complete departure process of aircraft, from taxiing from the gate to the take-off entry and initiating take-off, to the moment when the tail fully crosses the runway boundary. Under the condition that rapid exit taxiways are used for take-off by small aircraft, the coordinated optimization of runway capacity and taxiing efficiency is investigated [3].

## **2. Feasibility Analysis of RET-Based Take-off**

A rapid exit taxiway (RET) is a taxiway connected to the runway at an acute angle, designed to enable landing aircraft to vacate the runway at higher speeds compared with conventional exit taxiways. This minimizes runway occupancy time, improves runway operational efficiency, and increases runway capacity [4]. The angle between the centerline of a RET and that of the runway typically ranges from 25 to 45 degrees, with standard configurations of 30 and 45 degrees.

Under the conventional airport operating mode, aircraft depart from the runway threshold and complete the take-off process when the tail fully clears the runway boundary. However, for small Code C aircraft with relatively short take-off distances, departures from the runway threshold may lead to inefficient utilization of runway resources, thereby constraining the overall operational efficiency of the airport. To address this issue, the use of rapid exit taxiways as optional take-off entries for small Code C aircraft is proposed, aiming to reduce runway occupancy time and consequently enhance runway capacity [5]. At most large civil transport airports in China, which are classified as 4E or 4F, rapid exit taxiways are typically located at distances ranging from 1500 m to 2500 m from the runway threshold. According to relevant performance standards, the take-off distance of Code C aircraft under standard operating conditions is generally less than 2500 m, as summarized in Table 1 for specific aircraft types. This indicates that such aircraft are capable of completing take-off using rapid exit taxiways. In addition, since the operational directions of take-off and landing are consistent, the rapid exit taxiways used by departing aircraft do not spatially overlap with those used by arriving aircraft to vacate the runway, and therefore no operational conflicts arise.

**Table 1.** Takeoff Distances of Major Code C Aircraft.

aircraft type	FAA-specified take-off distance (m)
A-318	1280
A-319	1436
A-320	1789
A-321	1920
B737-300	2030
B737-400	2356
B737-500	1859
B737-600	1800
B737-700	1676
B737-800	2240
B737-900	2408

### 3. Two-Stage Surface Operation Optimization Model Based on RET-Based Take-off

Under the conventional airport operating mode, departing aircraft typically enter the runway from the runway threshold to complete the take-off roll, resulting in a single take-off entry point. This paper introduces a concept that allows rapid exit taxiways (RET) to be utilized for the take-off of small aircraft. While maintaining the traditional runway-threshold departure mode, an additional RET-based take-off entry is proposed for eligible small aircraft. Consequently, departing aircraft are no longer confined to a single entry point but can choose among multiple take-off entries based on their aircraft type, operational state, and take-off distance requirements [6]. This approach transforms the taxiway routing problem from a conventional shortest-path problem into a coupled surface optimization problem that integrates take-off entry selection with taxi route planning.

Based on these characteristics, the departure process of aircraft is divided into two stages [7]. Stage 1 involves taxiway routing optimization, focusing on organizing aircraft movements from gates through the taxiway network to candidate take-off entries. Stage 2 addresses runway take-off optimization, which deals with the scheduling of take-offs at the selected entry point. By using the take-off entry selection and the arrival time at the selected entry obtained in Stage 1 as inputs for Stage 2, information transfer between the taxiway system and the runway system is achieved. This facilitates coordinated improvements in both taxiway and runway operational efficiency while ensuring the feasibility of the overall solution.

### 3.1. Model Assumptions and Notation

This paper adopts a graph-theoretic approach to construct an airport taxiway network model, in which the airport surface operation system is abstracted as a directed graph  $G=(V,E)$ . The node set  $V$  includes key locations such as taxiway intersections, runway entry/exit points, gates, and rapid exit taxiways, while the edge set  $E$  represents the taxi routes connecting these nodes. In addition,  $K$  denotes the set of all aircraft within the study period, and  $R$  denotes the set of candidate take-off entries [8]. Within the airport network model, departing flights start from gate nodes and reach runway entry nodes via the taxiway network, whereas arriving flights taxi from runway exit nodes to gate nodes through rapid exit taxiways. By capturing nodes and their connectivity relationships, the proposed model fully characterizes the topological structure of the airport taxiway network system, thereby providing a rigorous mathematical foundation for subsequent taxi route optimization and runway scheduling.

