A Method for Air Route Network Planning of Urban Air Mobility

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Abstract: Urban air mobility is an effective solution to address the current issue of ground traffic congestion in future cities. However, as the user scale continues to expand, the current civil aviation flight scheduling and control methods are becoming inadequate to meet the high-volume flight guarantee demands of future urban air transportation. In order to effectively handle and resolve potential issues in this field in the future, this paper proposes a method for planning urban air mobility route networks. The planning process is divided into two stages: construction and optimization. Methods for constructing urban air mobility route networks based on flight routes and global optimization methods based on node movement are proposed in each stage. In the construction stage, a complete construction process is designed to generate routes based on existing flight routes, in line with the trend of urban air transportation development. In the optimization stage, inspired by the ant colony algorithm, node transfer rules and information transfer rules are incorporated to design a global optimization process and algorithm for route networks. Experimental results demonstrate the effectiveness and advancement of the proposed planning method.

Keywords: urban air mobility; air route network; ant colony algorithm; global optimization algorithm

1. Introduction

The rise in household car ownership has led to increased pressure on urban transportation systems. In medium and large cities, commute times have become a significant source of social stress. While subways and other transportation options have alleviated ground congestion to some extent, they do not address the underlying issue, which is that the growing transportation demand is exceeding the capacity of existing infrastructure [1]. There are two potential solutions to this problem: updating the direction of vehicle development and modernizing urban transportation management systems [2]. Urban air mobility has captured the interest of a growing number of individuals [3,4], with many scholars conducting extensive research in this area [5–7], including exploration of management modes [8]. The European Aviation Agency issued the first relevant regulations in 2019, the ‘Regulations on the Airworthiness of eVTOL Aircraft with Special Provisions’, and in 2022, the ‘Technical Design Specifications for eVTOL Aircraft Airports’. The British Department for Transport has issued several documents to promote the development of urban air mobility since 2021. The United States enacted the ‘Urban Air Mobility Coordination and Leadership Act’ in 2022 and the ‘Urban Air Mobility Operations Concept 2.0’ in 2023 [9]. Building on existing research, this paper proposes a management mode for urban air mobility route networks, effectively combining methods to address current challenges and conflicting issues.

The air route network is typically divided into the high-altitude route network and the low-altitude public route network. In the high-altitude route network, routes are less affected by flight restrictions and buildings, and the planning process prioritizes user needs. In contrast, the low-altitude public route network, due to height limitations, requires more consideration of the impact of buildings and flight restrictions on the planning of the air route network. The urban air mobility route network mentioned in this paper belongs to the low-altitude public route network. Although the low-altitude public route network
plays a significant role in the future development of urban air traffic, research in this area started relatively late, with most studies focusing on drone [10–12] and drone logistic [13] route networks. As the development of eVTOL progresses, drone route networks and planning methods may not fully meet the usage requirements of eVTOL. Nonetheless, the concept of a route network remains applicable, and the structure of a single air highway has also been researched [14]. Therefore, the background of the proposed urban air traffic route network planning method in this paper originates from these considerations.

The urban air mobility route network is designed using the ‘ground road network’ as a model, with three-dimensional routes forming the basis for planning, as illustrated in Figure 1. Aircrafts take off and land at vertical take-off and landing sites, proceeding to the next site through the route network while adhering to predetermined flight regulations within the routes [15]. The urban air traffic management system, developed following this framework, focuses on planning the route network and establishing internal regulations within the routes to effectively oversee aerial vehicles.

Figure 1. Urban air mobility route network.

The planning of the air route network is typically divided into two phases: construction and optimization. In the construction phase, the initial establishment of the route network is accomplished to facilitate flights between different demand points. However, this phase often lacks sufficient consideration for avoiding flight-restricted areas. In the optimization phase, the route network is globally optimized with the objectives of minimizing the total path length and avoiding flight-restricted areas.

