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Research article

Study on 4D taxiing path planning of aircraft based on spatio-temporal network

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Abstract: In recent years, China vigorously develops energy conservation and emission reduction, in order to actively respond to the national call to make the aircraft operation process reduce unnecessary costs and strengthen the safety of the aircraft taxiing process. This paper studies the spatio-temporal network model and dynamic planning algorithm to plan the aircraft taxiing path. First, the relationship between the force, thrust and engine fuel consumption rate during aircraft taxiing is analyzed to determine the fuel consumption rate during aircraft taxiing. Then, a two-dimensional directed graph of airport network nodes is constructed. The state of the aircraft is recorded when considering the dynamic characteristics of the node sections, the taxiing path is determined for the aircraft using dijkstra's algorithm, and the overall taxiing path is discretized from node to node using dynamic planning to design a mathematical model with the shortest taxiing distance as the goal. At the same time, the optimal taxiing path is planned for the aircraft in the process of avoiding aircraft conflicts. Thus, a state-attribute-space-time field taxiing path network is established. Through example simulations, simulation data are finally obtained to plan conflict-free paths for six aircraft, the total fuel consumption for the six aircraft planning is 564.29 kg, and the total taxiing time is 1765s. This completed the validation of the dynamic planning algorithm of the spatio-temporal network model.

Keywords: spatio-temporal network model; path optimization; dynamic programming; dijkstra's algorithm; mathematical model

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1. Introduction

With the rapid development of civil aviation industry, the problem between the increase of passenger turnover and limited airport resources makes the aircraft airport field taxiing conflict increasingly serious. In order to reduce the operating pressure of the airport, ensure the safe and orderly taxiing of the field, and improve the on-time rate of flight operation, the study will carry out conflict-free planning for the aircraft field taxiing path, so as to put forward a scientific and effective scheme to improve the operation efficiency of the airport apron. There are more studies on field conflict at home and abroad, such as Liu et al. [1] proposed the method of delaying the launch time of aircraft in conflict resolution with lower priority, deceleration, waiting at the precursor point, re-planning a new taxiing path, and processing the model with A* algorithm to complete the conflict avoidance and reduction of taxiing time for airport taxiing path planning within a certain time. Yu et al. [2] constructed a spatio-temporal network by discretizing time and setting up time steps associated with spatial elements can plan the expected path efficiently and reasonably under the condition of conflict avoidance. They used dijkstra's algorithm to solve their model. In the comparison of the final optimization results with the GA model, the efficiency of their dynamic planning algorithm is tens of times higher than that of the ordinary GA algorithm. Li et al. [3] used aircraft taxiing speed profiles considering both taxiing time and taxiing fuel consumption. They obtained different Pareto-optimal speed profiles by giving different weights to taxiing time and fuel consumption to complete the path planning of aircraft on the airport field considering the turning factor. Zhang and Yu [4] obtained the preliminary taxiing path results by Dijkstra algorithm, then made adjustments to different aircraft launch times based on the taxiing complexity of the aircraft. They continuously iterated until the threshold of taxiing complexity was satisfied, which further optimized the fuel consumption by converting the conflicting waiting time of the departing aircraft into the waiting time before driving, but the delayed driving time of the departing aircraft. However, the delayed departure time of departing aircraft can affect airport traffic and passenger sentiment. Wang [5] constructed an airport structure model to optimize aircraft taxiing paths, conditional on the spatial and temporal distribution characteristics of airport conflicts, and the results showed that the model can reduce aircraft taxiing time and the number of field taxiing conflicts. In order to reduce the number of aircraft field conflicts, Li et al. [6] constructed a field taxiing optimization model with airport field taxiing rules and conflict avoidance restrictions as constraints and field conflict minimization as the objective function, and solved it with A* algorithm to obtain the optimized aircraft taxiing time. Brownlee et al. [7] applied the method of rolling time window containing genetic algorithm to build an aircraft taxiing model with A * algorithm to find the shortest path of aircraft taxiing, which can allocate a reasonable taxiing path for aircraft and reduce the total time of aircraft taxiing under the premise of avoiding aircraft taxiing conflicts. Landry et al [8] designed the airport field model of complex network to solve the conflicts that may occur in aircraft taxiing, which can solve the conflict problem under the situation of small airport traffic and simple airport field path. Ravizza et al. [9] took both aircraft fuel and taxiing time as the object of consideration and optimized the constructed model by the method of sequence diagram. Li et al. [10] took aircraft taxiing time as the solution function of model construction, listed the constraints with the conflict interval of aircraft passing node time, and solved the optimization by genetic algorithm, which to some extent alleviated the aircraft up conflict problem and reduce the field taxiing time of aircraft. From the domestic and foreign research on the optimization of taxiing paths, it is found that most scholars use the static planning method for aircraft path planning, which optimizes the objective but is too tedious due to the static planning for the traversal verification of conflict nodes. In the field taxiing 4D trajectory planning research, Chen et al. [11] used aircraft field taxiing speed profile to combine 4D trajectory and route scheduling together into a multi-objective optimization problem to calculate a low-cost, environmentally friendly 4D trajectory. Wickramasinghe et al. [12] quantified the optimization of 4D trajectory in relation to aircraft flight planning, and the results showed that 4D trajectories can optimize aircraft flight plans. Zhang et al. [13] used linear programming to assign control point arrival times and then used particle swarm methods to optimize the velocity of assigned control points to generate improved and more accurate taxiing velocity profiles. Gao et al. [14] obtained an optimized 4D trajectory prediction using the equirectangular trajectory modeling method. The research on 4D planning mainly focuses on optimization objectives such as time, fuel volume and cost, and relatively little research has been conducted on the detection of conflicts. Therefore, the object of this study is the four-dimensional glide trajectory of aircraft, namely (x, y, h, t), (horizontal coordinate, vertical coordinate, height, time). Since the glide height of the aircraft scene is zero, the research mainly focuses on the horizontal and vertical coordinates and time of aircraft field taxiing. So this study uses the time-space network model method to dynamically plan aircraft surface taxiing, which can timely reflect aircraft dynamic information, generate effective aircraft conflict-free taxiing paths, and provide scientific reference for safe and economic surface operation planning of aircraft surface operation.

