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Airport Taxiway–Gate Joint Scheduling Problem: A Multi-Objective Optimization Approach Based on a Spatiotemporal Graph

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Abstract

The optimization of gate allocation and taxiway routing represents a critical challenge in enhancing airport ground operations performance. To simultaneously address these two closely coupled tasks, their interconnected processes are first modeled as flows in a spatiotemporal graph. On this basis, we develop a multi-objective optimization approach that accounts for both temporal and spatial factors across different operational aspects, effectively balancing the diverse needs of travelers, carriers, and airport authorities. To mitigate differences in scale and preference among various optimization objectives, min-max normalization combined with the linear weighting method is employed to transform the multi-objective problem into a single-objective one, which is solved by binary integer linear programming. Based on the actual operational data of Terminal 1 at Shanghai Pudong International Airport, three typical scenarios of different complexity are constructed for validation purposes. Performance comparisons with the state-of-the-art methods demonstrate the superiority of the proposed model in terms of various operational costs and parameter sensitivity. The integrated scheduling solution offers airport operators a reliable and efficient decision-making tool with practical applicability.

Keywords: airport ground operations; gate allocation; taxiway routing; spatiotemporal graph; multi-objective optimization; binary integer linear programming

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1. Introduction

Airports, particularly hub airports (HAs), generally serve as distribution centers of air transportation and critical nodes of the route network. Their surface operations involve balancing multiple stakeholders (such as air traffic control, airports, and airlines) and optimizing the allocation of various resources (such as gates, taxiways, and runways) [1]. In the post-pandemic era, the relatively limited supply of airport resources is increasingly unable to meet operational needs for different stakeholders. The intensifying conflict between capacity and demand has led airports to face numerous challenges, such as frequent flight conflicts, complex flight control, and excessive operating pressure, resulting in a series of real-world issues that need to be addressed, including airport congestion, flight delays, and declining passenger satisfaction.

In fact, enhancing airport operational capacity lies in the scheduling and optimization of core airside resources, mainly including gates, taxiways, and runways [2]. The task of gate allocation provides the usage of each gate by flights within a time period and its

results also exert an impact on the ground movements of flights. Taxiway routing, on the other hand, is a combinatorial problem involving path planning (i.e., the spatial dimension) and resource scheduling (i.e., the temporal dimension). Under constraints such as safety regulations, it aims to dynamically plan conflict-free and time-efficient surface movement paths for aircraft on airport taxiways from the perspectives of time and space. For most past studies, gate allocation and taxiway routing tasks were considered separately [3]. When optimizing airport gate allocation schemes, the historical average taxiing time is usually used as the potential taxiing cost for the gate. This macro-level estimation is rough and greatly increases the risk of conflicts at taxiway nodes on a micro level [4–6]. Similarly, when performing taxiway routing, the basic attributes of the gates (such as size information and physical layout) are not considered, which may cause a waste of gate resources (for example, parking small-sized aircraft at large gates), or result in excessively long walking distances for passengers [7–9].

Generally speaking, the gate serves as either the origin or the destination of taxiway planning, which makes gates and taxiways highly coupled resources. Based on the above facts, recent research has increasingly considered both tasks simultaneously and modeled them as a joint scheduling problem [10–14]. For example, Jiang et al. [10] utilized bi-level programming models to sequentially output the optimal solutions for the two tasks, where an improved genetic algorithm based on single-point crossover and loop-nested iteration was designed. Empirical data demonstrated that this dual-layer optimization framework captures the interaction between the two and enhances their respective performance. On this basis, Sun et al. [11] further considered the problem of pushback time delay and proposed a genetic-routing integrated algorithm to solve the three problems sequentially. In addition to the aforementioned sequential models, other representative studies construct integer programming models to simultaneously output the results of gate allocation and taxiway routing [12–14]. Considering the uncertainty of aircraft active time, Yang and Gao [12] developed a probabilistic scheduling framework using mixed-integer linear programming. Although the framework demonstrated operational efficiency at Hangzhou International Airport, its application scope was restricted to a small scenario with only five flights. Liu et al. [13] further introduced multi-commodity flow theory to concurrently solve both optimization challenges. Experimental results at Nanjing Lukou Airport revealed that the proposed model has lower idle time cost when benchmarked against conventional heuristic approaches. Similarly, Yu et al. [14] proposed connection-based and time-space based networks to simultaneously address the gate reassignment and taxiway path planning problems under free-routing settings, where a diving heuristic algorithm was implemented to enhance computational efficiency. The performance of the proposed models was verified to surpass sequential methods at Hong Kong International Airport. Table 1 provides a comprehensive comparison of the differences among various representative methods across different dimensions.

From Table 1, it can be observed that although temporal efficiency metrics like taxi duration, operational time, waiting periods, and aircraft occupancy time remain the principal optimization objectives across all methodologies, spatial considerations have received comparatively less attention. These spatial factors significantly impact multiple stakeholders involved in the schemes of gate allocation, such as passengers and airport operators [15,16]. It is worth mentioning that the runway sequencing task has also been attempted to be optimized together with gate allocation and taxiway routing tasks [17,18]. However, due to their being influenced by multiple influencing variables such as runway operational configuration, adverse weather patterns, and terminal airspace structure, the optimal allocation of runway resources is not within the scope of this paper.

Table 1. Summary of representative methods.

Refs.	Integrated Model	Multi-Objective Optimization	Time or Space Costs	Scale of the Test	Multidimensional Evaluation
Jiang et al. [10]	×	×	only time cost	Small	×
Sun et al. [11]	×	√	time and space costs	Medium	×
Yang and Gao [12]	√	×	only time cost	Small	×
Liu et al. [13]	√	×	only time cost	Medium	√
Yu et al. [14]	√	×	only time cost	Large	√

Therefore, to effectively tackle the challenges associated with the coordinated management of taxiways and gates, this paper employs a novel spatiotemporal graph structure to represent the movement of arriving and departing flights at airports. On this basis, a multi-objective optimization approach is developed that accounts for the interests of various stakeholders by integrating multiple time-related and space-related costs. Specifically, aircraft taxiing time, gate occupancy time, passenger walking distance, and gate compatibility costs are defined as four optimization objectives, with network flow, taxiing conflicts, and gate usage as practical constraints. To integrate multiple objectives, the regularized linear weighting technique with the dual-objective balancing parameter are introduced to flexibly meet the performance objectives of different decision-makers. The transformed optimization objective is solved by binary integer linear programming. Take the Terminal 1 at Shanghai Pudong International Airport as a case study; we validate the performance of the proposed model in three typical scenarios representing different traffic complexity. Compared with the classic first-come-first-served (FCFS) model and the state-of-the-art models, the applicability of our model is analyzed in detail from multiple dimensions, including the trade-off between time and space costs, comparison of performance indicators, and parameter sensitivity.

In summary, the main contributions are summarized as follows:

(1) A multi-objective optimization approach based on a spatiotemporal graph is developed for taxiway–gate joint scheduling, which comprehensively considers both time-related and space-related objective functions and realistic constraints.
(2) To address the differences in scale and preferences among various objective functions, the min-max normalization technique and linear weighting method are introduced to obtain the integrated objective, which is solved by binary integer linear programming.
(3) A series of experiments are performed across three typical real-world scenarios of varying complexity. The proposed model is rigorously evaluated against the state-of-the-art models, with particular emphasis on assessing objectives performance and parameter robustness.

The rest of this paper is organized in the following manner. Section 2 provides the detailed modeling process, including the structure of the spatiotemporal graph and the multi-objective optimization approach. In Section 3, the case study composed of three typical scenarios is described. Section 4 presents a variety of experimental comparison results and conducts sensitivity analysis of the key parameter. Finally, Section 5 summarizes the key findings and outlines potential directions for further research.

