IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received November 30, 2020, accepted December 12, 2020, date of publication December 18, 2020, date of current version January 4, 2021.

Digital Object Identifier 10.1109/ACCESS.2020.3045586

A Priority-Based Conflict Resolution Strategy for Airport Surface Traffic Considering Suboptimal Alternative Paths

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This research was supported in National Natural Science Foundation of China (U1933118, 71971114).

ABSTRACT Currently, the surface topology at large domestic airports with increasing traffic flow is becoming more complex. Taxiing conflicts grow as well. This paper proposed a strategy based on aircraft priority to solve the problem. Under the premise of ensuring aircraft priority, this strategy resolved the problem reasonably and improved the safety and efficiency of airport operation. With the purpose of minimizing time cost of all aircraft, an aircraft taxiing model was built. Simulation results showed the advantages of this strategy. Compared with a common conflict resolution strategy, taxiing routes of 9 aircraft changed. The total waiting time was reduced by 50% and the running time was reduced by 43.6s. In addition, to ensure taxiing efficiency of high-priority aircraft, low-priority aircraft tended to choose more tortuous routes when choosing suboptimal alternative routes.

INDEX TERMS Aircraft priority, dynamic taxiing, rolling horizon, taxiing conflict resolution strategy.

I. INTRODUCTION

With the increase of air traffic, available resources during busy period of large airports can't meet the demand of air transport, which causes much congestion. Such congestion not only reduces the operating efficiency of airports, resulting in air pollution and noise pollution, but also increases the workload of controllers and the risks of runway invasion. It brings many unsafe factors to the operation of airports [1]. How to improve the operational efficiency of airport surface has become a hot spot in air transport management research.

Airport surface operation mainly includes runway scheduling, taxiway scheduling and gate assignment. Taxiway system connects the apron system and runway system. It is the key resource of airport surface operation. Improving the operating efficiency of taxiways can reduce air pollution and noise pollution caused by aircraft engine. It is helpful to environmental protection and reducing operating cost of airlines and workload of controllers. Therefore, improving the efficiency of taxiways is the key to improving the efficiency of airports.

The major contributions of this paper are as followed: a concept of aircraft priority based on the relative aircraft cost rate, and a new aircraft taxiing conflict resolution strategy considering suboptimal alternative taxiing paths are proposed. From the perspective of aircraft attributes, we established a dynamic aircraft taxiing model based on priority with the objective of minimizing time cost of all arrival and departure aircraft. It not only ensured the safety of operation, but also reduced aircraft's time cost as much as possible.

The rest of this paper is structured as follows. Section 2 presents a review of existing work in Airport Taxiing Scheduling Optimization. Then, the requirements and preliminary description of the rolling horizon-based conflict resolution strategy will be explained in Section 3. Section 4 formulates the aircraft taxiing problem as a model combined with rolling horizon, and the proposed conflict resolution strategy. The performance of the proposed strategy is validated in Section 5 using problem instances based on real-world airport layouts. Finally, conclusions and future directions are presented in Section 6.

II. LITERATURE REVIEW

With the rapid development of civil aviation transportation industry, airport surface management is gradually becoming more complicated and increasingly detailed. The taxiway system is an important part of the airport, connecting the

The associate editor coordinating the review of this manuscript and approving it for publication was Michail Makridis.

runway system and the apron system. Its operational efficiency directly affects the entire airport surface. Research on the optimization of aircraft taxiing has attracted significant attention in recent years. Minimizing taxi time is the most common objective function in taxiway optimization. Li *et al.* [2] took the change of velocity profile into account when aircraft turned. They established a path optimization model for aircraft taxiing at airport surface with the shortest total taxi time as the target. Kariya *et al.* [3] put forward two strategies to reduce taxi time. Strategy one was to control the time interval between two consecutive departure aircraft, and strategy two was to adjust the total time of aircraft from the beginning to the end of taxiing. Both of them can effectively reduce taxi time. Weiszer (2015) *et al.* [4] used active routing strategy when considering sliding factors and established a dynamic model with the shortest taxi time. Xing and Lu [5] developed a taxiing route optimization algorithm for departures based on backpressure routing. The taxiing routes, which possessed the maximum airline satisfaction and minimum taxiway load rate reduced taxi time of aircraft effectively, and improved the throughput of airport. In addition to taxi time, there were studies considering other goals, such as least congestion, least taxi delay, least aircraft emissions, etc. On the basis of Cellular Automata, Mori [6] simulated the running process of aircraft at Tokyo International Airport with a model mainly considering taxiing speed and time. Congestion phenomenon was modeled well with an average accuracy of about 30s. Badrinath and Balakrishnan [7] considered the optimal control of tandem queues, whose evolution of the mean lengths were described with ordinary differential equations, in order to mitigate surface congestion at large airports. Guépet *et al.* [8] applied mixed integer programming (MIP) to solve the problem. He extended the problem from single paths to alternate paths and creatively added punctuality index into the objective function. Adacher *et al.* [9] proposed a general approach to optimize the airport ground movement problem, with the goal of minimizing total routing taxi delay and the pollution emissions. Evertse and Visser [10] designed a real-time airport surface movement planning tool, which was capable of creating conflict-free timed taxiing trajectories for aircraft, while minimizing the total emission of pollutants, fuel usage, departure slot time deviations and taxi time. Zhang *et al.* [11] proposed a multi-objective optimization method for aircraft taxiing based on the airport's environment and traffic conflicts. With the in-depth study of taxiway optimization, in order to simulate the operation of airports, more and more detailed factors were incorporated into aircraft taxiing models. Brownlee *et al.* [12], Chen *et al.* [13] proposed an adaptive Mamdani fuzzy rule based system to estimate taxi time and their uncertainties. The Quickest Path Problem with Time Windows (QPPTW) algorithm was adopted to estimate fuzzy taxi time. Benlic [14] *et al.* presented the first local search heuristic for the coupled runway sequencing and taxiway routing problems, based on the receding horizon (RH) scheme. It took into account the interactions between arrival and departure aircraft on the airport surface. Chen *et al.* [15] developed a new holistic active routing framework for efficient airport ground operations.