The construction of the air route network can be categorized into three main types based on current research methods by scholars. These include the method based on transportation hubs, the AirMatix method, and the method based on existing ground infrastructure. The method based on transportation hubs involves constructing the air route network using airports as transportation hubs in the civil aviation field. Dai Fuqing et al. [16] introduced the civil aviation gravitational field space model in complex networks and utilized the small-world effect for analysis and modeling. They successfully generated the regional feeder route network. The method based on AirMatix utilizes the AirMatix theory to grid the urban airspace and assigns four-dimensional coordinates to each spatial grid for conflict resolution. Qingyu Tan et al. [17] proposed ‘application-planning-adjustment’ flight rules for aircraft based on this method. The management department conducts path planning based on demand points to establish the air route network. During actual use, aircrafts confirm the starting point and destination and apply to the management department. The department then conducts path planning for the application, checks for conflict points, and adjusts departure times based on conflicts. The ‘staggered’ method is used to regulate conflicts in the air route network. The planning method based on existing ground infrastructure takes urban planning into full consideration. Mohammed Faisal Bin Mohammed Salleh et al. [18] directly utilized the urban ground road network as a reference, elevating it to a certain height to effectively avoid buildings while meeting the travel needs of residents. Honghai Zhang et al. [19] employed clustering algorithms to cluster high-rise buildings, generated representative obstacle points as Voronoi seed nodes, and used Voronoi diagrams to establish the initial routing network. Shan Li et al. [20] introduced the ‘plan first, then merge’ concept to solve the drone logistics network problem. They
separately planned the required paths based on logistics demand points and established certain indicators to evaluate and obtain the optimal network. He Xinyu et al. developed a path-planning algorithm aimed at designing the route network for urban air transport. They proposed a priority framework that separates multipath planning into single-path planning, resulting in faster computational speed. Additionally, they introduced a new spatial cost function [21]. Similarly, Ye Mian et al. focused on urban low-altitude vacant types and introduced various risk models. They also improved the A * algorithm to plan the eVTOL route network, which effectively reduced security costs [22].

The optimization of the air route network can be classified into three main types based on current research methods by scholars, depending on their overall impact on the route network: optimization methods based on ‘node/segment deletion’, ‘node movement’, and ‘segment local adjustment’. The optimization method based on ‘node/segment deletion’ involves removing specific nodes and segments from the constructed route network to achieve optimization. Typically, reverse thinking is utilized to identify critical segments and nodes. Li Jiawei et al. [23] consider the air route network as a complex network and introduce the concept of the minimum connected dominating set to ensure network connectivity. By using optimization algorithms to identify critical nodes and segments, they construct a backbone network accordingly. The optimization method based on ‘node movement’ includes relocating nodes within the route network, monitoring changes in network performance, and determining the optimal combinations of node positions. Kai-quan Cai et al. [24] combine node movement algorithms with path-searching algorithms. While moving nodes, they simultaneously analyze changes in path lengths between various origin–destination pairs in the entire route network to minimize path lengths between all origin–destination pairs in the route network. The optimization method based on ‘segment local adjustment’ involves re-planning conflicting or irrational segments within the route network. Shijin Wang et al. [25] address the issue of excessive nodes when optimizing the route network through local adjustments, which complicates processing. They initially merge nodes through clustering and then conduct local path planning on the merged nodes to reduce network complexity while avoiding flight-restricted areas.

Drawing from the current research landscape, this paper presents a novel approach to developing an urban air mobility route network based on flight routes, alongside a global optimization strategy for the urban air mobility route network focusing on node movement. The subsequent sections of the paper will delve into the principles underlying the planning methods, analyze the specific details of the planning methods, and conduct case verification and result analysis.

2. The Method for Constructing Urban Air Mobility Route Network Based on Flight Routes

The method of constructing an urban air mobility route network based on flight routes involves establishing an urban air mobility route network that meets airspace conflicts and flight trajectory requirements based on predetermined airspace utilization and flight routes. On the one hand, the development of urban air traffic progresses from disorder to order. Initially, the flight routes of small-scale aircraft reflect the flight demands of different points, and constructing route networks based on these routes can significantly reduce changes in aircraft routes, reflecting real needs. On the other hand, integrating current airspace utilization effectively standardizes the route network, attempting to avoid already utilized or restricted airspace during the construction process. This not only reduces conflicts in airspace utilization but also minimizes the workload for subsequent route network optimization.

The core principle of this construction method involves ‘merging’ existing flight routes to create the air route network. This process entails identifying hub points within the airspace environment and then connecting these hub points based on the directional flow of the flight routes, thereby shaping the air route network. The specific steps of this fundamental principle are illustrated in Figure 2.
Identification of start and end points: The air route network must connect multiple starting and ending points, facilitating travel between any origin and any destination. As a result, identifying the start and end points is a vital initial step in the construction process of the air route network.

Identification of airspace environment: The airspace environment encompasses different types of airspaces within a specified volume. During the construction of the air route network, the airspace environment comprises various structures, restricted airspaces (e.g., those above critical areas), and other factors. It is essential to pre-determine the position, dimensions, and central coordinates of each airspace segment.

Import of flight routes: Flight routes are strategically planned by aviation professionals, considering the departure and arrival points, as well as the airspace environment, while leveraging their expertise. To ensure the connectivity of the air traffic route network, flight routes must be designed to connect every possible pair of starting and ending points.