To facilitate model formulation, the following assumptions are made based on actual airport operational characteristics:

1. During the study period, each aircraft performs only one arrival or departure operation and enters or leaves the taxiway system according to predetermined times.
2. Medium and large aircraft are only allowed to take off from the runway threshold, while small Code C and lower aircraft may select either the runway threshold or a rapid exit taxiway (RET) as the take-off entry, subject to the available take-off distance.
3. During Stage 1, the taxiing speed of aircraft is assumed to be constant at 10 m/s, and the effects of acceleration and deceleration are neglected.
4. During Stage 2, only the take-off roll time on the curved segment of the rapid exit taxiway is explicitly calculated; the subsequent acceleration roll time on the straight runway segment is approximated using empirical parameters.

### 3.2. Taxi Route Optimization Model

Under the RET-based take-off mode, the taxiing destination of departing aircraft is no longer restricted to a single runway-threshold entry. Instead, it is defined as a set of candidate take-off entries, which include both the runway-threshold entry and the available rapid exit taxiway (RET) entries. Consequently, the optimization problem in Stage 1 becomes a joint optimization task that integrates taxi route selection with take-off entry assignment. The objective of this stage is to minimize the total taxi time for all aircraft within the study period, while adhering to constraints such as taxiway capacity, taxiing safety separation, crossing conflicts, head-on conflicts, and the first-in-first-out rule.

#### 3.2.1. Objective Function

For the taxi route optimization problem, previous studies have primarily focused on objectives such as minimizing total taxi time, reducing taxi distance, and lowering emissions. In this paper, the objective function is defined as minimizing total taxi time, which is expressed in the following formulation:

$$\min Z_1 = \sum_{k \in K} \sum_{(i,j) \in E} T_{ij}^k x_{ij}^k$$

Here,  $T_{ij}^k$  represents the taxi time required for aircraft  $k$  to traverse arc  $(i,j)$ , and  $x_{ij}^k$  is a binary variable indicating whether the aircraft selects arc  $(i,j)$ . If  $x_{ij}^k=1$ , aircraft  $k$  traverses arc  $(i,j)$ ; otherwise, if  $x_{ij}^k=0$ , the aircraft does not traverse arc  $(i,j)$ .

#### 3.2.2. Constraints

Taxi route continuity constraint

Let the origin node of aircraft  $k$  be denoted as  $o_k$ ; then, for the origin node, the following constraint holds:

$$\sum_{j:(o_k,j) \in E} x_{o_k j}^k = 1, \forall k \in K$$

For any intermediate node, the flow conservation constraint must be satisfied:  

$$\sum_{i:(i,m) \in E} x_{im}^k - \sum_{j:(m,j) \in E} x_{mj}^k = 0, \forall k \in K$$

The above constraint ensures that each aircraft can taxi continuously along the taxiway network from the origin node and eventually reach one of the candidate take-off entries [9].

**Take-off Entry Selection Constraint**

For each departing aircraft, only one take-off entry is allowed to be selected; therefore, the following constraint is imposed:

$$\sum_{r \in R_k} y_r^k = 1, \forall k \in K$$

Where  $y_r^k$  is the take-off entry selection variable. If  $y_r^k=1$ , aircraft  $k$  selects take-off entry  $r$ ; otherwise, if  $y_r^k=0$ , the aircraft does not select this entry.  $R_k$  denotes the set of candidate take-off entries available to aircraft  $k$ . For small aircraft, the available take-off entries include the runway-threshold entry and rapid exit taxiway (RET) entries, whereas for medium and large aircraft, only the runway-threshold entry is available [1].