2. Modeling

The joint scheduling of airport taxiways and gates covers the arrival and departure processes of flights and is an optimization problem with high complexity. To better model aircraft ground movements, the structure of the spatiotemporal graph is introduced to characterize the traffic flow of arriving and departing flights, as shown in Figure 1. The green

line segments represent the inbound process of flights, and the red line segments represent their outbound process. The arrow directions indicate the movement directions of flights. From a broader perspective, it integrates the taxiways and gate resources, accounting for continuous aircraft movements during taxiing and gate utilization. Temporally, it spans from the arrival time to the departure time of the flights, incorporating gate holding time (i.e., time required for flights to complete ground services). Spatially, it encompasses all surface areas traversed by aircraft from the runway exit after landing to the runway entry before takeoff.

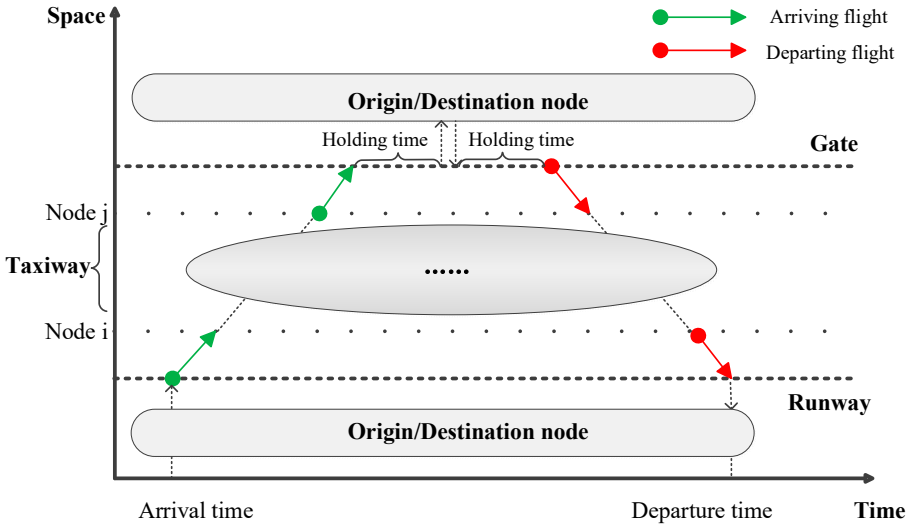


Figure 1. Diagram of the spatiotemporal graph for airport surface movement.

At the microscopic level, arriving flights enter the origin node of the spatiotemporal graph from their arrival time and sequentially visit each taxiway node according to the planned taxi route until reaching the designated gate. After the gate is occupied for a certain period (i.e., the holding time at gate), it is reclaimed at the destination node and restored to an idle state. Subsequently, the flight initiates the gate occupancy process for the departure phase to make adequate preparations for passenger boarding and flight take-off. On this basis, the flight is pushed back from the gate and taxis along the pre-planned taxiing route until it enters the runway and takes off at the departure time. To simplify the complexity of the problem, this paper assumes that the taxiing speed of all aircraft is a fixed constant.

Based on the spatiotemporal graph described above, a multi-objective optimization approach is developed to simultaneously achieve gate allocation and taxiway routing tasks, with the relevant variable definitions as follows:

$S = (V, E)$ denotes the basic structure of the airport spatiotemporal graph.

$V = \{v_0, v_1, \ldots, v_n, v_{n+1}\}$ stands for the set of nodes, which includes both virtual origin and destination nodes (i.e., v_0 and v_{n+1}) along with actual nodes corresponding to taxiways and gates. It should be noted that gate nodes, in addition to being accessible like taxiway nodes, can also be continuously occupied. This corresponds to the waiting process while flights are being serviced at the gate.

G is the set of gate nodes, and G_r is the set of remote gate nodes.

$E = \{(i, j) | i, j \in V\}$ is the set of edges with time weights $w_{i,j}$. If $i \neq j$, $w_{i,j}$ represents the taxiing time between node v_i and node v_j; if $i = j \in G$, $w_{i,j}$ denotes the holding time at gate node v_i. Notably, according to the actual operation of the airport, some edges are set as bidirectional to enhance the flexibility of taxiway planning.

F is the set of all flights, including both arriving flights F_A and departing flights F_D.

$H = \{t_s, \ldots, t_l\}$ is the set of time steps in the entire time horizon, including the first time step t_s and the last time step t_l. Hereby, one minute is set as the basic time step.

t_f denotes the initial time step of flight f. For arriving flights, it refers to the instant when they touch down on the runway, while for departing flights, it indicates the moment when they begin their pushback procedure from the gate.

$v(i)$ denotes the set of nodes adjacent to v_i.

$x_{i,j}^f(t)$ denotes the binary decision variable to be optimized. For the case $i \neq j$, $x_{i,j}^f(t)$ equals 1 indicates that flight f moves from node v_i to node v_j at time step t; otherwise, it equals 0. As for the case $i = j \in G$, $x_{i,i}^f(t)$ equals 1 indicates that flight f utilizes gate node i at time step t; otherwise, it equals 0.

2.1. Optimization Objectives

Based on the variables defined above, the proposed multi-objective optimization model considers two types of costs: temporal cost and spatial cost. The temporal cost includes the taxiing time on taxiways and the occupation time of gates, while the spatial cost focuses on the selection of gates, mainly taking into account the walking distance of travelers and the compatibility of the gates.

(1) Minimize total aircraft taxiing time. Whether for arriving or departing flights, the choice of taxiway routes should minimize taxiing time as much as possible in order to control fuel consumption and its associated environmental impact. Hence, the primary optimization goal is to minimize the cumulative taxi time of all flights, as expressed in the following equation:

$$\min C_1 = \min \sum_{f \in F} \sum_{t \in H} \sum_{(i,j) \in E, i \neq j} w_{i,j} x_{i,j}^f(t) \tag{1}$$

(2) Minimize total gate occupancy time. The duration of gate occupancy is an important component of an aircraft's time resources. By considering both taxiing time and gate occupancy time, the maximum utilization of time resources can be achieved. Typically, in scenarios where airport surfaces are congested, slightly extending an aircraft's occupancy time at the gate can allow for a taxi route with shorter taxiing time, thereby reducing fuel consumption and operational costs. The second optimization objective is expressed as follows:

$$\min C_2 = \min \sum_{f \in F} \sum_{t \in H} \sum_{i \in G} x_{i,i}^f(t) \tag{2}$$

Besides time resources, how to reasonably allocate gates (i.e., space resources) is also one of the key tasks. In this paper, passenger walking distance and gate compatibility cost are considered, respectively. The former aims to increase passenger travel satisfaction and is regarded as the primary purpose of gate allocation. The latter further considers the efficient use of gate resources, ensuring the optimal match between the size of gates and aircraft.

(3) Minimize total passenger walking distance. From the perspective of passenger satisfaction with flight services, the total walking distance for passengers is the product of the number of passengers and the physical distance between the gates and the terminal. More specifically, the terminal refers to baggage waiting position for arrival flights and security check position for departure flights. Hence, the third optimization objective is given as follows:

$$\min C_3 = \min \sum_{f \in F_A} \sum_{j \in G} \sum_{i \in v(j)} \sum_{t \in H} n_f^a l_j^a x_{i,j}^f(t) + \sum_{f \in F_D} \sum_{j \in G} \sum_{i \in v(j)} \sum_{t \in H} n_f^d l_j^d x_{i,j}^f(t) \tag{3}$$

where n_f^a and n_f^d correspond to the passenger counts for inbound and outbound flight f; l_j^a and l_j^d represent the walking distances between the gate node j and the terminal for arriving and departing passengers, respectively.