The difference between taxiway scheduling and routing problem is that taxiway scheduling problem needs to consider the safety distance between aircraft. We must ensure that there are no conflicts during taxiing. Research on taxiing conflict resolution has achieved many results. Luo *et al.* [16] developed a colored taxiway-oriented Petri net model for real-time adjustment for conflict-free route planning. Taxiing routes were adjusted by decreasing the priority of delayed aircraft to access road section. For the detection of aircraft intersection conflict, Zhu *et al.* [17] proposed an Extended Hybrid Petri-nets (EHP) to model the airport surface operation. Su and Qiu [18] established a dynamic Petri net model by adding the time attribute to the static model and simulated conflict-free taxiing. Hang and Jiang [19] planned the taxiing routes according to conflict detection and searched the shortest routes of static network with improved A$*$ algorithm. Landry *et al.* [20] utilized the properties of complex conflict networks for effective conflict detection and resolution. Mou *et al.* [21] established a threshold traits model for conflict detection alarm based on the analysis of the operation rules of aircraft on the ground and exclusive principle of accessing to critical resources. Wang and Zuo [22] planed taxiing routes for aircraft based on airport surface hotspots in order to avoid hotspots. It turned out that no conflicts occurred, which effectively alleviated the risk level of hotspots. Zhang *et al.* [23] proposed a systematic approach for online speed profile generation with the goal to generate fuel-efficient speed profiles respecting timing constraints imposed by routing and scheduling. Zhang *et al.* [24], [25] used zone control rules to avoid conflicts between aircraft with a taxiway partition model, and developed the trajectory-based surface operations concept to deal with different characteristics of lanes and intersections. Okuniek *et al.* [26], Okuniek and Beckmann [27] applied the management tool Taxi Routing for Aircraft: Creation and Controlling (TRACC) to trajectory-based ramp traffic management, where TRACC generated conflict-free aircraft trajectories in a congested ramp area.

In the past, during the process of conflict resolution, the order of passing through conflict areas was usually specified for aircraft according to First Come First Serve (FCFS) principle. But this priority can no longer meet the requirements of actual operation, and scholars have done research on this. Priority Queueing theory was used in a mathematical model proposed by Sivaramasastry *et al.* [28] for network traffic analysis. Nakawicz *et al.* [29] proposed a mathematical framework that could be used to analyze a general set of priority rules and enabled proofs of important properties. Specific properties including safety, exclusiveness, and stability was considered. Shi *et al.* [30] developed a dynamic hyper-heuristic algorithm for the Aircraft Landing Scheduling (ALS) problem. The Scatter Search algorithm was chosen as the high level heuristic to build a chain of intensification and diversification priority rules.

III. PROBLEM DESCRIPTION

Taxiway scheduling is a routing problem, which is regulated by safety rules that impose spatial and time separation between each pair of aircraft in the airport. Time-efficient routes without conflicts must be allocated to aircraft seeking to traverse the taxiways between the runways and stands. Routes must respect allocated runway time, route restrictions, and safety constraints on the proximity of other aircraft. Interactions between moving aircraft indicate that a more sophisticated approach is required at busy airports. In this work, with the goal of the shortest taxi time, we seek to find suboptimal alternative routes for conflicting aircraft, which doesn't exactly follow pre-determined routes, allowing for greater flexibility.

The actual network of airport surface includes major resource subsystems of runways, taxiways and aprons. The actual distribution is more complicated. This paper is based on graph theory and builds a topological network of airport surface based on actual resource distribution, as shown in Fig. 1. Inside the dotted frame is an apron. The long black bold solid line is runway. The remaining short solid lines are taxiways. The network is an undirected graph network containing only nodes and edges. Each intersection belongs to the set of nodes, which only contain location information, not physical information such as specific size and length. All taxiways, including apron taxiways, parallel taxiways, belong to the set of edges. A taxiing route can be described as a sequence of nodes, and the corresponding spatial taxi trajectory can be easily reproduced using the connecting taxiway central lines.

A rolling horizon framework is selected for implementation of aircraft surface taxiing. The purpose is to decompose a single large problem into a number of smaller problems, rendering the approach amenable to real-time aircraft surface scheduling. Moreover, by periodically advancing the time window, the total aircraft taxiing schedule can be dynamically updated, allowing to deal with unexpected events or perturbations on taxiways.

The inputs to the priority-based scheduling model consist of, (i) a directed graph representing the taxiway grid, (ii) the characteristics and parameters for each aircraft (type, seat number, speed, fuel consumption), (iii) a fixed flight schedule for inbound and outbound traffic. This flight schedule consists of starting taxi time for all aircraft, as well as the entry and exit node of each flight, (iv) constraints such as the minimum safety interval, speed limitation, etc.

IV. MODEL

A. ASSUMPTION OF THE MODEL

1) The taxiing speed of all aircraft are constant and they are only dependent on the aircraft type;
2) The minimum safety distance between aircraft, shown in Fig. 2, is set to 20s [8], [31];
3) The starting and ending points of taxiing paths of all aircraft are known;

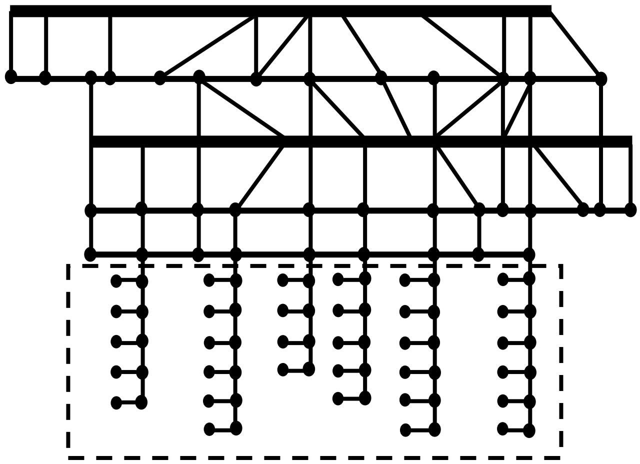

FIGURE 1. A topological network of airport surface.

4) All aircraft have continuous taxiing paths;
5) Information about aircraft is known, such as standard seating number, taxiing fuel consumption, etc.

B. DEFINITION OF VARIABLES

F The set of all aircraft; $F = \{f_1, f_2, \cdots, f_k\}$

N The set of airport surface nodes; any node $p, q \in N$

L_{pq} Length of the taxiway between node p and node q

T_{ip} The actual time of aircraft f_i arriving at node p with conflict resolution (if aircraft f_i doesn't reach node p, then $T_{ip} = 0$)

t_{ip} The time of aircraft f_i reaching node p without conflict resolution (if aircraft f_i doesn't reach node p, then $t_{ip} = 0$)

t_{ij}^e Minimum safety distance

v_i Taxiing speed of aircraft f_i

$$C_{pq} = \begin{cases} 0 & \text{otheisize} \\ 1 & \text{There is a directly connected and available} \\ & \text{taxiway from node p to node q} \end{cases}$$

$$R_{ipq} = \begin{cases} 1 & \text{Aircraft } f_i \text{ slides from node p to node q} \\ 0 & \text{othersize} \end{cases}$$

$$Z_{ijp} = \begin{cases} 1 & \text{Aircraf t } f_i \text{ arrives at node p before } f_j \\ 0 & \text{othersize} \end{cases}$$

N^i The taxiing route of aircraft f_i, composed of a series of nodes

M^i The set of nodes passed by aircraft f_i, $M^i = o^i, n_1^i, n_2^i, , , n_{k_i}^i, d^i$, o^i is the starting point, d^i is the ending point.