**Taxiing Safety Separation Constraint**

On any taxi route, a minimum safety time separation must be maintained between aircraft.

$$t_j^l - t_j^k \geq \Delta_{kl}^{taxi} - M(1 - \theta_{klj})$$

$$t_j^k - t_j^l \geq \Delta_{lk}^{taxi} - M\theta_{klj}$$

Where  $t_j^k$  denotes the time at which aircraft  $k$  arrives at node  $j$ ,  $\Delta_{kl}^{taxi}$  denotes the safety time separation between aircraft  $k$  and aircraft  $l$  during taxiing on the taxiway, and  $\theta_{klj}$  is a binary variable indicating the passing order of aircraft at node  $j$ . If aircraft  $k$  passes node  $j$  before aircraft  $l$ , then  $\theta_{klj}=1$ ; otherwise,  $\theta_{klj}=0$ .  $M$  is a sufficiently large constant. The safety time separation between different aircraft types during taxiing is shown in Table 2.

**Table 2.** Aircraft Safety Time Separation in Taxiways (Unit: seconds).

leading aircraft type	trailing aircraft type		
	heavy aircraft	medium aircraft	light aircraft
heavy aircraft	21.6	14.4	7.2
medium aircraft	21.6	14.4	7.2
light aircraft	21.6	14.4	7.2

**Taxiway Capacity Constraint**

To prevent the same taxi route segment from being occupied by two aircraft simultaneously, for aircraft  $k$  and  $l$  sharing the same arc  $(ij)$ , the following constraint must be satisfied:

$$t_i^l \geq t_j^k + \Delta_{kl}^{taxi} - M(1 - u_{ijkl})$$

$$t_i^k \geq t_j^l + \Delta_{lk}^{taxi} - Mu_{ijkl}$$

Where  $u_{ijkl}$  is a binary auxiliary variable indicating the passing order of aircraft  $k$  and  $l$  on arc  $(ij)$ . If aircraft  $k$  traverses arc  $(ij)$  before aircraft  $l$ , then  $u_{ijkl}=1$ ; otherwise,  $u_{ijkl}=0$ . This constraint reflects the requirement that at any given time, a taxi route segment can only be occupied by one aircraft [7].

**Crossing, head-on, and overtaking constraints**

**Crossing conflict constraint:** when two aircraft pass through the same intersection node, only one aircraft is allowed to pass first; therefore, the following constraint is imposed:

$$t_j^k + t_j^l = 1$$

**Head-on conflict constraint:** for any two aircraft on the same taxi route, they are not allowed to taxi toward each other in opposite directions at any time.

$$x_{ij^k} t_j^k - x_{ij^l} t_j^l \geq 0$$

Overtaking conflict constraint: aircraft taxiing in the same direction must follow the first-in-first-out rule, and overtaking of the leading aircraft by the trailing aircraft on any taxi route segment is not allowed [9].

$$(x_{ij^k t_i^l} - x_{ij^k t_i^l}) (x_{ij^k t_j^k} - x_{ij^l t_j^l}) > 0$$

After solving the Stage 1 model, the optimal taxi route, the selected take-off entry, and the arrival time at the selected take-off entry for each aircraft can be obtained [10, 11]. The arrival time at the selected take-off entry can be expressed as follows:

$$r_k = \sum_{r \in R_k} t_r^k y_r^k, \forall k \in K$$

Where  $t_r^k$  denotes the time at which aircraft  $k$  arrives at the runway holding point or the taxiway holding point, and  $r_k$  denotes the time at which aircraft  $k$  enters the Stage 2 take-off scheduling system, serving as a key coupling variable linking the two-stage models [12].

### 3.3. Take-off Roll Optimization Model

In Stage 1, the take-off entry selection results and the arrival time at the selected take-off entry for each aircraft have been obtained. To facilitate subsequent runway capacity analysis, this stage adopts runway occupancy time (ROT) as the optimization objective. Runway occupancy time refers to the duration from the moment an aircraft enters the runway to the moment it fully vacates the runway. Here, fully vacating the runway means that the aircraft body (with the tail as the reference) has completely crossed the runway boundary or the runway holding position marking and has entered the taxiway or other non-runway areas, no longer occupying runway resources or affecting subsequent take-off and landing operations.

Due to the fact that the take-off roll process on the runway in Stage 2 involves continuously changing aircraft acceleration and speed, in order to simplify the calculation, only the take-off roll time on the rapid exit taxiway (RET) is explicitly calculated, while the runway occupancy time (ROT) of other aircraft is uniformly specified based on aircraft type. On this basis, the focus is placed on analyzing runway occupancy time and runway capacity. Table 3 presents the average runway occupancy time of aircraft specified according to aircraft type.