Path planning algorithms that are currently available include the simulated annealing algorithm, the Dijkstra algorithm, the A* algorithm, the neural network algorithm, the ant colony algorithm, the genetic algorithm, and others. Only the Dijkstra algorithm can stably search the globally optimal path, whereas the other algorithms may search the sub-optimal path because they fall into the locally optimal path [15]. As a result, the Dijkstra algorithm is widely used in path planning, ship scheduling [16], and other applications. Because there is little research on aircraft surface taxiing paths using the Dijkstra algorithm at the moment, the research will plan the surface taxiing path using the Dijkstra algorithm.

2. Aircraft field taxiing conflict types and avoidance

1) Rear-end conflict: When different aircraft are taxiing in the same direction on the same section of taxiway, due to the different speed of the aircraft, the rear aircraft may catch up with or overtake the front aircraft. When the safety interval between the aircraft does not meet the requirements, there will be a collision risk of the aircraft.

2) Head-to-head conflict: Since the departure and destination points of different aircraft are not the same, it is possible that during taxiing, two aircraft taxi on the same taxiing section at similar time periods and in opposite directions, and once a head-to-head conflict occurs, the conflict cannot be resolved by stopping and waiting, but can only be avoided in advance in path planning.

3) Cross-conflict: When multiple aircraft choose to pass through the same node with the nature of being crossed during taxiing, i.e., having the property of turning, if the arrival time is dense, two or even more aircraft cannot meet the distance limit between aircraft and aircraft when passing through the node, or even the possibility of meeting and colliding [17].

When a conflict occurs, the model prioritizes planning a new path for the aircraft, and if a new conflict-free path cannot be found, the aircraft waits.

According to the ground control requirements, when different aircraft taxiing on the airport field need to have a spacing standard between aircraft and aircraft. This is to avoid the risk of collision between aircraft and aircraft in order to avoid aircraft being affected by the turbulence of other aircraft in the taxiing process. When the wake spacing is satisfied between two aircraft, the spacing to prevent collision must be satisfied. According to the regulations of the International Civil Aviation

Organization, aircraft are planned into three major categories: heavy aircraft (H), medium aircraft (M), and light aircraft (L) with the maximum takeoff weight of the aircraft as a reference and the minimum separation distances for different types of aircraft are shown in Table 1.

Heavy aircraft: Aircraft with a maximum permissible take-off weight greater than or equal to 136 tons.

Medium-sized aircraft: Aircraft with a maximum permissible take-off weight of less than 136 tons and greater than 7 tons.

Light aircraft: Aircraft with a maximum permissible take-off weight of less than or equal to 7 tons.

Table 1. Taxi separation minima between different types of aircraft (unit: Meter).

	Aircraft behind		
Aircraft in front	Heavy	Medium	Light
Heavy	300	300	300
Medium	200	200	200
Light	100	100	100

Since the model sets the aircraft field taxiing speed to be uniform, from the standard distance of the wake interval in the table above, then the time standard of the wake interval can be found.

3. Aircraft field taxiing fuel consumption analysis

Chen [18] studied four types of aircraft gliding the same path at different gliding speeds at uniform speed, the resulting fuel consumption varies, but all show the trend that the greater the speed, the smaller the fuel consumed by the aircraft gliding through a fixed length path. The study set the aircraft taxiing speed to uniform speed, because the taxiing speed during the taxiing is limited by the speed during the turn, the speed during the turn needs $v \leq 5.14$ m/s [19], so the aircraft taxiing speed is set to constant $v = 5$m/s. When the aircraft taxiing on the taxiway, the force model is analyzed, the aircraft is mainly subjected to gravity (G), the support force of the taxiing path (F_N), the thrust of the engine (F), and the rolling resistance between the taxiway wheels and the taxiway (F_r). While the aircraft is taxiing on the taxiway, to save fuel consumption, one engine is usually used to provide the thrust required for aircraft movement, and since the aircraft taxiing speed is set to be constant, the thrust provided by the engine is equal to the rolling resistance suffered by the aircraft while taxiing on the ground. Let the rolling resistance to each wheel of the aircraft be f_r, then

$$F_r = 3 * f_r = 3 * C_{rr} * m * g, \tag{1}$$

where, C_{rr} is the coefficient of rolling resistance of the aircraft during taxiing taken as 0.0015 [17], m is the take-off mass of the aircraft. G is the coefficient of gravity taken as 9.81 m/s^2.Based on the engine thrust equal to rolling resistance, the relationship between the rated output thrust of the aircraft engine and the fuel consumption, as shown in Table 2, the fuel consumption rate of the engine to provide the current required thrust is calculated. Therefore, the amount of fuel to be consumed by an aircraft from the start of taxiing to the end of taxiing is

$$\mathrm{Fuel} = \mathrm{Fuel}_{\mathrm{flow\ rate}} * T, \tag{2}$$

where Fuel is the total fuel flow for an aircraft taxiing, $\mathrm{Fuel}_{\mathrm{flow\ rate}}$ for this aircraft and T is the total taxiing time for this aircraft, and the relationship between aircraft fuel and engine thrust are shown in Table 2.

Table 2. Relationship between aircraft fuel and engine thrust.