(4) Minimize total gate compatibility cost. Generally speaking, gates and aircraft have various sizes that need to be considered when assigning a gate to an aircraft [15]. For example, a medium-sized gate can only accommodate medium-sized or smaller aircraft. To ensure the efficient use of gate resources, the match between the aircraft and the assigned gate should be maximized whenever possible. The fourth optimization objective is given as follows:

$$\begin{aligned} &\min C_4 = \min \sum_{f\in F}\sum_{j\in G}\sum_{i\in v(j)}\sum_{t\in H} m_j^f x_{i,j}^f(t) \\ &m_j^f = \begin{cases} 0, & S_j^{gate} = S_f^{flight} \\ 0.2, & S_j^{gate} = S_f^{flight} + 1 \\ 0.5, & S_j^{gate} = S_f^{flight} + 2 \\ 1, & j \in G_r \end{cases} \end{aligned} \tag{4}$$

where m_j^f is the compatibility cost between gate j and aircraft f, S_j^{gate} is the size level of gate j, and S_j^{flight} is the size level of flight j. Whether it is a gate or an aircraft, we set three sizes: large (L), medium (M) and small (S), corresponding to level 3, 2, and 1, respectively.

To balance time cost and space cost, the two types of objectives are linearly weighted and converted into a single objective, allowing adaptation to different preference choices by adjusting the weight parameter. The integrated objective function is shown as follows:

$$\min C = \min \alpha(C_1 + C_2) + (1-\alpha)(C_3 + C_4), \tag{5}$$

where α is the weight parameter used to balance time cost and space cost. In addition, it is easy to find that different objective functions have different scales of value. To eliminate its adverse effect, a min-max normalization operation is performed on each objective function, and the final objective function is shown as follows:

$$\min C_{norm} = \min \alpha\left(\frac{C_1 - C_1^{\min}}{C_1^{\max} - C_1^{\min}} + \frac{C_2 - C_2^{\min}}{C_2^{\max} - C_2^{\min}}\right) + (1-\alpha)\left(\frac{C_3 - C_3^{\min}}{C_3^{\max} - C_3^{\min}} + \frac{C_4 - C_4^{\min}}{C_4^{\max} - C_4^{\min}}\right), \tag{6}$$

where $C_1^{\max}$, $C_2^{\max}$, $C_3^{\max}$ and $C_4^{\max}$ represent the upper bounds of each objective function, and $C_1^{\min}$, $C_2^{\min}$, $C_3^{\min}$ and $C_4^{\min}$ are their respective lower bounds.

2.2. Optimization Constraints

With the final objective function in mind, multiple constraints need to be carefully considered to obtain an effective joint scheduling scheme for gates and taxiways, including network flow constraints and practical constraints related to gates and taxiways.

(1) Network flow constraints. This kind of constraint is used to ensure the integrity of the aircraft movement from the source node to the destination node in the spatiotemporal graph. It mainly involves virtual nodes (i.e., origin and destination nodes) and physical nodes (i.e., nodes for gates and taxiways).

$$\sum_{t=t_f}^{t=t_l}\sum_{i\in v(0)} x_{0,i}^f(t) = 1, \forall f \in F_D \tag{7}$$

$$\sum_{i\in v(0)} x_{0,i}^f(t_f) = 1, \forall f \in F_A \tag{8}$$

$$\sum_{t=t_f}^{t=t_l} \sum_{i \in v(n+1)} x_{i,n+1}^{f}(t) = 1, \forall f \in F \tag{9}$$

$$\sum_{j \in v(i)} x_{i,j}^{f}(t + w_{i,j}) = \sum_{j \in v(i)} x_{j,i}^{f}(t), \forall f \in F, \forall i \in \{1, 2, \ldots, n\}, \forall t \in [t_f, t_l] \tag{10}$$

Equation (7) describes the constraint of origin node for departure flights, and $t_f \leq t \leq t_l$ indicates that the departure flights can be allocated additional waiting time at the gate based on the scheduled pushback time. Equation (8) corresponds to the origin node constraint for arriving flights. For any given flight, its destination node can be uniformly expressed by Equation (9). In addition to the above virtual nodes, Equation (10) is designed to guarantee uninterrupted temporal and spatial progression of aircraft across the airfield surface by balancing the inflow and outflow at the node i.

(2) Taxiway conflict constraints. To enhance operational safety at the airport, aircraft must pay special attention to potential conflicts on taxiways, particularly head-on conflicts, node conflicts, and overtaking conflicts [19]. Figure 2 gives typical scenarios of various types of conflicts.

$$x_{i,j}^{f}(t) + \sum_{t'=t-w_{i,j}}^{t'=t+w_{i,j}} x_{j,i}^{f'}(t') \leq 1, \forall f, f' \in F, \forall (i,j) \in E_{bi}, \forall t \in [t_f, t_e] \tag{11}$$

$$\sum_{f \in F} \sum_{j \in v(i)} x_{i,j}^{f}(t) \leq 1, \ \forall i \in \{1, 2, \ldots, n\}, \forall t \in [t_s, t_l] \tag{12}$$



Figure 2. The typical three types of taxiway conflicts.

Equation (11) describes the head-on conflicts constraint, where E_{bi} is the set of bidirectional taxiways. It ensures that during the time period $[t - w_{i,j}, t + w_{i,j}]$, at most one aircraft passes through the bidirectional taxiway (i, j). Equation (12) avoids node conflicts by ensuring that at any given time, no more than one aircraft occupies the same actual node. It should be noted that since this paper assumes that all aircraft taxi at the same fixed speed, Equation (12) also considers a constraint to avoid overtaking conflicts.

(3) Gate usage constraints. A gate is a key resource that allows an aircraft to complete ground operations tasks, such as aircraft maintenance and passenger transfers. For practical reasons, the use of gates needs to ensure exclusivity and compatibility.

$$\sum_{f \in F} x_{i,i}^{f}(t) \leq 1, \ \forall i \in G, \forall t \in [t_s, t_l] \tag{13}$$

$$\sum_{t=t_f}^{t=t_l} x_{i,i}^{f}(t) \geq T_{service} \sum_{t=t_f}^{t=t_l} x_{0,i}^{f}(t), \forall f \in F^D, \forall i \in G \tag{14}$$

$$\sum_{t=t_f}^{t=t_l} x_{i,i}^{f}(t) \geq T_{service} \sum_{t=t_f}^{t=t_l} x_{i,n+1}^{f}(t), \forall f \in F^A, \forall i \in G \tag{15}$$

$$\sum_{t=t_{f'}}^{t=t_l} x_{0,i}^{f'}(t) - \sum_{t=t_f}^{t=t_l} x_{i,n+1}^{f}(t) = 0, \forall (f, f') \in U, \forall i \in G \tag{16}$$

$$S_f^{flight} \leq S_j^{gate} + M(1 - \sum_{i \in v(j)} \sum_{t=t_f}^{t=t_l} x_{i,j}^{f}(t)), \forall f \in F, \forall j \in G \tag{17}$$

Equation (13) achieves the exclusivity of gates by ensuring that at most one flight can occupy the same gate at any given time. Equations (14) and (15) are used to limit the occupancy time of departing and arriving flights at the gate, respectively. $T_{service}$ is the minimum occupancy time for each aircraft to ensure its ground services, which is set to 15 min. It should be noted that the 15 min applies only to arriving or departing flights. For flights that arrive and depart at the same gate (i.e., flight pairs), the minimum occupancy time is 30 min, with arriving and departing each accounting for half. Equation (16) serves as an auxiliary constraint to ensure that mutually related arrival and departure flights are parked at the same gate. U is used to save these associated flight pairs. Since both the aircraft and gate have size attributes, Equation (17) (i.e., the compatibility constraint) needs to be set to ensure that the assigned gate can accommodate the respective aircraft, where M is an arbitrarily large constant.

In summary, the proposed model takes Equation (4) as the final optimization objective, while also considering network flow constraints (i.e., Equations (7)–(10)), taxiway conflict constraints (i.e., Equations (11) and (12)), and gate usage constraints (i.e., Equations (13)–(17)). Based on the optimized decision variables, the optimal taxiing routes and gate allocation results with time attributes for each arriving and departing flight can be directly obtained.