C. OBJECTIVE FUNCTION

Based on the taxiing conflict resolution strategy proposed in this paper, we built a model with the goal of minimizing time cost of all aircraft. The taxi time and waiting time were

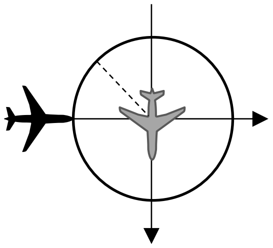

FIGURE 2. The minimum safety distance between aircraft.

main factors affecting time cost. Objective function Z was expressed as follows:

$$Z = min \sum_{f_i \in F} \sum_{p,q \in N} \frac{R_{ipq} L_{pq}}{v_i} + T_{ip} - t_{ip} \tag{1}$$

D. CONSTRANT CONDITIONS

Constraint (2) indicated that taxiing routes of aircraft must meet the physical connectivity.

$$R_{ipq} \leq C_{pq} \quad \forall f_i \in F, \quad \forall\, p, q \in N \tag{2}$$

Constraint (3) showed that taxiing routes of aircraft were continuous.

$$\sum\nolimits_{p \in N} R_{ipq} - \sum\nolimits_{s \in N} R_{iqs} = \begin{cases} 1, & q = d^i \\ 0, & othersize \\ -1, & q = o^i \end{cases}$$
$$\forall f_i \in F, \forall p, q, s \in N \tag{3}$$

Constraint (4) indicated that the distance between any two aircraft passing through the same node mustn't be less than the minimum safety distance. This included intersection conflict constraints.

$$Z_{ijp} \left(T_{ip} + t_{ij}^e - T_{jp} \right) \leq 0 \quad \forall\, f_i, \quad f_j \in F, \quad p \in N \tag{4}$$

Constraints (5) and (6) meant that no head-on conflicts were allowed. Constraints (7) and (8) revealed that no rear-end conflicts were allowed when two aircraft taxied in the same direction on the same taxiway.

$$Z_{ijp} - Z_{ijq} \leq 2 - \left(R_{ipq} + R_{jqp}\right) \tag{5}$$
$$Z_{ijp} - Z_{ijq} \geq -2 + \left(R_{ipq} + R_{jqp}\right) \tag{6}$$
$$Z_{ijp} - Z_{ijq} \leq 2 - \left(R_{ipq} + R_{jpq}\right) \tag{7}$$
$$Z_{ijp} - Z_{ijq} \geq -2 + \left(R_{ipq} + R_{jpq}\right)$$
$$\forall\, f_i, f_j \in F, p, q \in N \tag{8}$$

E. CONFLICT RESOLUTION STRATEGY

The conflict resolution strategy proposed in this paper was to choose taxiing paths by judging priority. Aircraft with high priority could pass directly through the conflict zone according to original planned paths. Low-priority aircraft had two options for taxiing. One was to slow down and wait before entering conflict zone. The other was to choose a sub-optimal alternative taxiing path in advance (a shortest path that didn't go through the conflict area and reached the end). The shortest route obtained by Dijkstra algorithm was as followed.

Assume W_j is the length of the shortest path from the starting point s to point j, p_j is the previous point of j in the path. S is the marker collection, T is the unmarked collection, and N is the collection of all points. d_{ij} represents the distance between point i and point j. (if i connects j directly, d_{ij} is the length, otherwise $d_{ij} = \infty$). Specific steps are as follows:

1) $S = \{s\}, T = M - S, W_j = d_{sj} (j \in T$, s and j connect each other directly) otherwise $W_{ij} = \infty (j \in T$, s and j connect each other indirectly).
2) Search point i in T, and ensure that the distance between s and i is the shortest, then add i into S (generally searching is started from the point j which is near s). If $d_{si} = min\left\{d_{sj} | j \in T\right\}$, also s and j connect directly. Add i into S, at this time $S = \{s, j\}$, $T = T - \{i\}, j \in T, p_i = s$
3) Update W_j in T, $W_j = min\left\{W_j, W_i + d_{ij}\right\}$; if W_j changes, then $p_i = i, j \in T, i \in S$
4) Choose all points with the least W_j, then add them into S: $W_i = \min W_j$, $S = S \cup \{i\}, T = T - \{i\}$. If the amount of elements in S is n, all points have been marked and the algorithm ends. Otherwise, it returns to step 3.

Suppose that we find a shortest path from O to D: O-2-4-3-7-9-D, and aircraft i and j have conflict at node 7. Keep O-2-4-3 unchanged, A* algorithm is used to find the kth shortest route from 3 to D. We set k as 2 and the sub-short route from 3 to D is found (e.g. 3-8-6-D). Then the taxiing route for aircraft i or j is O-2-4-3-8-6-D.

Let's set the priority of aircraft as p, the minimum waiting time as Δt, the difference between the length of the shortest route and the suboptimal alternative route as Δc, and the average taxiing speed as v. We calculated time cost of two strategies respectively. Strategy 1 was to decelerate and wait before entering conflict areas. The time cost was Δt. Strategy 2 was to select a suboptimal alternative route. By comparing Δt with $\Delta c / v$, we chose the smaller one and select a reasonable conflict resolution strategy. The process was shown in Fig. 3.

F. ROLLING HORIZON

Rolling horizon is a time decomposition method. Researches [32]–[39] show that the essence of rolling horizon is to replace a large-scale problem with a series of small-scale problems that are repeated over time. It aims at reducing calculation amount and being adapted to uncertain changes. Rolling horizon is a highly generic framework and can be used in a variety of scheduling models and environments. In this paper, it was adopted for aircraft taxiing scheduling, which only took into account the known information in a small range and neglected information in a larger range that was not completely clear at present. Rolling horizon included three elements: prediction window, scheduled time domain window (STDW) and rolling window. Fig. 4 showed the

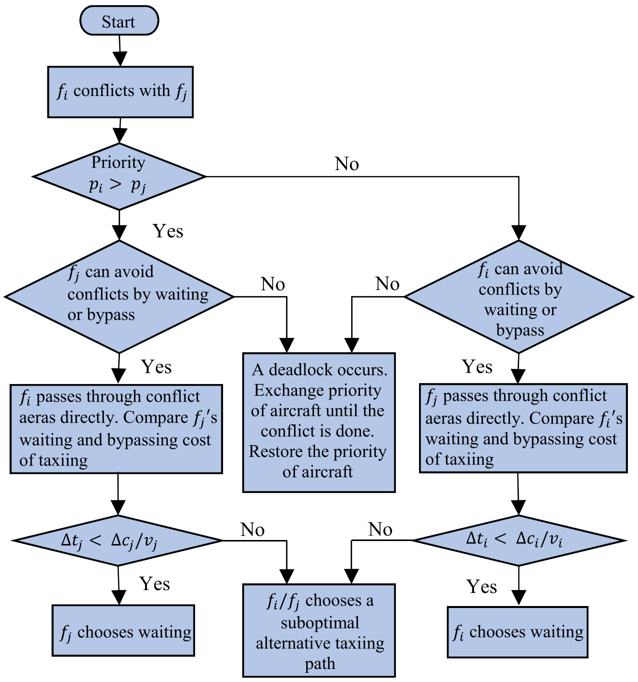

FIGURE 3. The flow chart of conflict resolution strategy.