Engine	Number of engines	rated power F0 (n)	The fuel flow (7%) kg/s	Fuel flow rate (30%) kg/s
CFM56-7B	2	242,880	0.116	0.349
CFM56-5-A1	2	222,400	0.1011	0.291
CFM56-5B1	2	266,900	0.117	0.364
CFM56-5B1	2	266,900	0.117	0.364
CFM56-5-A1	2	222,400	0.1011	0.291
CFM56-7B	2	242,880	0.116	0.349

Based on the relationship between the 7% fuel flow rate for both engines and the 30% fuel flow rate and thrust ratio eventually the fuel consumption rate for the required thrust at uniform taxiing is calculated when the taxiing weight of the aircraft is known.

4. 4D taxiing path planning model

Scholars in the United States and abroad have studied the space-time network method, and some have applied it to path planning. Xin and colleagues [20,21], for example, used the space-time network method to plan the horizon path planning of automated guided vehicles and collision-free routing of planar motions in a multi-robot station.

Before using space-time network to construct an aircraft taxi model, the following issues need to be noted as prerequisites for model construction.

a. The starting and ending points of each aircraft are known and will not change midway through the link.

b. The aircraft may adjust its course in a timely manner in accordance with tower instructions.

c. Aircraft that have taken off will be removed from the pool of all aircraft at the airport and will no longer participate in the dispatch.

d. All aircraft will be stopped in place as soon as they break down and may continue to participate in dispatch when repairs are completed. When an aircraft breaks down, the route it is on is impassable to other aircraft.

e. Taxi dispatch will only dispatch the aircraft to the appropriate ramp or runway end.

f. The priority of the departing aircraft is greater than that of the approaching aircraft.

g. Different types of aircraft are taxiing at 5 m/s, with different fuel consumption rates for different aircraft.

h. A single taxiway will support only one aircraft at a time.

i. Aircraft and aircraft need to meet wake spacing requirements during taxiing.

Spatio-temporal network discretization process:

a. The time axis is discretized by a distance of 1s. The time dimension is added to the two-dimensional airport network diagram, and the discretized time axis is increased by using $T = \{t_0, t_0+\psi, \ldots, t_0+n*\psi\}$, where t denotes a time node in the discretized time axis and ψ denotes the time interval on the discrete time axis. In the model ψ is taken to be 1s.

b. Construct the set of spatio-temporal network nodes, when the first aircraft starts taxiing, and for each node that the aircraft passes, create the set of spatio-temporal points $E_{st}(E_i,t)$.

c. Construct a space-time network travel arc [i, j, t, t+n*ψ] for the aircraft, denoting the aircraft taxiings from point i to point j in time Mψ, where $(i, j) \in E_i$.

d. Construct the aircraft taxiing spatio-temporal network waiting arc, [i, i, t, t+n*ψ], indicating that the aircraft stays at point i for N*ψ time,N is a large enough positive integer, which is set to 10000 in this paper.

e. Expand the properties of the aircraft in 3D space-time to determine the aircraft state at each moment in real time-M.

That is, the node experienced by the aircraft becomes a space-time arc after changing from [i, j, t, t+n*ψ] to [M_t , $M_{t+n*\psi}$, t, t+n*ψ]. is the state property of the aircraft at moment t, not limited to temporal and spatial properties.

1) The objective function of the model

$$\mathrm{T} = \min \textstyle\sum_{i=1}^{n}(t_{total(k)}), \tag{3}$$

$$\mathrm{F} = \min \textstyle\sum_{i=1}^{n}(Fuel_{total(k)}), \tag{4}$$

where $\mathrm{t_{total(k)}}$ is the total taxiing time of one aircraft, $\mathrm{Fuel_{total(k)}}$ is the amount of fuel consumed by one aircraft taxiing, and n is the number of aircraft involved in taxiing.

The goal of aircraft taxiing path planning in the airport is to plan conflict-free paths for all aircraft taxiing, so that the aircraft taxiing time or the amount of taxiing oil is minimum.

Since the aircraft speed is modeled as uniform, the fuel flow rate of the aircraft is a linear expression with respect to the taxiing time.

$$Fuel_{total(k)} = t_{total(k)} * Flow, \tag{5}$$

$$t_{total(k)} = D_k / V_k, \tag{6}$$

$\mathrm{V_k}$ is the speed of the aircraft k, and $\mathrm{D_k}$ is the total distance the aircraft taxiing, *Flow* is the fuel consumption per unit of time.

Since the aircraft speed is certain, the total aircraft taxiing path time is linearly related to the total aircraft taxiing path distance, so the optimization objective can be equated to the taxiing distance without considering the conflict, and the aircraft k taxiing distance is:

$$D_k = \min(\textstyle\sum_{i=1}^{n} \sum_{j=1}^{m} (L_{ij})) + d_\Delta. \tag{7}$$

$\mathrm{L_{ij}}$ is the taxi distance of aircraft k on link (i, j) and $\mathrm{d_\Delta}$ is the corrected length of the taxiing distance at the turn.

$$d_\Delta = \textstyle\sum_{i=1}^{m} R_r\,(d_r - 2\mathrm{l_r}). \tag{8}$$

When the aircraft turns at the node $\mathrm{V_i}$, $\mathrm{R_r} = 1$, otherwise $\mathrm{R_r} = 0$. $\mathrm{d_r}$ are the length of the aircraft k turns at the node $\mathrm{V_i}$, $\mathrm{2l_r}$ is the sum of the total distance from the starting turning point through the turning point $\mathrm{V_i}$ to the end of the turning point.

$$d_r = \theta_r * \pi * \mathrm{r}/180°, \tag{9}$$

$$\mathrm{l_r} = \mathrm{r} * \tan(\theta_r/2), \tag{10}$$

where the turn radius r of each turn point is known and the coordinates of the two nodes adjacent to the turn point are known, and according to the cosine theorem, θ_r can determine the magnitude [9].

$$\theta_r = \arccos\frac{(x_w-x_g)^2+(y_w-y_g)^2+(x_g-x_u)^2+(y_g-y_u)^2-(x_w-x_u)^2-(y_w-y_u)^2}{2\sqrt{(x_w-x_g)^2+(y_w-y_g)^2}\sqrt{(x_g-x_u)^2+(y_g-y_u)^2}}, \tag{11}$$

where, x_w, x_g, x_u respectively represent the horizontal coordinate of nodes V_w, V_g, and V_u, and y_w, y_g, and y_u respectively represent the vertical coordinate of V_w, V_g and V_u.