Airspace environment handling: The handling of the airspace environment involves dividing the airspace on a two-dimensional plane using the central point coordinates. This preprocessing operation identifies hub nodes to create connecting lines between airspaces and map boundaries. The process consists of two steps: Firstly, Delaunay triangulation is used with central points of each airspace to identify intersections between flight paths and auxiliary lines, creating auxiliary points that form hub nodes; secondly, The convex hull algorithm is applied to connect individuals on the outer side of the airspaces to the nearest boundaries, addressing limitations of the first step. This method complements the first step by accommodating flight routes that do not pass through auxiliary lines.

Identification of hub nodes: Following the intersections between the connecting lines generated from handling the airspace environment and the flight paths, the auxiliary points are processed. The auxiliary points that lie on the same auxiliary line are clustered [26,27], and hub nodes are determined.

Establishment of the air route network: The hub nodes are connected in sequence based on the direction of the flight paths, linking each origin point to each destination point. This process results in the formation of the air route network.

The fundamental process of constructing the urban air mobility route network based on flight routes is illustrated in Figure 3.
Figure 3. The process of constructing the urban air mobility route network.

3. The Global Optimization Method for Urban Air Mobility Route Network Based on Node Movement

3.1. Optimization Procedure

The global optimization method for the urban air mobility route network, which is based on node movement, represents a further in-depth exploration of the construction approach for the urban air mobility route network that is grounded on flight paths. This method seeks to address issues related to conflicts within air routes and airspace, as well as to enhance the overall optimization of the global outcomes of the route network in the construction phase.

In this method, the hub nodes generated during the construction process are uniformly referred to as nodes. The optimization objective is to connect these nodes according to a given connection matrix, forming the route network. The goal is to minimize the total length of routes between any two nodes while avoiding airspace obstacles. Since the air route network consists of nodes and route segments, moving any node will impact at least two route segments and affect the overall length of the route network and its conflict with airspace. Therefore, this method focuses on optimizing the movement of nodes based on this characteristic of the air route network. The aim is to achieve an optimal configuration that minimizes route lengths and airspace conflicts.

In the specific implementation process, using a simple exhaustive method to calculate the optimal route network is computationally impractical due to the immense computational load. For instance, if each node has a selection space of 10, the number of possible results for connecting 10 nodes with the least number of route segments would be $10^{10}$, significantly reducing calculation speed. Therefore, an optimization algorithm is required to handle the calculations more efficiently.

The ant colony algorithm [28,29] is a commonly used path optimization algorithm, typically employed in the planning of single paths. However, when applied to the air route network, using this algorithm for individual paths would only optimize those specific paths, failing to optimize the overall route network. Nonetheless, the optimization concept within the ant colony algorithm is widely applicable. Therefore, this study is designed to improve upon the basic principles of the ant colony algorithm and develop an enhanced global optimization algorithm specifically for the air route network. The specific principles of this algorithm are depicted in Figure 4.
Identification of start and end points: After the construction of the air route network, the hub nodes that are generated in the final stage are referred to as nodes. However, the start and end points of the routes remain unchanged and are not considered nodes within the network.

Identification of the node space: In this study, the node space refers to the set of coordinates that nodes can select from during the movement process. To determine the node space, auxiliary lines are established based on the locations of the hub nodes. Following the principle that points within the node space must not be located in airspace obstacles, the parts of the auxiliary lines that do not intersect with the airspace are designated as the node auxiliary lines. N points are then selected along these node auxiliary lines to form the node space. Figure 5 illustrates this concept.

Identification of the connection matrix: The connection matrix specifies the connection relationships between different nodes within the air route network. This matrix is established based on the outcomes of the network construction process, outlining how each node is connected to other nodes in the network.

Global optimization: Global optimization is a critical step in this method. During this stage, the global optimum is attained by considering the nodes and the connection matrix, while also ensuring avoidance of the obstacle airspace.

Conflict detection: As a node can be connected to multiple nodes during the process of air route network connection, there is a possibility of processing a node twice during the optimization process based on the connection matrix. This can lead to the second processing result overlapping and covering the first processing result. Consequently, it is essential to inspect the optimized results obtained from the ant colony algorithm to identify any potential conflicts that may still exist.
**Local optimization:** In the presence of conflicts, local adjustments are implemented in the conflicting areas, ensuring optimization is conducted with minimal changes to the overall path.

**Formation of air route network:** The air route network is established based on the optimization results.

### 3.2. The Fundamental Principles

The global optimization method for the urban air mobility route network, which is based on node movement, represents an enhanced approach derived from the ant colony algorithm to globally optimize route networks. The distinct steps involved in this process are outlined in Figure 6.