3. Case Study

In the subsequent experiments, Shanghai Pudong International Airport Terminal 1 was selected, and Figure 3 gives its basic layout, which includes 18 representative contact gates and 12 taxiway nodes. All contact gates are allocated to three parking aprons. For aircraft taxiing time, only the time an aircraft spends moving on the taxiway and its time to reach the apron are considered. The layout of individual gates within the same apron mainly reflects differences in passenger walking distances. Moreover, it should be noted that, in order to prevent flights from accumulating too much during certain periods and consequently lacking feasible solutions (i.e., an available contact gate that meets the operational constraints), an infinitely capacitated remote gate was assumed. For the taxiway segments, one-way and bidirectional taxiway segments are set up. The latter is used to enhance the flexibility of taxiway path planning in order to achieve better scheduling results. In addition, for the sake of simplifying the problem, only the takeoff and landing pattern for a single runway is considered.

As for each gate, they are categorized into three distinct groups (i.e., small, medium, and large gates) based on the wingspan size of aircraft they can accommodate. To keep the settings consistent, the specific types of gates and their corresponding passenger walking distances are all referenced from past literature [4], where G1~G5 are small-size gates, G6~G13 are medium-size gates, and G14~G18 are large-size gates. In addition, operational data from a typical three-day period from 19:00 to 22:00 (i.e., a total of 180 time slots per day) was selected. Table 2 shows the basic information of the flight data, where the size of aircraft is determined according to its wingspan and the passenger numbers of each flight are assigned to their corresponding maximum seating capacity.

The three days of operational data correspond to three scenarios with increasing complexity, and Figure 4 shows the number of flights and their distribution over time in different scenarios. It can be clearly observed that Scenario-1 has the fewest flights,

including 10 departures, 9 arrivals, and 8 flights involving both arrival and departure processes, totaling 35 operations. The flights are evenly distributed across all time periods. In contrast, Scenario-2 and Scenario-3 have more flights (42 and 45 operations, respectively), and the flights are concentrated in certain time periods, such as time period 46–60 (min) in Scenario-2 and time periods 76–90 (min), 91–105 (min), and 106–120 (min) in Scenario-3. It is conceivable that due to potentially more frequent conflicts on the airport surface, the path planning tasks for taxiways in Scenario-2 and Scenario-3 are more difficult than Scenario-1. Especially in Scenario-3, the number of flights continues to increase over three consecutive time periods. Therefore, in order to more comprehensively evaluate the model's performance, we conducted experimental validation using the three aforementioned scenarios with different levels of complexity.

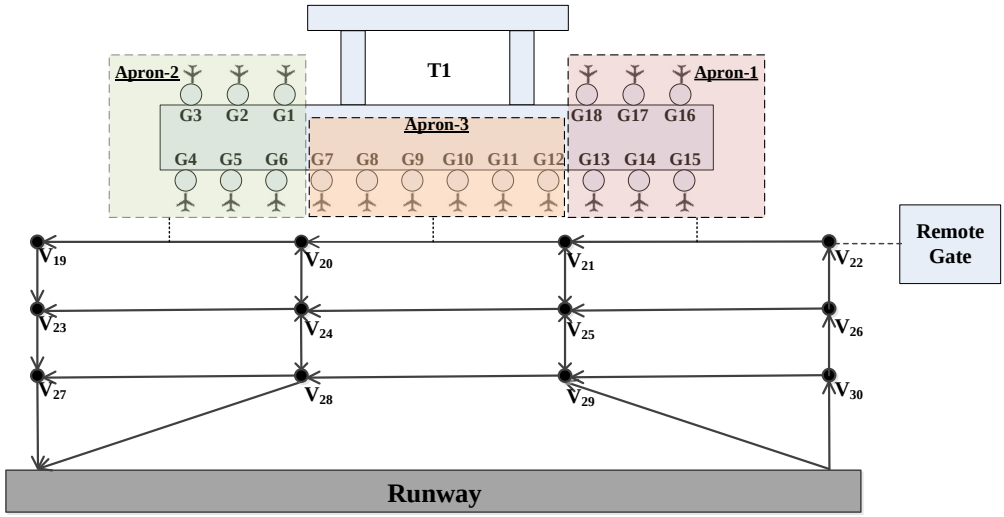


Figure 3. Basic layout of Terminal 1 in Shanghai Pudong International Airport.

Table 2. Example of flight data in the case study.

Arrival Flight ID	Departure Flight ID	Aircraft Size	Arrival Time (HH:MM)	Pushback Time (HH:MM)	Number of Passengers
CSH9222	CSH865	S	17:25	19:10	164
CSZ9513	CSZ9506	S	17:41	19:18	158
...	...	...	...	...	...
CBJ5665	CBJ5666	M	19:55	21:41	180
CCA4535	CCA4536	L	19:58	21:47	285
...	...	...	...	...	...
CSN3543	CSN3544	S	21:35	23:20	161
CSC8411	CSC8412	L	21:41	23:25	243

The size of the aircraft depends on its wingspan. S: <52 m; M: 52~65 m; L: >65 m.

Subsequent related experiments were all conducted on a ThinkBook X laptop equipped with an Ultra5-225H@1.70 GHz Intel Core processor and 32 GB DDR3 memory. The equipment is sourced from Lenovo Group Limited, located in Beijing, China. Since the proposed joint scheduling model is essentially a 0–1 integer linear programming (ILP) problem, its computational time complexity is $O(2^k)$, where k is the number of decision variables. In order to solve efficiently, the branch-and-cut (B&C) algorithm [20] is used to obtain optimal results for gate allocation and taxiway routing. The algorithm was implemented using the latest version of the Gurobi commercial optimizer 9.5.2 and Python 3.9.9, with parameters set to the default configuration. Considering the time cost requirements of real scenarios, the solution time was limited to 30 min.

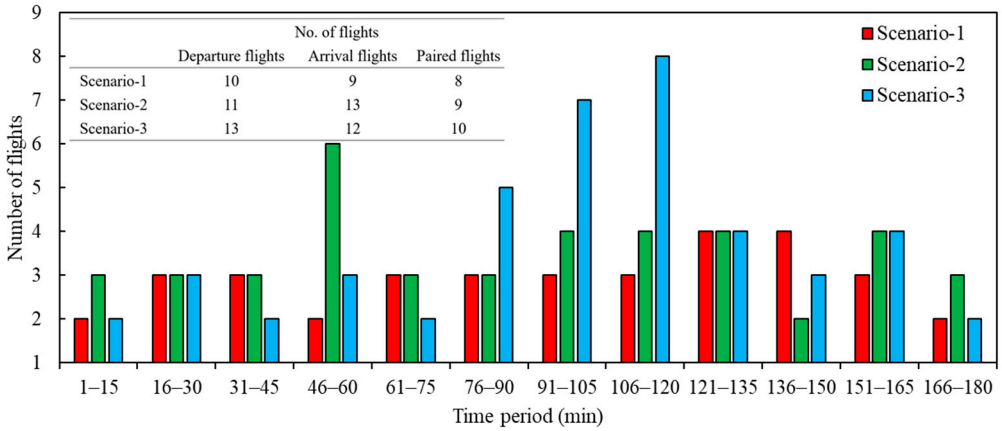


Figure 4. The time-varying distribution of flight numbers in three typical scenarios.

4. Results Analysis

4.1. Trade-Offs Analysis Between Time Cost and Space Cost

First, by adjusting the weight coefficient α within the range of 0 to 1, the optimal solution of the corresponding joint scheduling model is obtained, and on this basis, the respective spatial costs and time costs are calculated. Without loss of generality, Figure 5 shows the pareto frontiers with different weight coefficient α in Scenario-2, where $\alpha = 1$ minimizes only the time cost and $\alpha = 0$ is for the space cost. It can be observed that when α is between 0.7 and 1.0, the space cost changes significantly, while when α is between 0.0 and 0.5, the change in time cost is significant.