For example, an aircraft passing in sequence V_u, V_g, V_w, where V_g is the turning point (Figure 1). The taxiing route of the aircraft may be changed from the original (V_r,V_g,V_f) to (V_r,V_f), so that straight line taxiing becomes arc taxiing, and the taxiing route becomes shorter. Here, V_r and V_f are tangent points, so (V_r,V_g) and (V_g,V_f)have the same length ,the total length is recorded as $2\mathrm{l_r}$, and the arc (V_r, V_f) length is recorded as $\mathrm{d_r}$. And in the function ($\sum_{i=1}^{n}\sum_{j=1}^{m}(L_{ij})$), the change in distance due to the turn is not considered, so in this function, all routes are straight lines, and those that simply slide in the turn section are (V_r, V_g) with (V_g, V_f), not the actual arcs (V_r, V_f). And $\mathrm{d_r} = 2\mathrm{l_r} + (\mathrm{d_r} - 2\mathrm{l_r})$, so the value of the turn correction for this section is ($\mathrm{d_r} - 2\mathrm{l_r}$).

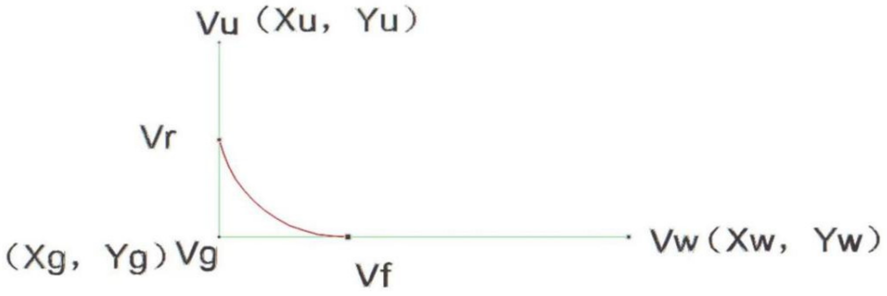


Figure 1. Aircraft turn path diagram.

2) Constraints on dynamic programming

In the process of dynamic planning, since the aircraft has solved the overall path problem, divided into multiple interconnected single-stage problems, the next step of path planning is made in the dynamic algorithm based on real-time information of the airport network when the aircraft performs path retrieval in the process of reaching the next point location point, so the constraints of static planning are converted into constraints in dynamic planning as:

The blocking of the aircraft passing through the node for the time period, as well as the pre-judgment of whether the next selected node is closed, removes the presence of the link in the search path of the aircraft, and thus the search for other links, and when no other links are available, the option to wait until the node is unblocked.

$$Z_{ijk} * T_{ik} + t_{ijk} < (T_{j(ban)} - t_{secure})Z_{ijk}, \tag{12}$$

$$Z_{ijk} * T_{ik} + t_{ijk} > (T_{j(ban)} + t_{secure})Z_{ijk}, \tag{13}$$

$$T_i = T_{i(ban)}, \tag{14}$$

$$Z_{ij} * Z_{ji} = 0, \tag{15}$$

$$\mathrm{t} \geq \mathrm{t}_{\mathrm{start}_\mathrm{k}}, \tag{16}$$

where: when aircraft k is preselected to travel from node i to node j, $\mathrm{Z_{ijk}}$= 1, otherwise $\mathrm{Z_{ijk}}$= 0. T_{ik} is the time for aircraft k to arrive at node i. t_{ijk} is the time required for aircraft k to taxi from node i to node j. $T_{i(ban)}$ is the moment of closure of airport node i, determined by the moment of arrival of the aircraft at the node. t_{secure} is the safety interval between aircraft; Z_{ij} indicates whether there is an aircraft sliding from point i to point j on the link (i, j) at the current time. When Z_{ij} = 1, there is an aircraft sliding from point i to point j at the current time； t is the current moment, t = 0 when the first aircraft starts taxiing. $\mathrm{t}_{\mathrm{start}_\mathrm{k}}$ is the expected start time of taxiing for aircraft k.

When either of (12) and (13) does not hold, the aircraft with lower priority is required to make a wait or change the preselected path (cross conflict), and when Eq (15) do not hold, the aircraft with lower priority is required to make a path change or wait (head-to-head conflict). When (16) holds, it means that aircraft k starts taxiing.

5. Algorithm design

Using dynamic planning method to solve the model, that is, the total problem of state substance is dispersed into sub-problems, the advantage is that in the state transfer model, in the process of conflict search, can greatly reduce the search complexity, that is, in this model dynamic planning, the node state search range will be much smaller than the static planning of the conflict node search range, the complexity of the algorithm will be greatly reduced, but has a certain. However, the algorithm complexity will be greatly reduced, but has certain shortcomings, that is, after the time discretization, the final path selection result is a combination of multiple time steps of a single taxiing path selection scheme, and the fine selection of the time step will directly lead to the accuracy of dynamic planning, step length is too long, although the computing time will be greatly reduced, but cannot meet the accuracy requirements of path planning, and the time step is too small will affect the speed of path dynamic planning, so the time step ψ = 1 in this model can complete the path planning in a shorter time, but also can ensure the accuracy of the path planning enough.

For finding the minimum time for an aircraft to taxi on the airport surface, it can be reduced to the problem of finding the shortest path if the starting and ending nodes are known. It is easy to understand for novices and the code is simple to write.