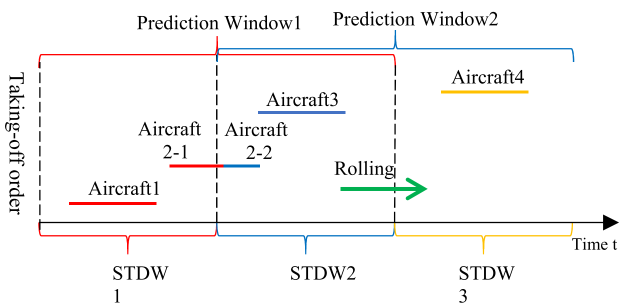

FIGURE 4. Scheduling process of aircraft taxiing based on rolling horizon.

relationship between three elements. For the scheduling of aircraft dynamic taxiing, they were defined as follows.

Prediction window. It was a predictable time domain range from a certain scheduling moment and contained all known and predictable information. Let's set the current scheduling time as t and the predictable time domain range as Γ. Then the prediction window was the set of all aircraft in the prediction time domain Γ starting from time t. The set included aircraft that didn't finish taxiing in the last period and those begun taxing in the prediction time domain Γ.

Scheduled time domain window (STDW). After the prediction window was determined, the information in it should be selectively entered into partial scheduling. The purpose was to avoid reducing the validity of calculation due to a large scale. The size of STDW was set as T. Aircraft scheduling was carried out in each scheduled time domain and every STDW was processed in time sequence. In each iteration, we considered not only aircraft starting taxiing in the current scheduled time domain, but also those aircraft that didn't complete taxiing in the last scheduled time domain. It was assumed that the taxiing scheduling of any aircraft could be completed within two consecutive STDW. As shown in Figure 2, aircraft 1 and 2-1 of aircraft 2 were scheduled in STDW 1 without considering aircraft 3. The remainder 2-2 of aircraft 2 was scheduled in STDW 2. In STDW 2, the taxiing scheduling of aircraft 2-1 was fixed.

Rolling window. It could roll forward based on time or events. When something that met the condition occurred, it triggered the rolling window rolling forward. In each iteration, we considered m aircraft, which were called the size of rolling window. We scheduled aircraft $1, 2, \ldots, m$ in the first iteration, and if there were n aircraft completing scheduling, we got rid of these aircraft in the next iteration. According to the earliest starting taxiing time of aircraft, we selected n new aircraft to enter the scheduling window and iterated repeatedly until the remaining aircraft waiting for scheduling were less than m. Then the iteration ended. At this time, if an aircraft was taxiing, the current information would be used as the new initial state and entered into the next scheduled time domain.

The following is the scheduling process based on rolling horizon.

1) We initialized the starting time of scheduling, and set it as t_0, then $t_i = t_0$;

2) At time t_i, assuming that aircraft information in the prediction time domain Γ was known, we selected aircraft that would start taxiing and aircraft that were taxiing in the scheduling time domain $[t_i, t_i + \Gamma]$ to form the prediction window. Information of aircraft could be updated through prediction window;

3) According to Dijkstra algorithm, we calculated the shortest taxiing paths of each aircraft in the prediction window;

4) A taxiing scheduling subproblem was formed in STDW. The objective function and constraints of taxiing subproblem were defined as same as the original problem. In addition to the newly added aircraft, the aircraft which didn't finish taxiing in the previous STDW were also included. The starting time and place of taxiing was the state at the end of the previous scheduled time domain;

5) We determined the length m of rolling window and the number n of aircraft completing scheduling, and then iterated. In the process of taxiing, if there was a conflict, we solved it according to strategy proposed in this paper. Until the number of aircraft in STDW was less than n, the scheduling in the current scheduled time domain was terminated;

6) Let $t_{i+1} = t_i + T, i = i + 1$. If $t_i < \Gamma$, go to step 2); otherwise, end.

V. SIMULATION RESULTS

A. SIMULATION INFORMATION AND PARAMETERS

In this paper, a part of a large airport in China was selected as the research object. We combined multiple adjacent stands into three centralized aprons G_1, G_2 and G_3. G_1 represented the near apron 1 and the remote western apron 2 in

TABLE 1. Information of aircraft in a large airport in China during research period.

Number	Starting Time	Starting Point	Ending Point	Type	Speed	Flight mission	Emergency condition
1	08:00:00	32	37	B733	10	airliner	normal
2	08:00:00	35	33	A320	12	airliner	normal
3	08:01:00	36	31	A330-300	12	airliner	normal
4	08:01:00	37	31	B737	8	Private	normal
5	08:02:00	37	32	B744	10	airliner	normal
6	08:03:00	36	33	A321	10	airliner	normal
7	08:04:00	35	32	B737	10	air-freighter	normal
8	08:04:00	34	35	B738	8	airliner	normal
9	08:05:00	32	36	A320	10	airliner	normal
10	08:05:00	31	37	A320	8	airliner	normal
11	08:05:00	34	36	B738	12	Private	normal
12	08:07:00	32	37	A321	10	airliner	normal
13	08:07:00	35	33	B744	10	airliner	normal
14	08:08:00	32	35	A320	10	air-freighter	normal
15	08:08:00	34	35	A330-200	12	airliner	Faulty
16	08:10:00	34	35	A320	8	airliner	normal
17	08:11:00	36	31	B738	10	airliner	normal
18	08:12:00	34	37	B733	10	airliner	normal
19	08:15:00	35	33	A321	12	airliner	Faulty
20	08:15:00	32	36	B738	12	airliner	normal
21	08:16:00	31	37	B737	10	airliner	normal
22	08:16:00	37	32	A320	12	airliner	normal
23	08:17:00	34	35	B738	8	airliner	normal
24	08:17:00	32	36	A320	10	airliner	normal
25	08:18:00	31	37	A320	8	airliner	normal
26	08:19:00	34	36	A321	12	air-freighter	normal
27	08:19:00	32	37	A321	10	airliner	normal
28	08:19:00	35	33	B744	10	airliner	normal
29	08:20:00	31	35	B733	10	air-freighter	normal
30	08:20:00	34	35	A340-300	12	airliner	Faulty

terminal T1. G_2 represented the near apron 2 in terminal T2 and G_3 represented the remote apron 8. Some irrelevant taxiways and nodes were removed. Finally we formed a network diagram consisting of 37 nodes, 48 sides, 2 runways and 3 centralized aprons. Fig. 5 shows the structure of the network.