![Figure 6. The global optimization method.](image)

During each iteration of the global optimization algorithm for the urban air mobility route network based on node movement, the steps are as follows:

1. Nodes are selected within the node space based on the connection matrix to create an initial node selection matrix.
2. Conflict detection is performed using the connection matrix. If conflicts are identified, a node transition matrix is established based on predefined node transition rules, and the node selection matrix is updated accordingly.
3. In scenarios where no conflicts are detected, the node combination with the shortest total network length for the current iteration is determined.
4. If modifications occur in the node selection matrix during conflict detection, the pheromone information of the respective nodes in the initial node matrix is allocated to the final node combination, followed by pheromone updating.

By integrating conflict detection into the iteration process, nodes are updated directly upon detection, and when updating the pheromone information, the updated nodes are considered. This approach avoids the additional computational burden typically associated with post-iteration conflict detection, thereby accelerating the optimization process and enhancing its efficiency.

The details are as follows:

**Node selection:** Node selection refers to the process wherein ants choose within the node space at each node, combining these choices to form a node selection matrix. The node space is represented by $D_i = [x_{i1}, y_{i1}; x_{i2}, y_{i2}; \ldots; x_{ina}, y_{ina}]$, and $i$ denotes the $i$ node space. The node selection matrix is as follows, where $a$ represents the number of ants, and each row indicates the node selection results of an ant.
The ant colony algorithm still employs the selection mode in the node selection process, where it selects within the node space of each node, as illustrated in the following equation.

\[ j = \begin{cases} \text{arg max} \left( \frac{|\tau_{ia}|}{\eta_{ik}} \right) & q \leq q_0 \\ \text{other} & \end{cases} \]

(2)

where \( q \) is a random number within the range \([0, 1]\), \( q_0 \) is a parameter adjustable within the range \([0, 1]\), \( \eta_{ik} \) represents the heuristic value, and \( \tau_{ia} \) represents the pheromone information. The calculation for \( f \) involves sequentially determining the probability \( p_{ij} \) of the node to the points in the subsequent node space and then selecting the next node based on the roulette wheel method. The calculation method for \( p_{ij} \) is as follows:

\[ p_{ij} = \frac{\tau_{ij}^\beta \eta_{ij}^\beta}{\sum_{m} \tau_{im}^\beta \eta_{im}^\beta} \]

(3)

The selected nodes reflect the connections by utilizing the connectivity matrix, as shown in the following equation.

\[ A = \begin{bmatrix} 0 & a_{12} & \cdots & a_{1j} \\ 0 & 0 & \cdots & a_{2j} \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & 0 \end{bmatrix} \]

(4)

\[ a_{ij} = \begin{cases} 1 & \text{Nodes } i \text{ and } j \text{ are connected} \\ 0 & \text{Not} \end{cases} \]

(5)

**Node update**: Node update is a crucial step in improving the ant colony algorithm strategy. This step is necessary because the route network needs to avoid airspace obstacles. However, if simple conflict node combinations are removed, it can significantly increase the workload and may lead the algorithm into local difficulties, making it unable to calculate early. Therefore, in this study, when calculating the path length of a group of nodes, the connection between two nodes is checked using the connectivity matrix. If a conflict occurs, another node is searched within the node space until a conflict-free connection is found. The newly identified nodes are then combined to form a matrix \( \text{Path}(i,j)' \). The rules for node transfer during this process are illustrated in the following equation.

\[ \begin{cases} \text{Path}(i,j)' = \text{Path}(i,j) + 1 & \text{Path}(i,j) \neq n \\ \text{Path}(i,j)' = 1 & \text{Path}(i,j) = n \end{cases} \]

(6)

**Pheromone update**: The pheromone matrix serves as the foundation for updating the node selection matrix, as depicted below.

\[ \text{pher} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1a} \\ p_{21} & p_{22} & \cdots & p_{2a} \\ \cdots & \cdots & \cdots & \cdots \\ p_{ia1} & p_{ia2} & \cdots & p_{ia} \end{bmatrix} \]

(7)

In the above equation, each row corresponds to a node space, and the elements represent the remaining pheromone for the ants based on their final node selection. According to the principles of ant colony optimization, pheromone update consists of real-time updates
and trail updates. Real-time update refers to updating the pheromone on the selected node after the ant chooses the node, as shown in the following equation:

$$\tau_{ij} = (1 - \rho)\tau_{ij} + \rho\tau_0$$  \hfill (8)

Trail update refers to the updating of pheromones on the nodes after the ant has traversed the network, as shown in the following equation. \(\rho\) is the pheromone evaporation parameter.