Dijkstra’s algorithm process:

1) Enter the starting point s, the ending point t; initialize the set S of vertices for which the shortest path has been computed and the set U of vertices for which the shortest path has not been computed.

2) Put the starting point s into S, update the set U and compute the distance of all vertices in the set U to s.

3) Select the vertex v that is not in S and has the minimum distance; update the set S, the set U.

4) Whether the shortest paths of all vertices are found, if yes, the loop is launched, otherwise the loop continues

5) The shortest path from the starting point s to the end point t and the length of the path are output, while the data is later corrected.

Dynamic planning algorithm process.

1) Data initialization, reading the start time, start node and end node of the aircraft, generating the shortest path solution from the current node to the end of the taxi by dijkstra's algorithm for the aircraft that has started taxiing.

2) Determine if the current time is greater than or equal to the aircraft's starting taxiing time, if it is less, the aircraft waits in place, when it is greater than or equal, the aircraft starts to taxiing according to the minimum path generated by dijkstra's algorithm, after each time step update the situation of each node in the network node, and the distance of the aircraft from the upcoming node, determine whether the aircraft reaches the next node. If it does not arrive, the taxiing continues.

3) This aircraft starts at the node it is currently at and uses the global termination node as the target to solve for the next pre-arrival target point of this aircraft using dijkstra's algorithm.

4) By calculating the expected arrival time at the next node, and determine whether there is a conflict with the state of the next node, if not, determine whether there is a head-to-head conflict, if there is no conflict and the next target point can be solved correctly, then the aircraft enters the path of the current node at the next target point and continues to taxiing, and set the blocking time for this target node.

5) If the arrival time at the next node conflicts with the state of the next node, conflict resolution is performed by changing the adjacency matrix to break the link between the current node and the original pre-selected node to find the new shortest path, and if it cannot be solved, then the option is to wait in place for the node to open and continue to perform the slide.

6) When arriving at the next position node, discriminate whether the current node is the global endpoint of the aircraft taxiing, if the current node is the global endpoint of the aircraft, remove this flight from the optimization list, and let if it is not the global endpoint, the aircraft continue to perform the third step. The algorithm ends until all aircraft have finished scheduling to their respective global endpoints.

6. Case application analysis

Considering the specificity of the epidemic, the flight data of Xi'an Xianyang Airport during the time period from 15:16:00 to 15:28:20 on May 2, 2019 are collected here for simulation, and the flight taxiing time, aircraft type, TBT time, start point and end point information are shown in Table 3 below.

Table 3. Flight information sheet.

Aircraft	Station	TBT	Type	Start	End
NS8264	arrival	15:16:00	B738 (I)	05L (6)	126 (165)
HU7577	departure	15:17:00	A320 (I)	318 (166)	05R (137)
MU4405	arrival	15:18:55	A321 (I)	05R (154)	320 (167)
MU5569	departure	15:21:00	A319 (I)	315 (168)	05L (1)
HU7817	departure	15:26:02	A320 (I)	101 (169)	05L (1)
MU2158	arrival	15:28:20	B738 (I)	05L (7)	120 (170)

In order to carry out the planning of the trajectory, the network topology of Xi'an Xianyang International Airport was mapped according to the plan structure of Xi'an Xianyang International Airport, as shown in Figure 2.

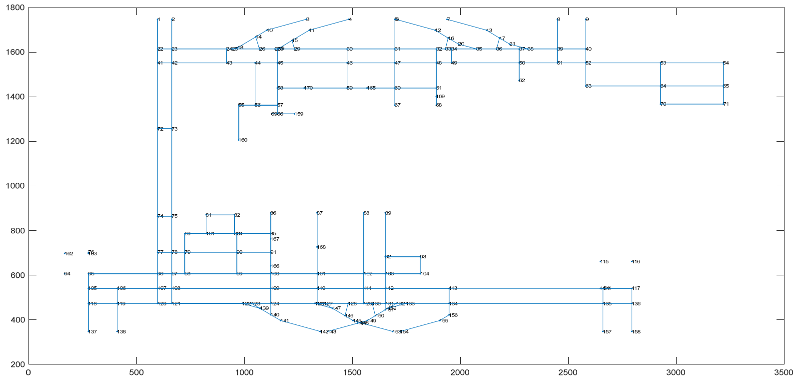


Figure 2. Xi'an xianyang international airport planar network topology map.

The solution based on the constructed model and algorithm yields the following taxiing paths for the six flights which can see from Figure3 to Figure 8.

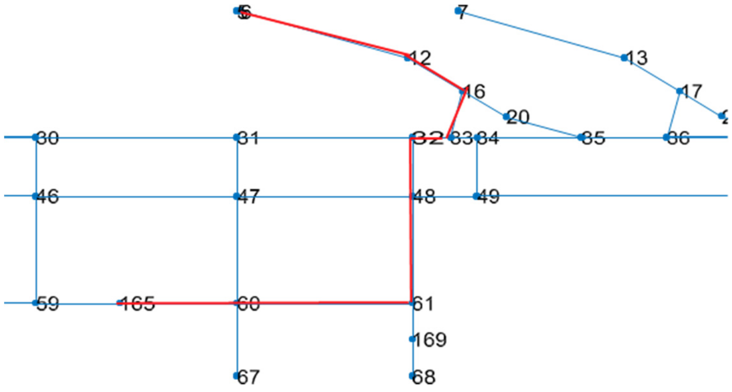


Figure 3. NS8264 flight taxiing path map.