**Table 3.** Average Runway Occupancy Time for Aircraft (Unit: seconds).

aircraft type	Runway occupancy time for take-off	Runway Occupancy Time for Landing
light aircraft	50	55
medium aircraft	55	50
heavy aircraft	65	45

The essence of runway capacity is determined by the time headway between consecutive aircraft [1]. For any two adjacent aircraft  $i$  and  $j$ , the time headway can be expressed as follows:

$$H_{ij} = \max(ROT_i, Sep_{ij})$$

Where  $ROT_i$  denotes the runway occupancy time (ROT) of the leading aircraft, and  $Sep_{ij}$  denotes the minimum safety time separation determined by aircraft type combinations and operational rules. Therefore, the core of this stage lies in calculating the runway occupancy time of each aircraft and determining the take-off sequence under separation constraints. Table 4 presents the minimum safety time separation between different aircraft types during take-off and landing on the runway.

To facilitate subsequent calculations, the runway capacity formulation for the airport considered in this study is given as follows.

$$\begin{aligned} \bar{H} &= \sum_{i,j} p_{ij} \cdot H_{ij} \\ C &= \frac{3600}{\bar{H}} \end{aligned}$$

Where  $C$  denotes the runway capacity of the airport, and  $p_{ij}$  denotes the proportion of each aircraft type.

**Table 4.** Runway Safety Time Separation Between Different Aircraft Types (Unit: seconds).

leading aircraft type	trailing aircraft type		
	light aircraft	medium aircraft	heavy aircraft
light aircraft	98	74	74
medium aircraft	138	74	74
heavy aircraft	167	114	94

For the conventional runway-threshold take-off mode, the runway occupancy time of aircraft  $k$  is denoted as  $ROT_k^{conv}$ . Under the RET-based take-off mode, the aircraft enters the runway via a rapid exit taxiway (RET) and completes part of the acceleration process before entering the runway. This portion of time originally belongs to the runway occupancy phase; however, under the RET-based take-off mode, it is transferred to the taxiway and therefore no longer occupies runway resources. Let this time be denoted as  $\Delta t_k$ , which is treated as a reduction in runway occupancy time, thus yielding:

$$ROT_k^{RET} = ROT_k^{TH} - \Delta t_k$$

Where  $ROT_k^{RET}$  denotes the equivalent runway occupancy time under the RET-based take-off condition. During the ground roll process, the aircraft is subjected to the combined effects of engine thrust, gravity, friction, and other forces, and its acceleration can be expressed as follows:

$$a = \frac{[F_N - \mu * W - (C_D - \mu * C_L) q * S_W] g}{W}$$

Where  $F_N$  denotes the engine thrust,  $\mu$  denotes the friction coefficient,  $W$  denotes the maximum take-off weight of the aircraft,  $C_D$  and  $C_L$  denote the drag coefficient and lift coefficient, respectively,  $S_W$  denotes the wing reference area, and  $g$  denotes the gravitational acceleration.

To simplify the calculation, it is assumed that the acceleration of the aircraft remains constant during the short acceleration period on the rapid exit taxiway [13]. In addition, for small aircraft using a rapid exit taxiway (RET) for take-off, the speed during acceleration on the RET must not exceed the maximum permissible taxiing speed on the taxiway. Specifically, if the aircraft does not reach the maximum permissible speed while accelerating on the RET, it remains in the acceleration phase throughout the process; otherwise, the process consists of an acceleration phase followed by a constant-speed phase. When the aerodrome reference code is 3 or 4, the maximum speed during take-off roll shall not exceed 93 km/h; when the aerodrome reference code is 1 or 2, the maximum speed during take-off roll shall not exceed 65 km/h.

Based on the above conditions, the overall objective function for the taxiing stage and the take-off stage is given as follows [14, 15].

$$\min Z = C_1 \sum_k Z_1 + C_2 \sum_k (s_k - r_k)$$

Where  $Z_1$  denotes the objective function of the taxiing stage,  $s_k$  denotes the time at which aircraft  $k$  fully vacates the runway, and  $r_k$  denotes the time at which aircraft  $k$  enters the Stage 2 take-off scheduling system [16, 17].  $C_1$  is the weight of total taxi time, and  $C_2$  is the weight of total take-off time.