The data of aircraft are selected from the flight data of peak hours from 8:00 to 8:20 on a certain day in July 2016, as shown in Table 1. The standard seats of different aircraft is shown in Table 2, and the fuel consumption is shown in Table 3. Table 3 refers to the ground taxiing fuel consumption benchmark in Air China's "aircraft performance data manual".

We adopted the CIF duty-paid price of aviation kerosene (standard product) approved by the National Development and Reform Commission in December 2018: RMB 4547 per ton. According to delay compensation, the waiting cost per passenger per unit time was RMB 100 per hour. The aircraft deceleration process was converted into the equivalent waiting time without considering the impact of turning on the speed. The safety distance between aircraft was set to 20s. Specific parameters were set as follows: the number of aircraft in the prediction window during peak hours was 30 and the period ΔT of STDW was 3min (180s). The shortest taxiing paths of aircraft obtained by Dijkstra algorithm showed that the time for the last aircraft completing taxiing

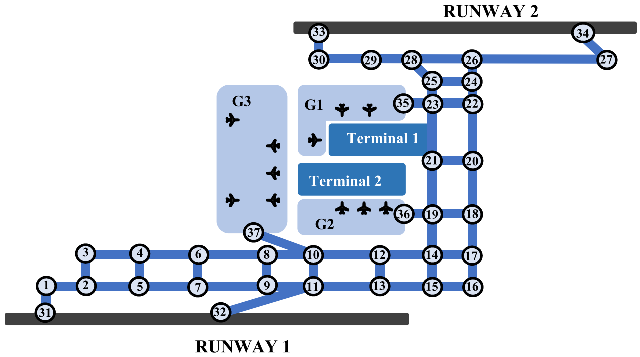

FIGURE 5. Partial configuration of taxiway system in the west area of a large airport.

Type	Seats
319	142
320	180
321	220
330-200	253
330-300	295
340-300	295
733	149
737	149
738	189
744	416

TABLE 2. Standard seat number of different aircraft.

TABLE 3. Taxiing fuel consumption of different aircraft.

Type	Reference type	20 minutes fuel consumption benchmark (kg)
310-300/319/320/321	A320	230
330-200/330-300/AB6	A330-200	500
340-300/340-500/340-600	A340-300	500
72Y/733/734/735/736/737 738/739/73G/73Y/BBJ/	B737-800	227
744/74E/74L/74U/74X/74Y	B747-400	908

was 1625s, $\lceil 1625/180 \rceil = 10$. Then there were 10 STDW, forming 10 scheduling subproblems.

B. ANALYSIS OF TAXIING ROUTES

Scheduling results based on priority were simulated in chronological order. Compared with results based on a common conflict resolution strategy (aircraft can only avoid conflicts by waiting), there were 9 aircraft whose scheduling results were changed, as shown in Fig. 6. The scheduling results were expressed by the nodes through which the aircraft passed and the time of arrival at the node. The first value in parentheses represented the node and the second value represented time. The red letter indicated the change of time and the underline indicated the change of node.

TABLE 4. Comparison of results of three different schemes.

	Scheme 1	Scheme 2	Scheme 3
Total waiting time	159.4s	274.8s	136.7s
Total running time	7053.2s	7018.4s	6974.8s
Total taxiing distance	68790m	67380m	68310m

In order to show the superiority of the conflict resolution strategy in this paper, we added two sets of experiments for comparison. Scheme 3 adopted the conflict resolution strategy and priority proposed in this paper based on routes obtained by Dijkstra algorithm. The only difference between scheme 2 and scheme 3 was that scheme 2 adopted a common conflict resolution strategy (aircraft can only avoid conflicts by waiting). Scheme 1 was based on the actual operation. In actual operation, FCFS was usually accepted. FCFS meant that the aircraft arriving at the node first had priority to pass through it. Subsequent aircraft needed to slow down or stop waiting until the distance between it and the previous aircraft met the minimum safety interval. In actual operation, taxiing routes of aircraft were previously assigned by ground controllers for each aircraft, not necessarily the shortest path. We compared the waiting time, running time (the sum of waiting time and taxi time) and taxiing distance of each scheme. The results were shown in Table 4 and Fig. 7.

The total number of conflict points based on the shortest paths was 26, including 17 intersection conflicts, 8 head-on conflicts and 1 rear-end conflict. According to Table 4 and Fig. 6, compared with the other two schemes, scheme 1 had the largest total running time and total taxiing distance. This was because in reality, in order to reduce the complexity of airport surface operation and the workload of controllers, the taxiing routes of aircraft were relatively fixed, and usually were not the shortest. Therefore, in actual operation, the taxiing routes of aircraft were 1410m longer than Dijkstra's shortest routes. The waiting time was between scheme 2 and scheme 3. Both scheme 2 and scheme 3 could resolve conflicts, but the cost was different. Scheme 2 selected the shortest routes and avoided conflicts by waiting. Therefore, the taxiing distance was the shortest, but the waiting time was the longest, which was 101% more than that of scheme 3. Scheme 3 sacrificed the taxiing distance to reduce the waiting time, so the waiting time was the shortest, which is 136.7s. However, when choosing suboptimal alternative routes, it tended to choose more tortuous routes to avoid conflict points, so the taxiing distance increased, which was 930m more than scheme 2. Scheme 2 and 3 showed the game of time and distance.

C. ANALYSIS OF PRIORITIES

We put forward the concept of priority based on the relative aircraft cost rate, which was mainly determined by aircraft