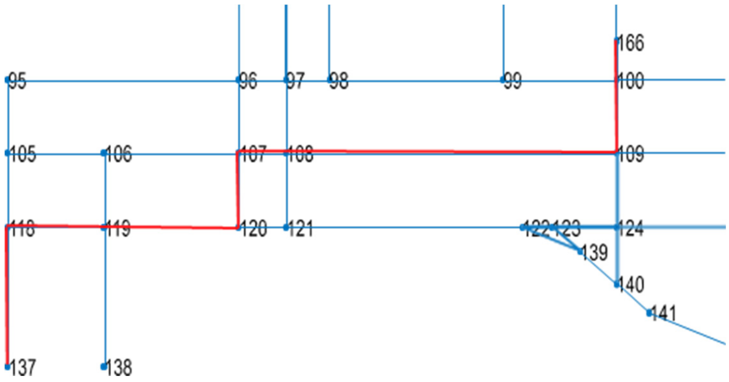


Figure 4. HU7577 flight taxiing path map.

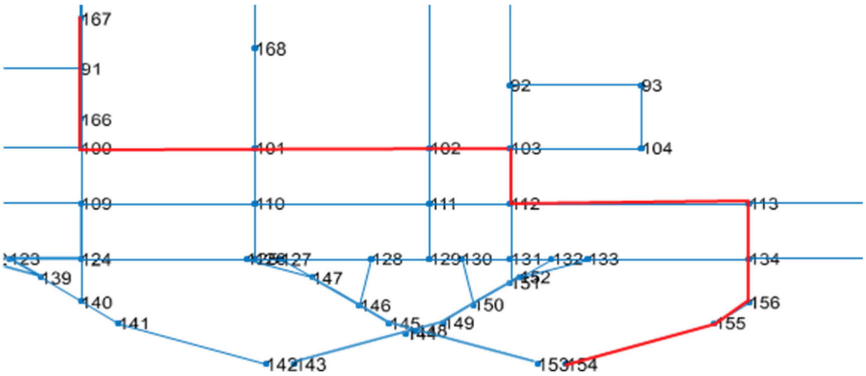


Figure 5. MU4405 flight taxiing path map.

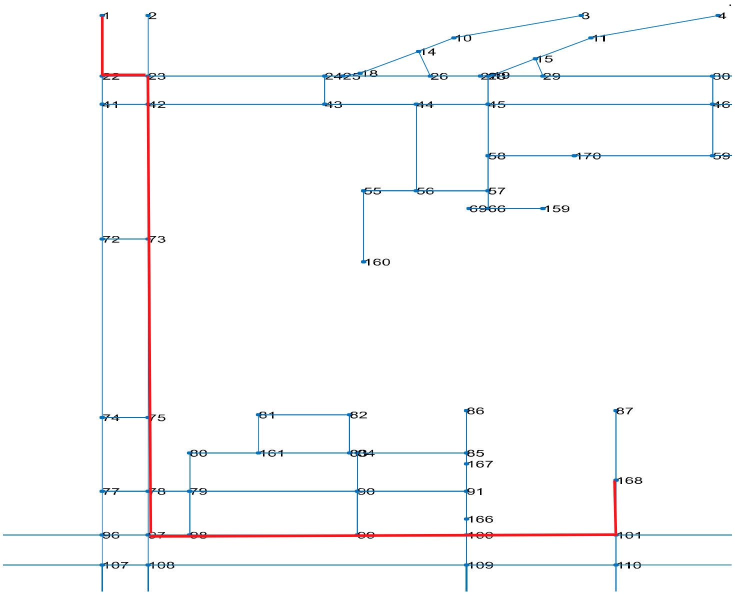


Figure 6. MU5569 flight taxiing path map.

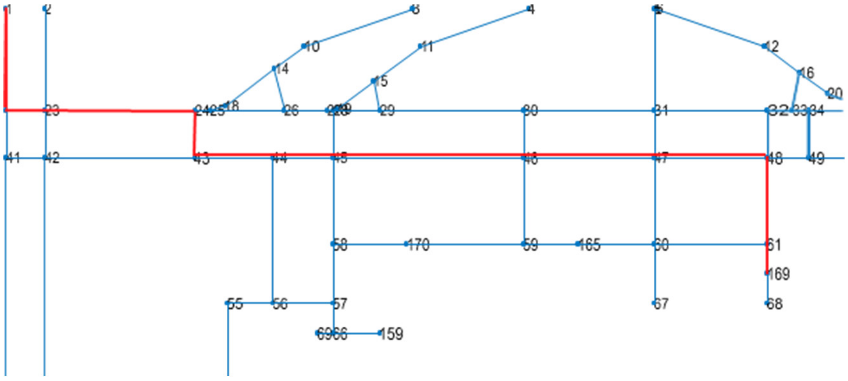


Figure 7. HU7817 flight taxiing path map.

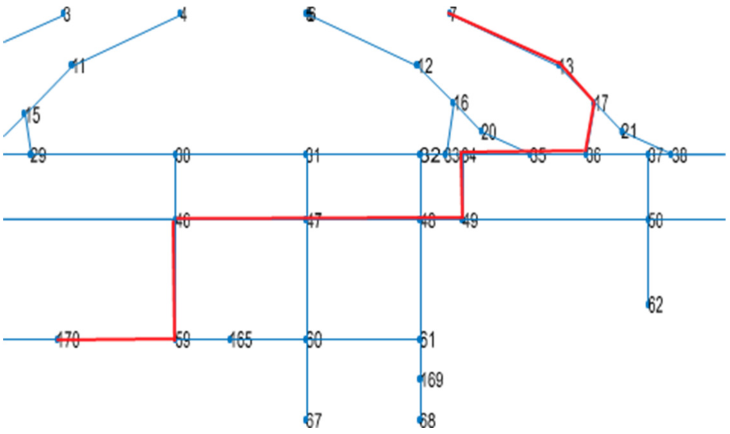


Figure 8. MU2158 flight taxiing path map.