During take-off and landing on the runway, to ensure that the wake turbulence generated by the leading aircraft does not affect the trailing aircraft, a minimum safety separation distance must be maintained between aircraft.

$$T_{ip} + T_{ij}^s (1 - Z_{ij}) M \leq T_{jp}$$

Where  $T_{ip}$  denotes the take-off start time of aircraft  $i$  on runway  $p$ ,  $T_{jp}$  denotes the landing start time of aircraft  $j$  on runway  $p$ ,  $Z_{ij}$  is the runway operation sequencing variable indicating the take-off and landing order, such that  $Z_{ij}=1$  if aircraft  $j$  operates before aircraft  $i$ , and  $Z_{ij}=0$  otherwise,  $M$  is a sufficiently large constant, and  $T_{ij}^s$  denotes

the safety time separation between aircraft  $i$  and aircraft  $j$  for runway take-off and landing operations [18].

#### 4. Case Study Analysis

##### 4.1. Case Data

This paper examines the surface taxiway network of Harbin Taiping International Airport as the study object. The airport operates two parallel runways, Runway East 1 and Runway East 2. Runway East 1 has a total length of 3200 m and a width of 45 m, while Runway East 2 measures 3600 m in length and 45 m in width, utilizing a closely spaced parallel configuration. Runway East 2 was officially commissioned on January 23, 2025. Since the data used in this study were collected prior to its commissioning, the analysis primarily focuses on Runway East 1. Runway East 1 is equipped with five rapid exit taxiways (RET). Among these, Taxiway A7 is located 740 m from the runway threshold, providing a remaining take-off distance of 2460 m, which meets the take-off performance requirements for small Code C aircraft. Consequently, it is selected as a feasible RET for RET-based take-off in this study. The study considers 25 aircraft operating between 17:00 and 18:00 on a specific day in December 2024 at Harbin Taiping International Airport as the sample, including 15 departing flights and 10 arriving flights. Of the 15 departing flights, 13 aircraft are capable of performing RET-based take-off under permissible runway conditions. Figure 1 illustrates a simplified surface network of Harbin Taiping International Airport, and Table 5 provides the taxiing information for the 25 flights analyzed in this study.

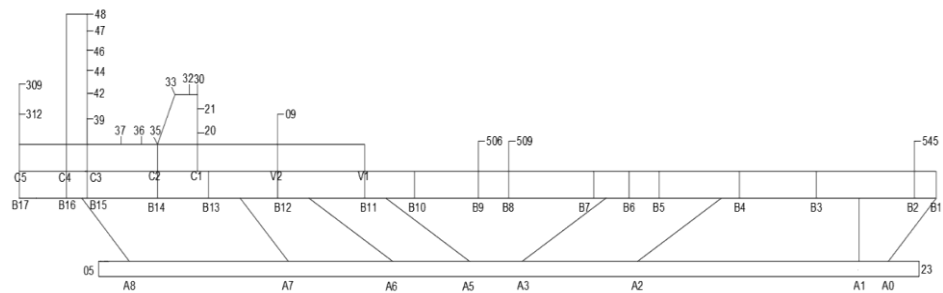


Figure 1. Taxiway System Network Diagram of Harbin Taiping International Airport (Partial).

Table 5. Aircraft Taxiing Information.

Aircraft ID	Flight Number	Arrival Time / Pushback Time	Aircraft Type	Origin Node	Destination Node	Operation Type
1	MF8739	17:03:00	B737	05	42	arrival
2	MU5198	17:03:00	A320	20	05	departure
3	MF8806	17:07:00	B738	05	37	arrival
4	CZ9106	17:07:00	A320	30	05	departure
5	ZH8446	17:09:00	A320	48	05	departure
6	PN6231	17:16:00	A321	05	47	arrival
7	CZ6360	17:17:00	A321	33	05	departure
8	CZ5970	17:19:00	A320	05	309	arrival
9	GX8864	17:19:00	A320	21	05	departure
10	MU5614	17:24:00	A320	44	05	departure