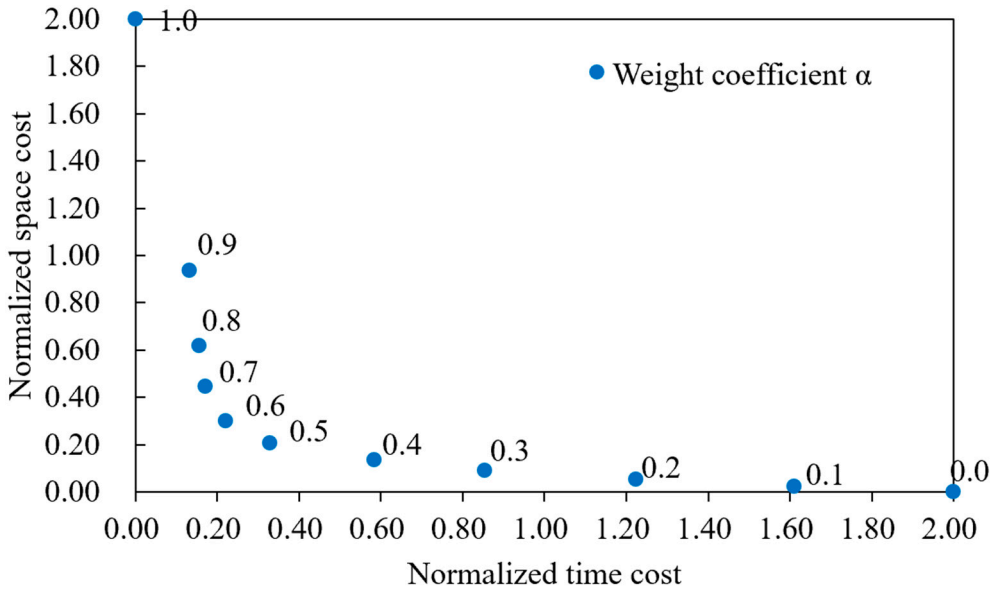


Figure 5. Pareto frontiers with different weight coefficients α (Scenario-2).

In addition, Figure 6 shows how the time cost and space cost change with the weight coefficient α in Scenario-2. In specific applications, the weight coefficient can be adaptively selected according to preferences for space cost and time cost. In the following experimental analysis, we adopted a representative method in multi-criteria decision-making, namely Order of Preference by Similarity to Ideal Solution (TOPSIS) [21], to quantitatively evaluate the solutions on the Pareto frontier and its corresponding weight coefficient. Specifically, solutions are ranked based on their proximity to the origin, and the solution with the smallest value is selected as the final optimal solution. Hence, through calculation, we determined that 0.6 is the optimal weight coefficient, as it yields the optimal solution.

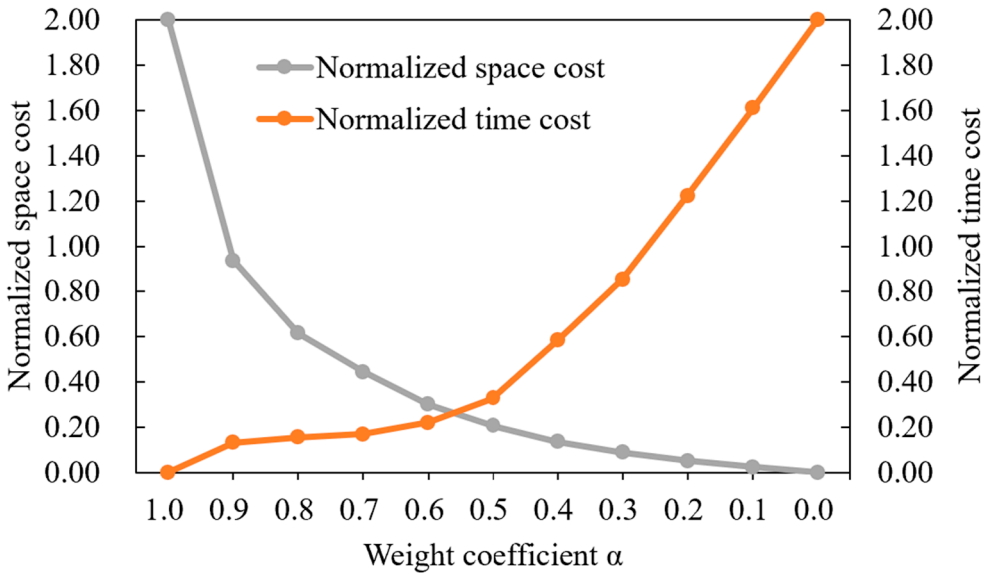


Figure 6. Normalized time and space cost under different weight coefficients α (Scenario-2).

4.2. Performance Comparison of Different Models

To assess the performance of the proposed model, a comparative analysis was conducted with the First-Come-First-Serve (FCFS) model, a standard benchmark in airport ground movement optimization studies. It applies Dijkstra's algorithm in the spatiotemporal graph to find the shortest path that meets the constraints. When taxiing paths are the same, it prioritizes the gate that best matches the aircraft size, and under the same conditions, it further selects the gate with a shorter walking distance. Furthermore, based on the same experimental setup, we reproduced the state-of-the-art sequential model (the bilevel planning model proposed by Sun et al. [11]) and the integrated model (the stochastic scheduling model proposed by Yang et al. [12]) to fully compare the differences between the models. Specifically, aircraft taxiing time and gate occupancy time are used to evaluate time-related performance, while passenger walking distance and gate matching degree are used to evaluate space-related performance. In addition, to evaluate the overall effectiveness of various models, an indicator Δ_{Gap} is introduced to measure the gap between the optimal linear solution and the integer solution. The smaller the indicator, the better the model performance, and it is calculated as follows:

$$\Delta_{\text{Gap}} = \frac{obj^{\text{model}} - obj^{\text{linear}}}{obj^{\text{model}}} \tag{18}$$

where obj^{model} is the objective value for each model, while obj^{linear} is the corresponding result after the model's linear relaxation. The runtime is used to reflect the computational efficiency of the model, with a maximum of 1800 s.

Table 3 displays the optimization results for the two models in three scenarios. Overall, according to the value of Δ_{Gap}, the proposed model achieves the optimal solution in all scenarios, whereas the other models do not. It directly reflects that the optimal solution of the proposed model is the linear relaxation solution, indicating that the model is sufficient to meet airport operational requirements within a 30 min solution time. In particular, as the complexity of the scenarios increases, the performance gap between the two models also grows, and the Δ_{Gap} of the FCFS model becomes larger. This fact indicates that the FCFS model is more prone to getting stuck in local minima, especially during busy times at the airport. In addition, aside from the gate occupancy time in Scenario-3, the proposed model outperforms the FCFS model in both time and space costs. In Scenario-3, although the pro-

posed model has two flights with occupancy times exceeding 15 min (i.e., 16 and 17 min), its aircraft taxiing time is much lower than that of the FCFS model. The fact proved that by slightly extending the gate occupancy time, a more flexible taxiway scheduling plan can be implemented, which effectively alleviates potential congestion conflicts at the airport. For sequence models, due to their integration with genetic algorithms for optimization process, they are able to generate satisfactory solutions within the specified time limits. However, considering the inherent limitations of bi-level planning, their performance in terms of taxiing time indicators is relatively poor, even lower than that of the FCFS model. As for the integrated model, it achieved performance similar to the proposed model in both Scenario-1 and Scenario-2. In Scenario-3, the model failed to find a feasible solution within a limited time, which greatly restricts its applicability in large-scale, high-density operational scenarios.