The node and moment data corresponding to the taxiing of the 6 flights according to the taxiing trajectory of the aircraft, i.e., the 4D trajectory information of the flight operation is shown in Table 4:

In order to analyze the relationship between the six flight trajectories more clearly, the horizontal coordinates (X axis, unit: meters) and vertical coordinates (Y axis, unit: meters) are taken to determine the node plane position, and the T axis (unit: seconds) is taken as the aircraft taxiing time axis, and the simulation is carried out using matalb software to generate the three-dimensional diagram of the six flight taxiing trajectories, and six different angle diagrams are selected here. It can be seen from the figure that the taxiing paths of the aircraft have no overlapping parts on the time axis, and the time coordinates of different aircraft are not the same in the case of the same plane coordinates (i.e., both X and Y are the same), i.e., there is no conflict between the trajectories of the six flights which can be seen from Figure 9 and the trajectories of the six flights operate at the same time to meet the safety time interval, such as the third aircraft MU4405 and the fourth aircraft MU5569 in closer time both have taxiing paths from node 101 to go to node 100, and in the taxiing process, the two aircraft possess a time interval of 68 seconds at the moment of reaching node 101, which is much larger than the required safety time interval, so the flight taxiing 4D trajectory planning model planned by the spatio-temporal network method constructed by the research can achieve the generation of conflict-free aircraft 4D taxiing paths for flight operations.

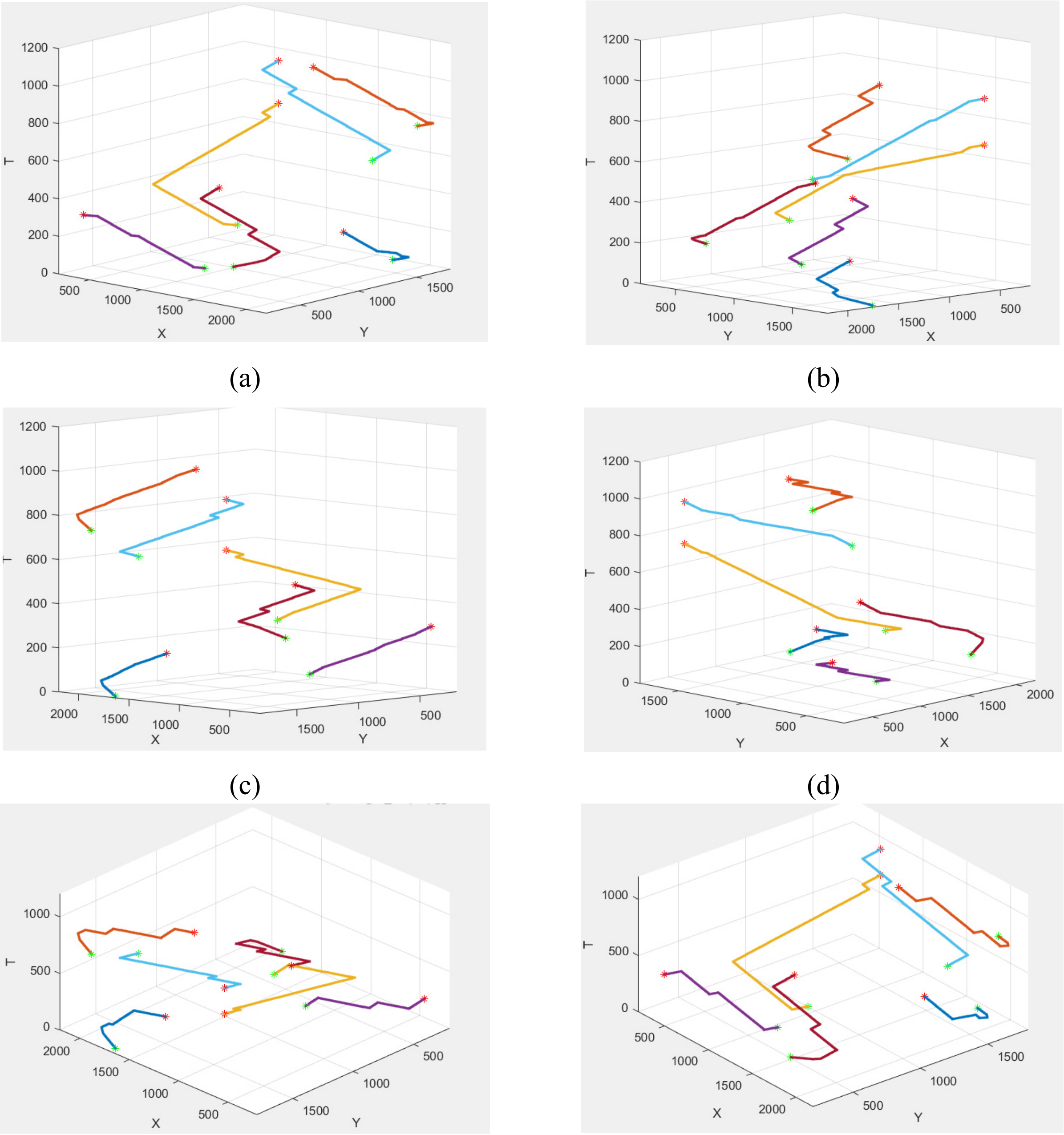
The selected six flights use a change of path for taxi conflict avoidance, and the spatio-temporal network model simultaneously enables waiting to avoid the conflict by advancing the initial taxi time of MU4405 by 50 seconds for a before-and-after conflict resolution comparison, from the left panel to the 4D taxi trajectory of the aircraft before conflict resolution, and the right panel to the 4D taxi trajectory of the aircraft after conflict resolution.

From the left panel of Figure 10 it is obvious that the taxi trajectories of MU5569 (yellow) and MU4405 (brown) have the same path time and short interval in the space-time diagram, and after replanning using the constructed model (shown in the right panel), it can be seen that there is a waiting time arc in the space-time path of the taxi trajectory of MU5569 (yellow), in which the yellow represented by flight MU5569 is in a waiting state, and avoids the conflict that will occur with flight MU4405 by waiting.