11	MU3761	17:28:00	A320	05	30	arrival
12	DZ6252	17:29:00	B738	509	05	departure
13	SC4846	17:32:00	B738	05	312	arrival
14	ZH9674	17:33:00	B738	36	05	departure
15	HU7326	17:36:00	A333	545	05	departure
16	HU7328	17:40:00	A333	506	05	departure
17	GS7641	17:43:00	A320	05	39	arrival
18	MU2174	17:44:00	B738	32	05	departure
19	MU5597	17:48:00	A321	05	44	arrival
20	HU7210	17:48:00	B738	39	05	departure
21	BL9556	17:51:00	B738	09	05	departure
22	CZ4922	17:52:00	A320	35	05	departure
23	AQ1162	17:54:00	B738	46	05	departure
24	JD5165	17:57:00	A321	05	36	arrival
25	CZ3623	18:00:00	A320	05	21	arrival

#### 4.2. Case Study Results Analysis

This paper adopts a staged solution approach to solve the proposed model. In Stage 1, the taxi route optimization is solved using a genetic algorithm, with a population size of 80, a maximum number of iterations of 200, a crossover probability of 0.85, a mutation probability of 0.10, and a uniform taxiing speed of 10 m/s. In Stage 2, the runway operation optimization is carried out based on the results obtained in Stage 1. A mixed-integer programming method is employed to minimize the total system operation time, and the optimal take-off sequence and corresponding operation scheme are obtained under the constraints of runway safety separation and stage coupling. Figure 2 shows the convergence behavior of the genetic algorithm in Stage 1, with a computation time of 178 s.

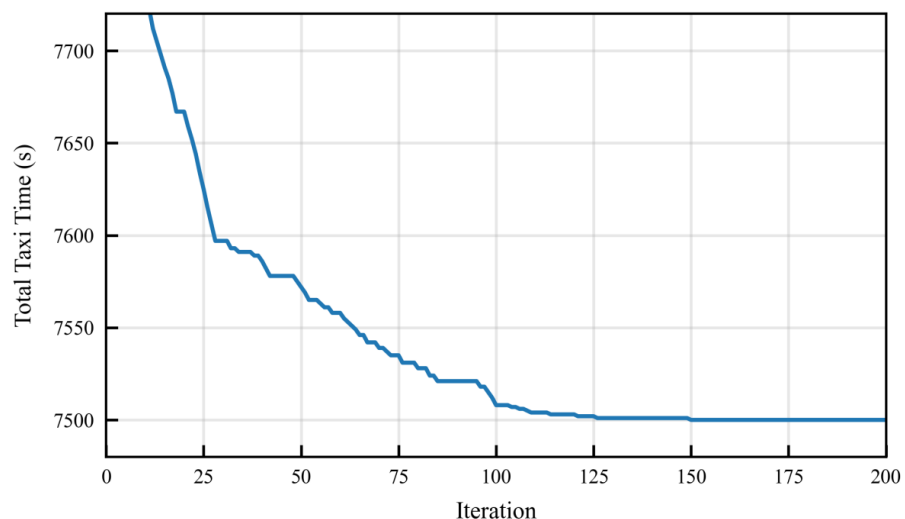


Figure 2. Convergence curve of the genetic algorithm optimization process.

Table 6 presents the final results of taxi route optimization and runway take-off optimization. It can be observed that the proposed RET-based take-off concept for small aircraft leads to significant improvements in both taxiing efficiency and runway operational efficiency. In the taxiing stage, the total taxi time is reduced from 7562 s to 6582 s, achieving a significant decrease of 13.41%, indicating that taxi route optimization

and the availability of multiple take-off entries can effectively enhance taxiing efficiency. In the take-off stage, the runway occupancy time (ROT) for take-off is reduced from 1345 s to 1253 s, corresponding to a decrease of 6.82%, demonstrating that adjusting the airport operation mode by introducing additional take-off entries reduces the runway resource occupation of individual aircraft and further improves runway capacity.