Table 3. Performance comparison of different models in three scenarios.

	Models	C_{norm}	Δ_{Gap}	Aircraft Taxiing Time (min)	Gate Occupancy Time (min)	Passenger Walking Distance (m)	Gate Compatibility Cost	Running Time (s)
Scenario-1	FCFS model	0.901	3.70%	296	525 (35×15)	3,059,538	0.2	1800
	Sequential model	0.932	3.82%	310	525 (35×15)	3,074,827	0.2	468
	Integrated model	0.868	0.00%	259	525 (35×15)	2,985,031	0	1630
	Proposed model	0.868	0.00%	259	525 (35×15)	2,985,031	0	387
Scenario-2	FCFS model	1.104	4.35%	377	630 (42×15)	3,744,813	1.2	1800
	Sequential model	1.110	4.90%	442	630 (42×15)	3,638,060	0	955
	Integrated model	1.069	1.03%	335	630 (42×15)	3,642,800	0.2	1800
	Proposed model	1.058	0.00%	328	630 (42×15)	3,620,035	0	742
Scenario-3	FCFS model	1.238	5.58%	459	675 (45×15)	4,181,508	2.4	1800
	Sequential model	1.255	6.97%	502	675 (45×15)	4,093,512	0.6	1337
	Integrated model	-	-	-	-	-	-	1800
	Proposed model	1.173	0.00%	381	678 ($43 \times 15 + 16 + 17$)	4,028,400	0.4	966

4.3. Analysis of Time-Space Resources Between the Proposed Model and the FCFS Model

Furthermore, taking Scenario-2 as an example, we compare the changes in taxiing time distribution corresponding to the flight sequence, as shown in Figure 7. It can be observed that for earlier flights (such as the first 12 flights), the FCFS model performs better than the proposed model, with relatively shorter taxiing times. However, for subsequent flights, the taxiing times under the FCFS model are generally higher compared to the proposed model. This phenomenon indicates that the FCFS model is unfair to later-arriving flights due to its inherent limitations. These flights inevitably have to detour because of conflicts with earlier flights on taxi routes. In contrast, the proposed model takes a global perspective, achieving a generally more optimal scheduling result.

In terms of the use of gate resources, the cumulative number of flights for different gates was counted, as shown in Figure 8. The comparison shows that the FCFS model tends to favor gates on both sides of the terminal, with more flights using gates 1–4 and 15–18. In contrast, the proposed model not only considers the gates on both sides but also pays more attention to the gates distributed in the middle of the terminal, such as gates 9–11. Combining the topology diagram of Shanghai Pudong Airport in Figure 3, the

inherent mechanism of the FCFS model prioritizes routes with smaller aircraft taxi times. For arriving flights, aircraft tend to prefer gates 17 and 18; likewise, for departing flights, FCFS looks for the shortest route, usually selecting gates 1 and 2. Nevertheless, gates near the runway exit are often located farther from the runway entrance, which can cause an imbalance in aircraft taxiing times for flight pairs (that is, it includes both the aircraft arrival process and the aircraft departure process), thereby increasing the total taxiing duration on the airfield. On the contrary, the proposed model makes greater use of the gates in the middle of the terminal and takes into account the arrival and departure processes of flight pairs to achieve an overall reduction in aircraft taxiing time. In addition, for gates of the same size, the proposed model can reduce the use of gates with longer walking distances, such as small gates for No. 3–4, medium gates for No. 12–13, and large gates for No. 15–16.

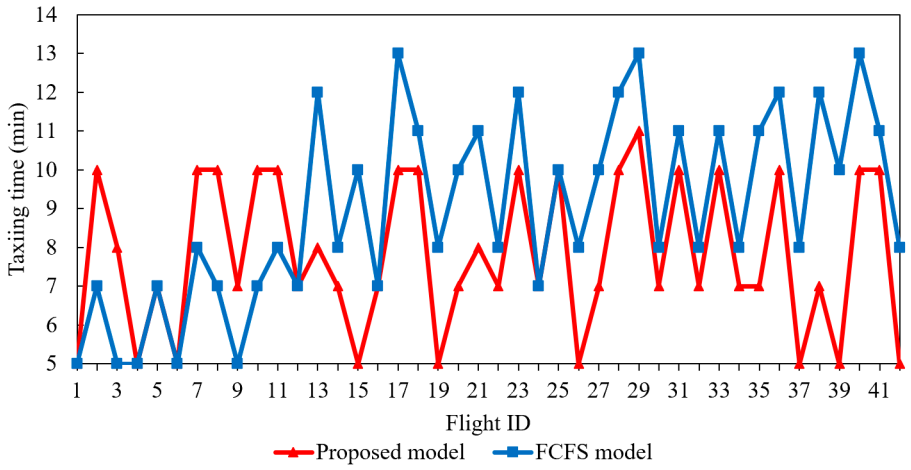


Figure 7. Comparison of taxiing time between the two models.

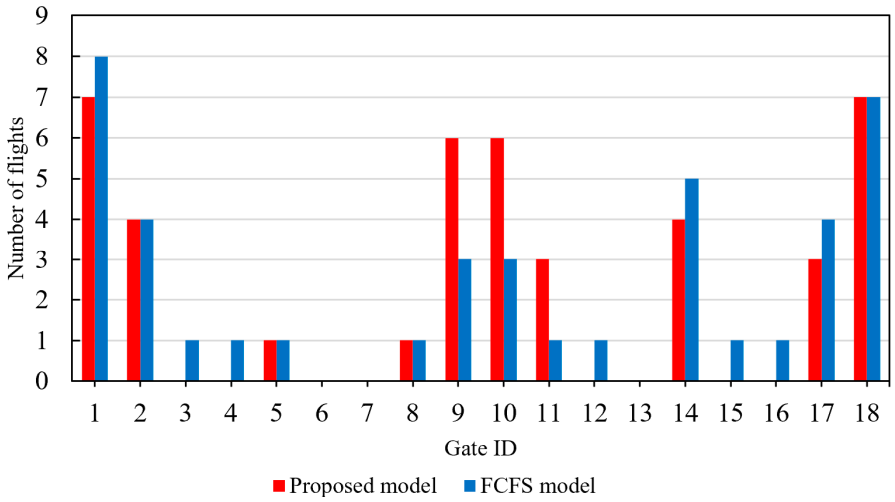
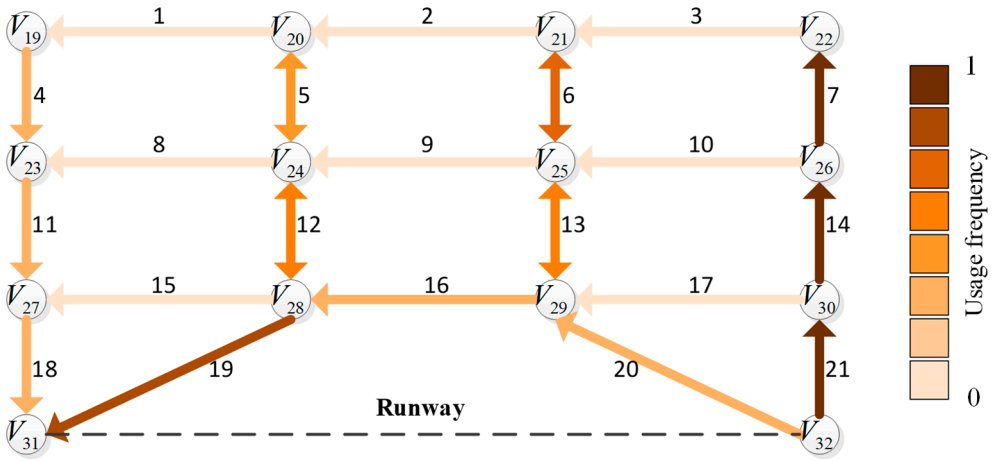
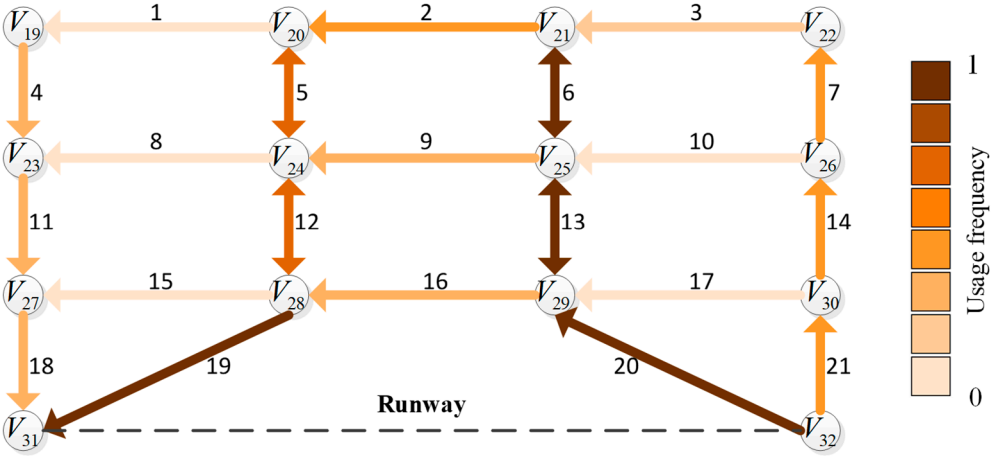