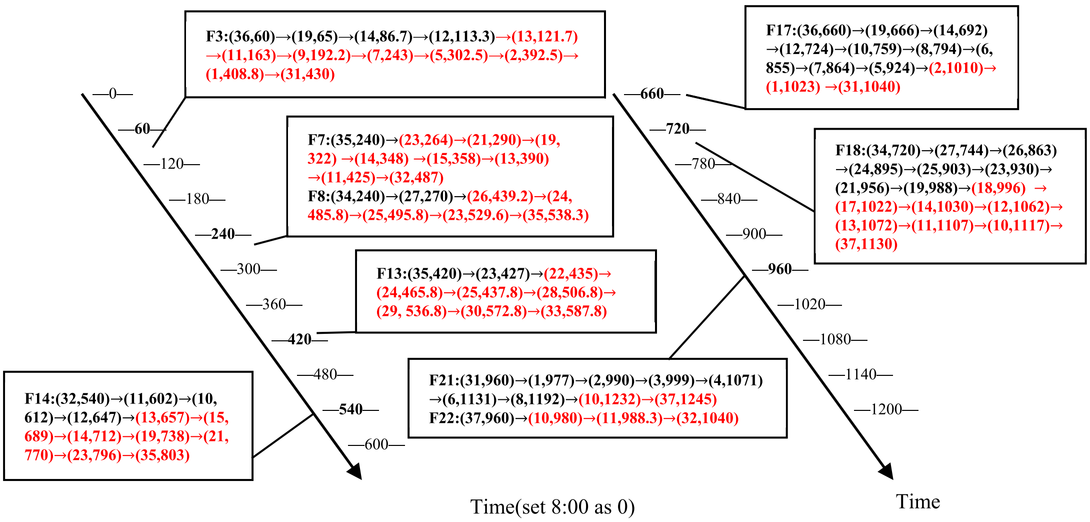

FIGURE 6. Changes in aircraft scheduling results.

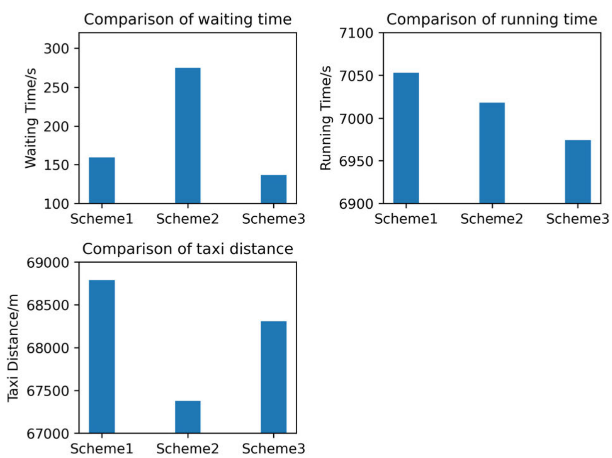

FIGURE 7. Comparison of results of three different schemes.

properties, such as aircraft type, aircraft passenger capacity, fuel consumption rate, and aircraft usage. The aircraft cost rate was mainly affected by two indexes: passenger capacity and average fuel consumption rate. Other factors, such as corporate reputation, staff workload and aircraft maintenance cost could be converted to waiting cost per unit passenger or fuel price. The standard seat number of aircraft was set as K and the fuel consumption rate was set as N (kg/min). The loss value of each passenger waiting on the ground for one minute was set as H and the fuel price was set as P. The aircraft cost rate CT could be calculated by formula: $CT = K * H + N * P$, and the relative aircraft cost rate was $CR_i = CT_i / \max_{k \epsilon F}(CT_k)$.

The priority of aircraft was judged according to their attributes (flight mission and emergency situation). The priority of faulty aircraft was the highest, set as 3, and the priority of private aircraft was set as 2. The priority of a normal airliner was set as 1 and the air-freighter had the lowest priority, set as 0. When aircraft with the same property had taxiing conflicts, aircraft with higher CR_i could taxi first. K was determined by table 2 and N was determined by table 3. $H = 0.2\ RMB/\min$, $P = 7.139\ RMB/kg$. The calculation results were shown in Table 5.

As can be seen from Table 5, there were 4 aircraft with priority number 0, 21 aircraft with priority number 1, 2 aircraft with priority number of 2, and 3 aircraft with priority number of 3. For aircraft with the same priority number, the priority order needed to be further determined according to relative aircraft cost rate CR_i. for the four aircraft with priority number 0, $CR_7 = CR_{29} < CR_{14} < CR_{26}$; for the twenty one aircraft with priority number 1, $CR_1 = CR_8 = CR_{21} < CR_2 = CR_9 = CR_{10} = CR_{16} = CR_{22} = CR_{24} = CR_{25} < CR_{17} = CR_{20} = CR_{23} < CR_6 = CR_{12} = CR_{27} < CR_3 = CR_{18} < CR_5 = CR_{13} = CR_{28}$; for the two aircraft with priority number 2, $CR_4 < CR_{11}$; for the three aircraft with priority number 3, $CR_{19} < CR_{15} < CR_{30}$. According to the above rules, the accurate priority order of 30 aircraft could be finally determined.

It could be seen from Table 6 that in case of taxiing conflicts, all aircraft with high priority were guaranteed to taxi first based on priority proposed in this paper. However, according to FCFS, only aircraft 5, 6, 11, 13, 20, 21 and 27 had priority to taxi first when arriving at the conflict area.

D. ANALYSIS OF CONFLICT RESOLUTION PROCESS

In this example, conflicts were divided into two types: "there were no secondary conflicts" and "there were secondary conflicts". The definition of "secondary conflicts" in this paper was as followed. After the first conflict between aircraft f_i and f_j was successfully released, f_i and f_j conflicted in other areas, or conflicted with other aircraft f_k. We called these conflicts "secondary conflicts". In addition, the "secondary conflicts" in this paper not only referred to the second taxiing conflict, but also a relatively broad concept. All taxiing con-

TABLE 5. Relative cost rate and priority number of aircraft.

Number	Type	CT (kg/min)	CR_i	Remark	Priority
1	B733	110.83	0.27	Airliner	1
2	A320	118.10	0.29	Airliner	1
3	A330-300	237.48	0.58	Airliner	1
4	B737	110.83	0.27	Private aircraft	2
5	B744	407.31	1	Airliner	1
6	A321	126.10	0.31	Airliner	1
7	B737	110.83	0.27	Airfreighter	0
8	B738	118.83	0.292	Airliner	1
9	A320	118.10	0.29	Airliner	1
10	A320	118.10	0.29	Airliner	1
11	B738	118.83	0.292	Private aircraft	2
12	A321	126.10	0.31	Airliner	1
13	B744	407.31	1	Airliner	1
14	A320	118.10	0.29	Airfreighter	0
15	A330-200	229.08	0.56	Faulty airliner	3
16	A320	118.10	0.29	Airliner	1
17	B738	118.83	0.292	Airliner	1
18	B733	110.83	0.27	Airliner	1
19	A321	126.10	0.31	Faulty airliner	3
20	B738	118.83	0.292	Airliner	1
21	B737	110.83	0.27	Airliner	1
22	A320	118.10	0.29	Airliner	1
23	B738	118.83	0.292	Airliner	1
24	A320	118.10	0.29	Airliner	1
25	A320	118.10	0.29	Airliner	1
26	A321	126.10	0.31	Airfreighter	0
27	A321	126.10	0.31	Airliner	1
28	B744	407.31	1	Airliner	1
29	B733	110.83	0.27	Airfreighter	0
30	A340-300	237.48	0.58	Faulty airliner	3

flicts caused by previous conflict relief operation belonged to the category of "secondary conflict". All conflicts on the same aircraft except the first conflict were called secondary conflicts. So the detection of secondary conflicts was a cyclic iterative process.