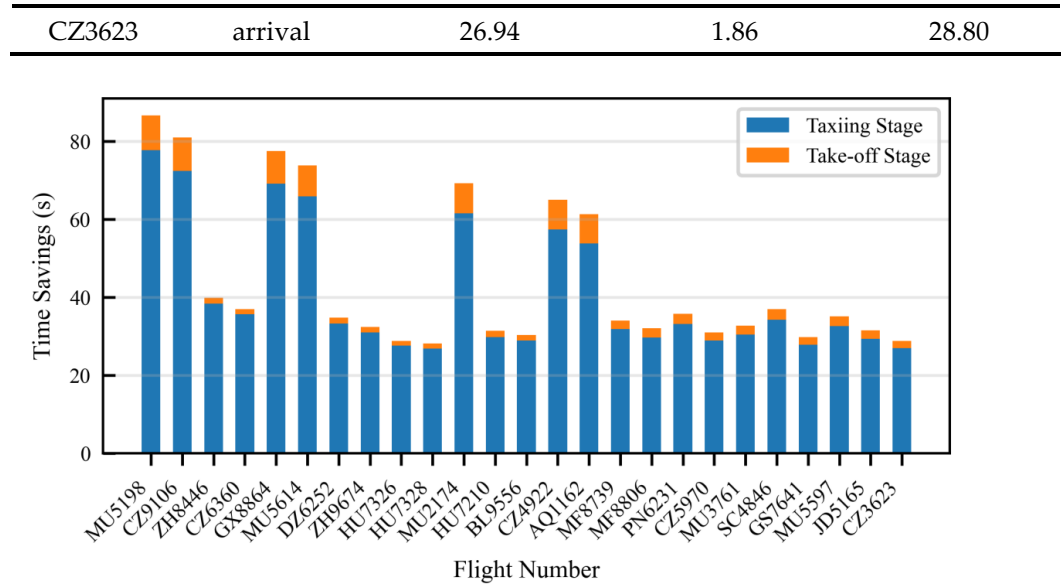
**Table 6.** Comparison of Indicators before and after optimization.

Metric	Before Optimization	After Optimization	Improvement
Total Taxi Time (s)	7562	6582	13.41%
Total Take-off Time (s)	1345	1253	6.82%
Runway Capacity (operations·h <sup>-1</sup> )	36.80	39.35	6.93%

To further analyze the overall optimization performance, the time savings in each stage are separately extracted and analyzed by stage, as presented in Table 7. Based on the results in Table 7, a comparative analysis is conducted on the proportion of total time savings contributed by the taxiing stage and the take-off stage, as shown in Figure 3.

**Table 7.** Two-stage optimization results.

Flight Number	Take-off Mode	Taxiing Stage Time Savings/s	Take-off Stage Time Savings/s	Total Time Savings/s
MU5198	RET-based	77.64	8.92	86.56
CZ9106	RET-based	72.38	8.57	80.95
ZH8446	conventional	38.42	1.48	39.90
CZ6360	conventional	35.67	1.32	36.99
GX8864	RET-based	69.15	8.34	77.49
MU5614	RET-based	65.84	7.98	73.82
DZ6252	conventional	33.26	1.56	34.82
ZH9674	conventional	30.94	1.41	32.35
HU7326	conventional	27.58	1.27	28.85
HU7328	conventional	26.83	1.35	28.18
MU2174	RET-based	61.47	7.76	69.23
HU7210	conventional	29.76	1.62	31.38
BL9556	conventional	28.94	1.44	30.38
CZ4922	RET-based	57.36	7.58	64.94
AQ1162	RET-based	53.82	7.43	61.25
MF8739	arrival	31.84	2.16	34.00
MF8806	arrival	29.72	2.38	32.10
PN6231	arrival	33.15	2.64	35.79
CZ5970	arrival	28.96	2.05	31.01
MU3761	arrival	30.48	2.27	32.75
SC4846	arrival	34.26	2.71	36.97
GS7641	arrival	27.85	1.94	29.79
MU5597	arrival	32.63	2.52	35.15
JD5165	arrival	29.37	2.18	31.55