Figure 8. Comparison of gate usage between the two models.

In addition, Figure 9 visualizes the usage frequency of each taxiway segment at the airport, where the numbers indicate the taxiway segment IDs and the colors reflect the usage frequency, with darker colors indicating higher usage. It can be seen that for arrival flights, the FCFS model tends to prioritize taxiway route 21-14-7, whereas the proposed model more frequently chooses taxiway route 20-13-6. This choice is consistent with the preferences for gate usage. Specifically, the proposed model shows a higher usage frequency than the FCFS model on bidirectional taxiway segments, such as 5, 6, 12, and 13. This indicates that the proposed model can more effectively search for and utilize appropriate flexible paths to reduce taxiway conflicts and optimize taxiing time.



(**a**) The usage frequency of taxiway segments in the FCFS model.



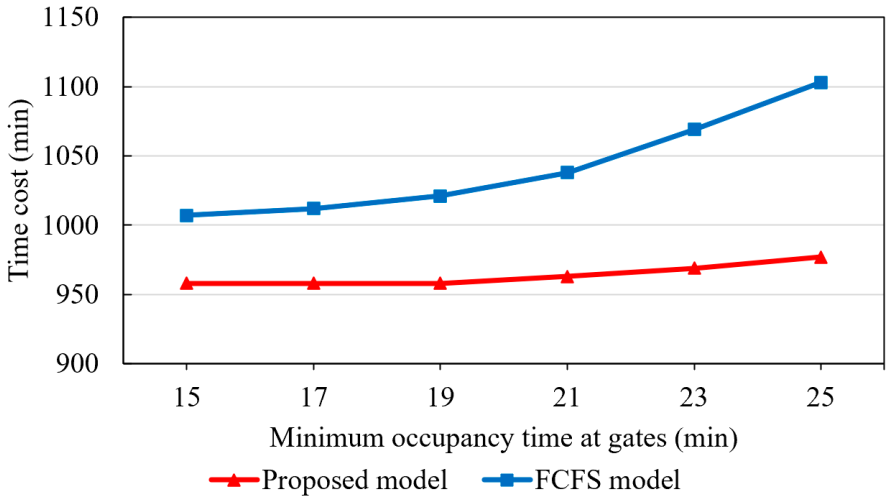
(**b**) The usage frequency of taxiway segments in the proposed model.

Figure 9. Comparison of taxiway segments usage between the two models.

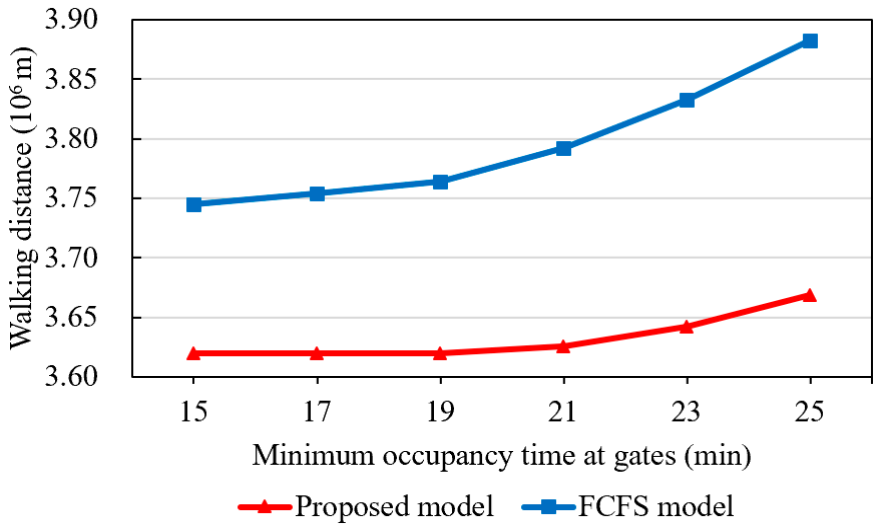
To summarize, the proposed model demonstrates superior optimization performance compared to the FCFS method in balancing the space costs related to gate allocation and the time costs related to taxiing route planning from a global perspective. In fact, the FCFS model also has significant advantages, as it can find feasible solutions within polynomial time complexity, which is why it is widely used in practical scenarios.

4.4. Sensitivity Analysis

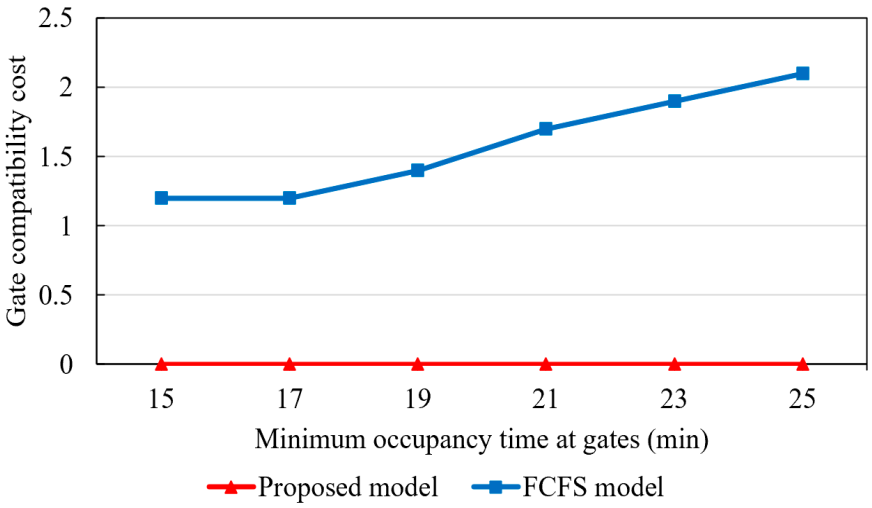
Since the occupancy time of the gates is one of the main sources of uncertainty in airport surface operations, in order to verify the robustness of the proposed integrated model, we varied the minimum gate occupancy time (i.e., $T_{connect}$) from 15 to 25 and analyzed its impact on the fluctuations of various objectives. Figure 10 shows the impact on time cost, walking distance cost, and gate compatibility cost, respectively. It can be seen that the time cost of the proposed model is not sensitive to this parameter. When the occupancy time is 15, 17, or 19, the time cost remains unchanged, while when the occupancy time increases to 21, 23, or 25, the time cost changes slightly. In contrast, the time cost of the FCFS model is more sensitive to this parameter, and the time cost continues to increase as the occupancy time increases. The increase in time costs in the FCFS model is mainly related to the exclusivity constraint. When the minimum gate occupancy time increases, the exclusivity constraint for some flights is no longer satisfied, so it is necessary to replan routes with longer taxiing times to avoid multiple flights occupying the same gate simultaneously.