Table 4. Aircraft taxi paths.

Flight	Glide path nodes and elapsed time						
NS8264	【6】 【15:16:01】	→	【12】 【15:16:39】	→	【33】 【15:17:06】	→	【32】 【15:17:16】
	【48】 【15:17:30】	→	【61】 【15:17:54】	→	【60】 【15:18:34】	→	【165】 【15:19:01】
HU7577	【166】 【15:17:00】	→	【100】 【15:17:07】	→	【109】 【15:17:22】	→	【108】 【15:18:55】
	【107】 【15:19:10】	→	【120】 【15:19:25】	→	【119】 【15:20:04】	→	【118】 【15:20:32】
	【137】 【15:20:59】						
MU4405	【154】 【15:18:55】	→	【155】 【15:19:33】	→	【156】 【15:19:44】	→	【134】 【15:19:56】
	【113】 【15:20:11】	→	【112】 【15:21:11】	→	【103】 【15:21:26】	→	【102】 【15:21:47】
	【101】 【15:22:32】	→	【100】 【15:23:16】	→	【166】 【15:23:24】	→	【91】 【15:23:38】
	【167】 【15:23:51】						
MU5569	【168】 【15:21:00】	→	【101】 【15:21:24】	→	【100】 【15:22:08】	→	【99】 【15:22:41】
	【98】 【15:23:31】	→	【97】 【15:23:44】	→	【78】 【15:24:05】	→	【75】 【15:24:39】
	【73】 【15:25:59】	→	【42】 【15:27:00】	→	【23】 【15:27:14】	→	【22】 【15:27:29】
	【1】 【15:27:57】						
HU7817	【169】 【15:26:02】	→	【61】 【15:26:10】	→	【48】 【15:26:34】	→	【47】 【15:27:14】
	【46】 【15:28:00】	→	【45】 【15:29:06】	→	【44】 【15:29:28】	→	【43】 【15:29:56】
	【24】 【15:30:10】	→	【23】 【15:31:02】	→	【22】 【15:31:17】	→	【1】 【15:31:45】
MU2158	【7】 【15:28:20】	→	【13】 【15:28:58】	→	【17】 【15:29:13】	→	【36】 【15:29:25】
	【35】 【15:29:45】	→	【34】 【15:30:09】	→	【49】 【15:30:23】	→	【48】 【15:30:39】
	【47】 【15:31:19】	→	【46】 【15:32:05】	→	【59】 【15:32:29】	→	【170】 【15:33:10】

After the completion of the dynamic planning of the taxiing path for the six aircraft without conflicts according to the spatio-temporal network model, and then corrected by the turning distance, the fuel consumption and taxiing distance data for the six flights were calculated as shown in the following Table 5



(a)

(b)

(c)

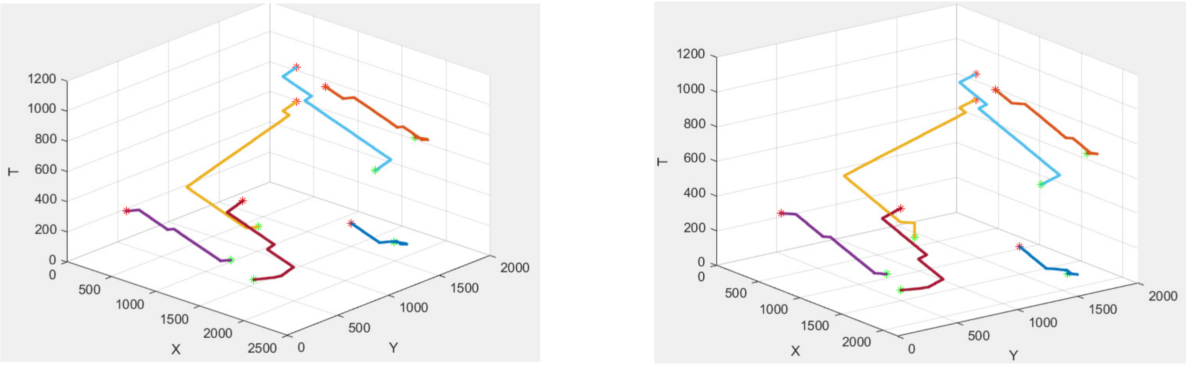
(d)

(e)

(f)

Figure 9. Three-dimensional path diagram.

The calculated data showed that the total fuel consumption of the six aircraft was 564.29 kg and the total taxiing distance of the planned taxiing path of the six aircraft was 9115.66 m. Also, there was no conflict during the taxiing.



(a)

(b)

Figure 10. Spatio-temporal path diagram.

Table 5. Aircraft fuel and route.

Flight	Taxiing distance(m)	Fuel Consumption(kg)
NS8264	883.31	60.48
HU7577	1250.77	69.55
MU4405	1498.48	107.74
MU5569	2200.77	129.27
HU7817	1808.14	99.81
MU2158	1474.19	97.44
Summary	9115.66	564.29

7. Conclusions

For the first time, the study combines a time-space network with the Dijkstra algorithm, builds a collision-free 4D taxiing path model for aircraft, and employs the Dijkstra algorithm to design a solution scheme for the model. The results of a six-flight application analysis at Xi'an Xianyang Airport show that the model can make conflict-free planning for flight taxiing paths by changing the path and waiting strategies, resulting in safe surface operation. It serves as a scientific reference for the implementation of conflict-free 4D airport aircraft taxiing route planning. However, the study is limited to small-scale data. If the volume of data grows, a new solution must be developed. Simultaneously, the model assumes that the aircraft taxiing on the surface moves at a constant speed. A systematic study of the construction scheme of the planning model for the non-uniform surface taxiing trajectory will be conducted in the future.

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Conflict of interest

There is no conflicts of interest.

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