**Figure 3.** Two-stage optimization results.

In the taxiing stage, under the condition that departing flights selectively adopt RET-based take-off, the increase in available take-off entries directly reduces taxi route length, thereby effectively improving the operational efficiency of the taxiing stage for departing aircraft and generating a coordinated effect on arriving aircraft. As shown in Table 7, improvements in taxiing stage operation time are observed for all flights. For flights that do not adopt RET-based take-off (including arriving flights and some departing flights), efficiency gains are mainly achieved through taxi route optimization and conflict mitigation, with time savings in the taxiing stage generally concentrated in the range of 25~40 s. For departing flights adopting RET-based take-off, due to the forward shift of the take-off entry, taxi routes are reconfigured, and the need to continue taxiing to the runway threshold is avoided, resulting in a significant reduction in taxi distance; consequently, the time savings in the taxiing stage are mostly within the range of 65~80 s. In addition, the introduction of RET-based take-off alters the traffic distribution of the taxiway network, allowing flights that were previously concentrated at the runway threshold to access alternative take-off entries, thereby reducing taxiway congestion. For conventional take-off flights, although they still need to taxi to the runway threshold, their taxi time is also effectively reduced due to decreased taxiing conflicts, improved route throughput, and alleviated queuing pressure at the runway threshold.

In the take-off stage, for departing flights adopting RET-based take-off, the runway occupancy time (ROT) can be reduced by approximately 7~9 s. This is because RET-based take-off shortens the time required for aircraft to occupy the runway after entry by enabling part of the acceleration process to be completed on the rapid exit taxiway, allowing runway resources to be released earlier. For conventional take-off flights that do not adopt RET-based take-off, although they cannot directly reduce runway occupancy time through rapid exit taxiways, the increase in available take-off entries reduces queuing and waiting time at the runway threshold, resulting in a time improvement of approximately 1~3 s in the take-off stage. Although the improvement in the take-off stage for conventional flights is relatively small, this result indicates that under the RET-based take-off mode, the enhancement in operational efficiency is not limited to aircraft adopting RET-based take-off, but extends to nearly all departing flights to varying degrees. Therefore, the use of rapid exit taxiways for take-off not only accelerates the release of runway resources by reducing runway occupancy time, but also enhances overall airport operational efficiency under mixed operation conditions by reducing departure queues at the runway threshold.

In summary, the joint optimization of taxi route and runway operations based on RET-based take-off achieves a coupled optimization of the taxiway system and the runway system by restructuring the taxiway network, mitigating surface conflicts, and optimizing the sequencing relationships of arrival and departure flights. The observed efficiency improvement is not derived from localized enhancements of a single flight type or a single operational stage, but rather reflects a system-level optimization effect resulting from the coordinated interaction between the taxiing stage and the take-off stage [12].

### 5. Summary

1. This paper addresses the challenge of insufficient runway resource utilization under the conventional single runway-threshold entry take-off mode and introduces an innovative airport operation mode where rapid exit taxiways (RET) are utilized as additional take-off entry points for small aircraft. A two-stage coordinated optimization model, encompassing "taxi route optimization-runway take-off scheduling," is developed to achieve integrated optimization of take-off entry selection and taxi route planning. By focusing on the time at which aircraft complete the taxiing stage and transition into the Stage 2 take-off scheduling system, the model effectively integrates the taxiway and runway systems. This approach provides a novel modeling framework and theoretical basis for optimizing airport operations.
2. The results of the airport case study demonstrate that incorporating rapid exit taxiways (RET) as additional take-off entry points for small aircraft significantly enhances airport operational efficiency. Specifically, total taxi time is reduced by 13.41%, runway occupancy time (ROT) decreases by 6.82%, and runway capacity increases by 6.93%. Further analysis reveals that the RET-based mode not only directly improves the efficiency of aircraft utilizing RET-based take-off by reducing taxi route distances and runway occupancy times but also indirectly benefits other flights by alleviating queuing at the runway threshold and reducing taxiway congestion. This coordinated improvement effect underscores the broader operational advantages of the proposed approach.
3. While the proposed model effectively captures the impact of RET-based take-off on airport operational efficiency, certain simplifications remain. For instance, during the take-off stage, the acceleration of aircraft on the rapid exit taxiway is assumed to be constant, and the take-off roll time on the straight runway segment is approximated using empirical parameters. The model does not fully account for dynamic factors such as variations in engine thrust and environmental conditions, which could influence actual take-off performance. Future research should incorporate more detailed flight performance models to enhance the accuracy and applicability of the proposed framework.

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