In the type of 'no secondary conflicts', aircraft with lower priority only needed to change taxiing scheme once and reached destination without conflicts.

Example 1: slow down and wait. The time when aircraft 6 arrived at node 23 was 244 (set 8:00 as 0) and the time when aircraft 7 arrived at node 23 was 247. The interval was less than 20s. Therefore, there was a conflict at node 23. The conflict resolution strategy was as follows: first, according to table 5, we compared the priority number of two aircraft and we knew that the priority of aircraft 7 was lower. Then we compared $\Delta c_7^{23}/v_7$ with Δt_7^{23} and got $\Delta c_7^{23}/v_7 > \Delta t_7^{23}$. So, aircraft 7 chose to slow down and wait at node 35 before

TABLE 6. Guarantee of aircraft priority.

Conflict aircraft	Conflict node	Compa-rison of priority	Priority	FCFS
			First taxing aircraft	First taxing aircraft
3,5	10,11	3<5	5	5
3,4	1,31,5,(5,2)	3<4	4	3
6,7	23	7<6	6	6
8,11	26	8<11	11	8
11,13	24,25	13<11	11	11
8,13	24	8<13	13	13
14,17	14	14<17	17	14
20,22	10	22<20	20	20
17,21	2	17<21	21	21
18,20	14	18<20	20	18
18,24	10	18<24	24	18
21,27	10	21<27	27	27

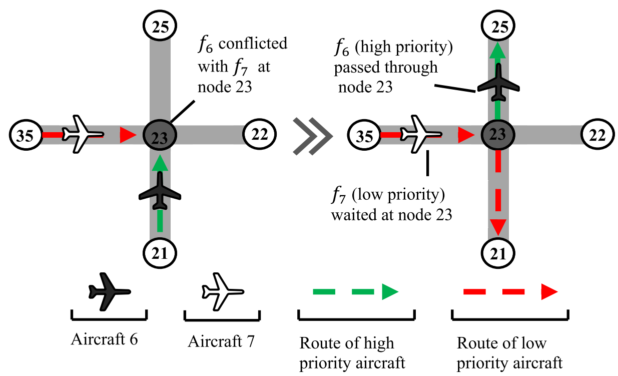

FIGURE 8. Example 1 of conflict resolution process (slow down and wait).

node 23 in advance. Then we updated the taxiing scheme of aircraft 7 and continued conflict detection with other aircraft until it reached the end. It was found that there were no conflicts. The conflict detection was completed and the resolution process was shown in Fig. 8.

Example 2: choose a suboptimal alternative taxiing route. The time when aircraft 24 arrived at node 10 was 1092 and the time when aircraft 18 arrived at node 10 was 1102.8. The interval was less than 20s. The conflict resolution strategy was as follows: first, we compared the priority number of two aircraft according to table 5 and we knew that the priority of aircraft 18 was lower. Then, we compared $\Delta c_{18}^{10}/v_{18}$ with Δt_{18}^{10} and got $\Delta c_{18}^{10}/v_{18} < \Delta t_{18}^{10}$. Therefore, aircraft 18 chose a suboptimal alternative taxiing path 12-13-11-10-37 at node 12 before node 10 in advance. Afterward, we updated the taxiing scheme of aircraft 18 and continued conflict detection with other aircraft until it reached the end. It was found that there was no conflict. The conflict detection was completed and the resolution process was shown in Fig. 9.

In the type of 'there were secondary conflicts', after the aircraft with lower priority changing taxiing scheme, they conflicted with the original aircraft or a third aircraft. According to subjects that caused secondary conflicts, we could

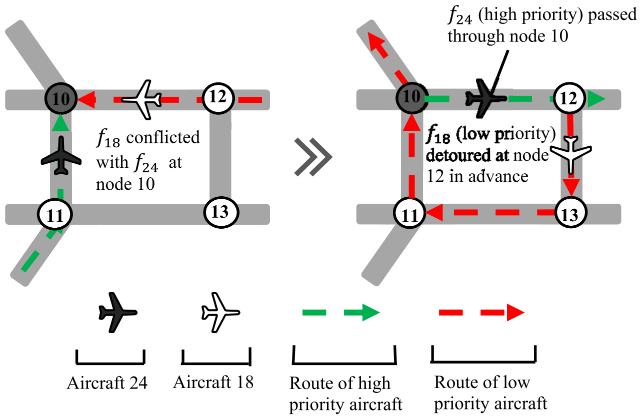

FIGURE 9. **Example 2 of conflict resolution process (choose a suboptimal alternative taxiing path).**

divide secondary conflicts into two categories: "secondary conflicts that didn't involve a third aircraft" and "secondary conflicts that involved a third aircraft".

Example 3: secondary conflicts not involving a third aircraft. The time when aircraft 11 arrived at node 25 was 452.5 and the time when aircraft 13 arrived at node 25 is 452.5.

A conflict occurred at node 25. The conflict resolution strategy was as follows: first, we compared the priority number of two aircraft and it could be seen that the priority of aircraft 13 was lower. Then, by comparing $\Delta c_{13}^{25}/v_{13}$ with Δt_{13}^{25}, we got $\Delta c_{13}^{25}/v_{13} < \Delta t_{13}^{25}$. Therefore, aircraft 13 chose a suboptimal alternative taxiing path 23-22-24-25-28-29-30-33 at node 23 before node 25 in advance. Update the taxiing scheme of aircraft 13. We re-conducted conflict detection between the new taxiing scheme of aircraft 13 and the taxiing scheme of aircraft 11. It was found that the time when aircraft 11 reached node 24 was 445.8 and the time when aircraft 13 reached node 24 was 462. The interval was less than 20s. Therefore, a secondary conflict occurred at node 24. We compared $\Delta c_{13}^{24}/v_{13}$ with Δt_{13}^{24} and got $\Delta c_{13}^{24}/v_{13} > \Delta t_{13}^{24}$. So, aircraft 13 chose to slow down and wait at node 22 before node 24 in advance. Finally, we updated the taxiing scheme of aircraft 13 and continued conflict detection with other aircraft until it reached the end. It was found that there were no other conflicts. The conflict detection was completed and the resolution process was shown in Fig. 10.