(**a**) Impact of minimum gate occupancy time on time costs.



(**b**) Impact of minimum gate occupancy time on walking distance.



(**c**) Impact of minimum gate occupancy time on gate compatibility cost.

Figure 10. Sensitivity analysis of minimum occupancy time at gates.

As for the space cost of the proposed model, it can be observed that as $T_{connect}$ increases, the walking distance exhibits similar trends with time cost, while the gate compatibility cost remains unchanged. This phenomenon indicates that despite the increase in $T_{connect}$,

the proposed model can still find the optimal matching between gates and aircraft, though possibly at the cost of a slight increase in walking distance. In contrast, the space cost of the FCFS model is more susceptible to the influence of $T_{connect}$. Both the walking distance cost and gate compatibility cost increase with the increase of $T_{connect}$, and the increase is relatively significant.

5. Conclusions

The tasks of gate allocation and taxiway routing have always been key issues in airport operations. This paper fully takes into account multiple objectives in both time and space, and develops a multi-objective optimization approach based on a spatiotemporal graph to address the two tasks simultaneously. Moreover, the min-max normalization technique and linear weighting method are introduced to integrate multiple objective functions with different value ranges. In order to verify the effectiveness of the proposed model, we compared it with the FCFS model in three typical scenarios at Terminal 1 of Shanghai Pudong International Airport. The results indicate that the proposed model achieves better outcomes in multiple performance metrics and robustness, which can serve as an important reference for airport operators in decision-making.

Since the arrival time and the pushback time of inbound and outbound flights are fixed, future work can further quantify the impact of their uncertainties on the results of joint scheduling, and further design more robust and flexible stochastic scheduling models to solve the problem. In addition, how to incorporate dynamically changing taxiing time into the integrated model is a key factor in ensuring that the model better aligns with real operational scenarios.

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Abbreviations

The following abbreviations are used in this manuscript:

FCFS	First-Come-First-Served
HAs	Hub Airports
B&C	Branch-and-Cut
ILP	Integer Linear Programming

References

1. Morris, R.; Pasareanu, C.S.; Luckow, K.S.; Malik, W.; Ma, H.; Satish Kumar, T.K.; Koenig, S. Planning, Scheduling and Monitoring for Airport Surface Operations. In Proceedings of the the Workshops of the Thirtieth AAAI Conference on Artificial Intelligence Planning for Hybrid Systems, Phoenix, AZ, USA, 12–17 February 2016; pp. 608–614.
2. Atkin, J.A.D.; Burke, E.K.; Ravizza, S. The airport ground movement problem: Past and current research and future directions. In Proceedings of the 4th International Conference on Research in Air Transportation (ICRAT), Budapest, Hungary, 1–4 June 2010; pp. 131–138.
3. Yu, C.; Zhang, D.; Lau, H.Y.K.H. A heuristic approach for solving an integrated gate reassignment and taxi scheduling problem. *J. Air Transp. Manag.* **2017**, *62*, 189–196. [CrossRef]
4. Du, J.; Hu, M.; Yin, J.; Zhang, W. Multi-objective gate allocation problem based on multi-commodity network flow model. *Appl. Sci.* **2022**, *12*, 9849. [CrossRef]
5. Wang, R.; Allignol, C.; Barnier, N.; Gondran, A.; Gotteland, J.-B.; Mancel, C. A new multi-commodity flow model to optimize the robustness of the Gate Allocation Problem. *Transp. Res. Part C Emerg. Technol.* **2022**, *136*, 103491. [CrossRef]
6. Jiang, Y.; Wang, Y.; Hu, Z.; Xue, Q.; Yu, B. Airport gate assignment problem with harbor constraints based on Branch-and-Price algorithm. *Transp. Res. Part E Logist. Transp. Rev.* **2023**, *176*, 103192. [CrossRef]
7. Deng, W.; Zhang, L.; Zhou, X.; Zhou, Y.; Sun, Y.; Zhu, W.; Chen, H.; Deng, W.; Chen, H.; Zhao, H. Multi-strategy particle swarm and ant colony hybrid optimization for airport taxiway planning problem. *Inf. Sci.* **2022**, *612*, 576–593. [CrossRef]
8. Zhu, J.; Han, G.; Shang, P.; Zhao, Z.; Huang, H.; Xiao, F. A Q-Learning based Particle Swarm Optimization for Aircraft Routing and Scheduling in Airport Terminal Area. *IEEE Trans. Autom. Sci. Eng.* **2025**, *22*, 22609–22624. [CrossRef]
9. Shen, J.; Guo, Q.; Lin, L.; Zhong, Y.; Deng, L. Taxiway path planning at airports based on dynamic directed graphs and DQN. *Aerosp. Sci. Technol.* **2025**, *168*, 111295. [CrossRef]
10. Jiang, Y.; Xu, C.; Cai, M.T.; Chen, L.L. Joint scheduling of both taxiway and gate re-assignment based on bi-level programming model. *J. Beijing Univ. Aeronaut. Astronaut.* **2018**, *44*, 2437–2443.
11. Sun, R.; Li, J.; Niu, K.; Tian, Y.; Xu, C. Research on joint ground movement optimization based on bilevel programming. *Aerospace* **2022**, *9*, 502. [CrossRef]
12. Yang, Y.; Gao, Z. Stochastic scheduling of ground movement problem integrated with taxiway routing and gate/stand allocation. *IET Intell. Transp. Syst.* **2022**, *16*, 1143–1163. [CrossRef]
13. Liu, J.; Guo, Z.; Yu, B. Optimising Gate assignment and taxiway path in a discrete time–space network: Integrated model and state analysis. *Transp. B Transp. Dyn.* **2023**, *11*, 1–23. [CrossRef]
14. Yu, C.; Xu, S.X.; Xu, G. A synchronized method for airport operation management: Gate reassignment and taxi routing. *Ind. Manag. Data Syst.* **2026**, *126*, 97–126. [CrossRef]
15. Bouras, A.; Ghaleb, M.A.; Suryahatmaja, U.S.; Salem, A.M. The airport gate assignment problem: A survey. *Sci. World J.* **2014**, *2014*, 923859. [CrossRef] [PubMed]
16. Daş, G.S.; Gzara, F.; Stützle, T. A review on airport gate assignment problems: Single versus multi objective approaches. *Omega* **2020**, *92*, 102146. [CrossRef]
17. Yin, S. Integrated and Joint Optimisation of Runway-Taxiway-Apron Operations on Airport Surface. Ph.D. Thesis, Imperial College London, London, UK, 2022.
18. Jiang, Y.; Liu, Z.; Hu, Z.; Zhang, H.; Xu, C. Variable neighbourhood search for the integrated runway sequencing, taxiway scheduling, and gate reassignment problem. *Transp. B Transp. Dyn.* **2023**, *11*, 744–759. [CrossRef]
19. Zhao, N.; Li, N.; Sun, Y.; Zhang, L. Research on Aircraft Surface Taxi Path Planning and Conflict Detection and Resolution. *J. Adv. Transp.* **2021**, *2021*, 9951206. [CrossRef]
20. Padberg, M.; Rinaldi, G. A branch-and-cut algorithm for the resolution of large-scale symmetric traveling salesman problems. *SIAM Rev.* **1991**, *33*, 60–100. [CrossRef]
21. Olson, D.L. Comparison of weights in TOPSIS models. *Math. Comput. Model.* **2004**, *40*, 721–727. [CrossRef]

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