Example 4: secondary conflicts involving a third aircraft. In example 3, aircraft 13 found a taxiing scheme that didn't conflict with aircraft 11 after a secondary conflict resolution. However, the new taxiing scheme of aircraft 13 conflicted with aircraft 8. The time when aircraft 8 arrived at node 24 was 479.2 while the time when aircraft 13 arrived at node 24 was 465.8. The interval was less than 20s. So, a conflict occurred at node 24. From table 5 we knew that the priority of aircraft 8 was lower. Then, we compared $\Delta c_8^{24}/v_8$ with Δt_8^{24} and got $\Delta c_8^{24}/v_8 > \Delta t_8^{24}$. Therefore, aircraft 8 chose to slow down and wait at node 28 before node 24. After that, we updated the taxiing scheme of aircraft 8 and continued conflict detection with other aircraft until it

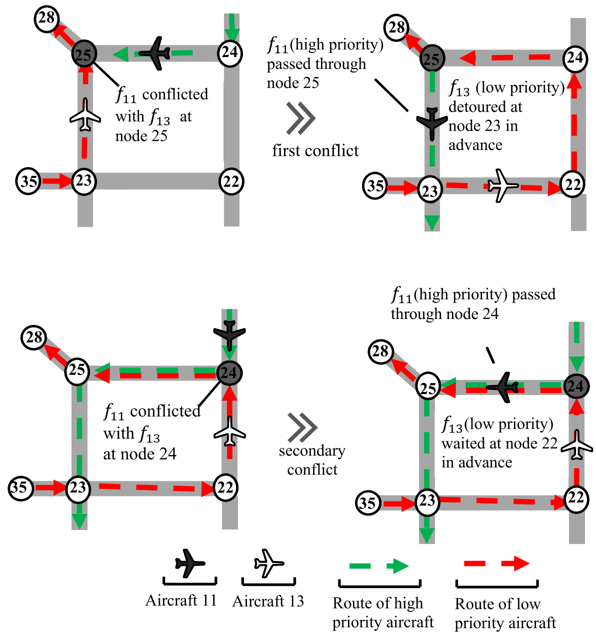

FIGURE 10. **Example 3 of a secondary conflict resolution process (no third aircraft involved).**

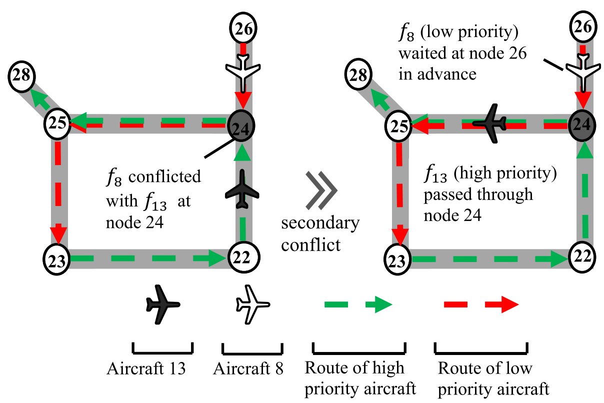

FIGURE 11. **Example 4 of a secondary conflict resolution process (involving a third aircraft).**

reached the end. It was found that there was no other conflict. The conflict detection was completed and the resolution process was shown in Fig. 11.

In addition, in the actual operation process, there may be taxiing conflicts, which couldn't be solved by slowing down and waiting, or choosing suboptimal alternative paths. That was deadlock. When a deadlock occurred, the priority policy may not be strictly implemented. The priority of aircraft could be temporarily exchanged. After the conflict was relieved, the respective priority of aircraft was restored.

Example 5: deadlock. The time when aircraft 17 arrived at node 2 was 996 and the time when aircraft 21 arrived at node 2 was 990. The interval was less than 20s, so a conflict occurred at node 2. The general resolution strategy was as follows: first, according to table 5, it could be seen that the priority of aircraft 21 was lower. Then aircraft 21 would slow

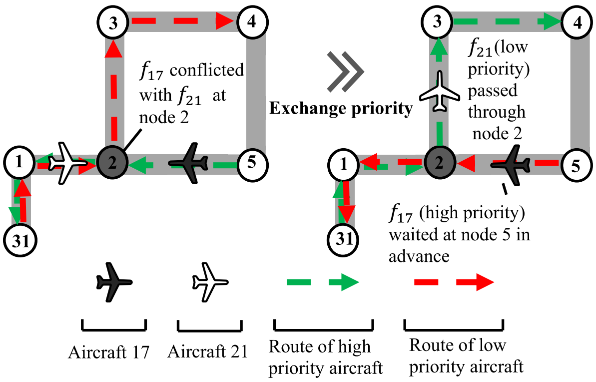

FIGURE 12. Example 5 of a conflict resolution process (deadlock).

down and wait, or choose a suboptimal alternative taxiing path at node 1 before node 2. However, the taxiing path of aircraft 21 and aircraft 17 completely coincided in the 31-1-2 segment and the direction was opposite. Therefore, the waiting of aircraft 21 (at node 1 and node 31) before node 2 couldn't avoid conflicts. Since node 1 only connected node 2 and node 31, there was no suboptimal alternative taxiing paths for aircraft 21 at node 1 and node 31, resulting in deadlock. The conflict resolution strategy in case of deadlock was as follows: we temporarily exchanged the priority of aircraft and made the priority of aircraft 17 lower. Then we compared $\Delta c_{17}^2/v_{17}$ with Δt_{17}^2 and got $\Delta c_{17}^2/v_{17} > \Delta t_{17}^2$. Therefore, aircraft 17 chose to decelerate and wait at node 5 before node 2. After the conflict was solved, the priority of aircraft 17 and 21 were restored. The process was shown in Fig. 12.

VI. CONCLUSION

In this paper, in combination with the accurate airport surface structure, we established a dynamic taxiing model of aircraft based on priority. The model aimed at minimizing time cost of all aircraft. A conflict resolution strategy that considered suboptimal alternative paths was proposed to improve the original way of avoiding conflicts only by waiting. The essence of this strategy was the game of time and distance. By converting the increased distance of detour into time and comparing it with the original strategy, the one with less running time was selected, which improved the flexibility of path selection.

The data of flight and surface structure in this article were collected from a large domestic airport. Other data such as cost and jet fuel prices were all from relevant documents. Simulation results based on MATLAB showed that the strategy in this paper reduced the waiting time by 50%. Combined with taxiing time, the total running time was reduced by 43.6s. On the premise of ensuring safety, this strategy could provide optimization theories and methods for the taxiing of aircraft at large airports that was in line with actual operating conditions.

Although preliminary results are promising, there is still many pieces of research for future work. Firstly, in terms of priority, airline fairness should be considered. In actual operation, how to ensure the fairness of each airline is very important for airport management. Secondly, in the selection of taxiing paths, soft constraints should be added to avoid taxiing routes with higher usage rates. Different weights to taxiing paths can be tried. Thirdly, future research will increase the actual interference factors of the airport, comprehensively analyze the actual situation of the airport's inbound and outbound flights, dynamically adjust the taxiing path of the aircraft and maintain the real-time performance of the system.

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