$$\tau_{ij} = (1 - \rho)\tau_{ij} + \rho\Delta\tau_{ij}$$  \hfill (9)

$$\Delta\tau_{ij} = \frac{1}{L}$$  \hfill (10)

However, in this method, if the node selection matrix changes and the pheromone update of the initial node matrix continues, no further optimization is completed in this round, and the node combination of the shortest total path found in this cycle is not the node combination of the pheromone update. Therefore, in the process of path updating, if \(Path\) and \(Path'\) are equal, indicating no change in the node selection, the calculation remains the same; if not equal, the node selection has changed and to effectively utilize the updated node combination, the pheromone of the original unchanged nodes is not updated. Instead, the pheromone of the changed node is updated, as shown below, where \(\tau_{ij}\) represents the pheromone content corresponding to the updated node combination.

$$\begin{cases} 
\tau'_{ij} = (1 - \rho)\tau'_{ij} + \rho\Delta\tau'_{ij} & Path' \neq Path \\
\tau_{ij} = (1 - \rho)\tau_{ij} + \rho\Delta\tau_{ij} & Path' = Path 
\end{cases}$$  \hfill (11)

**Conflict Detection:** Due to the characteristics of the air route network, during the updating of \(Path'\), the same node will be repeatedly processed, with the results of subsequent processing overriding previous results, which may lead to conflicts between the final result and the air route network and obstacle airspace. Therefore, conflict detection is required for the final result, and a secondary optimization of the air route network is needed.

**Local Optimization:** The air route network established through the aforementioned method achieves global optimality. In the secondary optimization phase, efforts are dedicated to minimizing the overall network’s disturbance. To this end, the concept of node degree is introduced throughout the optimization procedure.

Node degree signifies the number of edges linked to a specific node. A higher node degree implies that relocating the node will result in a more pronounced alteration to the overall path. Consequently, nodes are prioritized for conflict resolution in ascending order of their node degrees.

The optimization technique entails sequentially refining the segments associated with the chosen nodes. Nodes are adjusted within the node space based on the distance until the specified conditions are satisfied. This method serves to mitigate the impact on the overall air route network.

### 3.3. Constraints

**Turning angle constraint:** The turning angle refers to the angle of deviation from the original flight path during an aircraft’s turning process. During a flight, the turning angle is typically small due to speed limitations. Despite the lower flight speeds of aircraft in urban air traffic compared to commercial aircraft, a large turning angle still poses a significant safety risk. Therefore, when planning the air route network, it is crucial to constrain the turning angle as follows:

$$s.t. \ A(i,j) = 1 \ and \ A(j,k) = 1 \ and \ p_i, p_j, p_k \in L_a$$

$$\left| \frac{p_i - p_j}{p_j - p_k} \right| \leq \frac{\pi}{2}$$  \hfill (12)
In the formula above, \( L_a \) represents the \( a \) route, \( p_i \) represents the \( i \) node in the airway network, and \( A \) is the node connection matrix. The turning angle is set to be less than or equal to 90 degrees.

However, in cases where four or more route segments are connected to a single node, this constraint cannot be satisfied. Therefore, when the degree of a node is greater than or equal to 4, the turning angle constraint is not considered.

**Conflict Constraint:** During the air route network planning process, it is imperative to avoid flying through restricted areas. Hence, conflict constraints must be established between each route segment and restricted areas. These conflict constraints are vital for ensuring flight safety, and they encompass the following specific constraints:

\[
\text{s.t. } p_i, p_j \in P, A(i, j) = 1, (x_m, y_n) \in L_{p_i, p_j}, (x_m, y_n) \notin Z
\] (13)

In the formula above, \( p_i, p_j \) represents any two nodes, \( P \) represents the set of nodes, and \( (x_m, y_n) \) represents the coordinates of any point on route segment \( L_{p_i, p_j} \). In this paper, the restricted flight areas are denoted by the set \( Z \), and all points within this set signify areas that are prohibited from being traversed.

### 3.4. Objective Function

In urban air mobility, economic efficiency is a key priority following safety assurance. Therefore, once the conflict constraints are established, the objective function aims to minimize the total route length. The total route length encompasses the combined lengths of routes from every origin to every destination within the air route network. The specific objective function is defined as:

\[
L_w = \min_b \sum_{a=1}^{b} L_a
\]

\[
L_a = \sum_{i=1}^{c} \sum_{j=1}^{c} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}, A(i, j) = 1
\] (14)

In the expression above, \( L_w \) denotes the total length of the air route network, \( L_a \) represents a specific route, \( b \) indicates the number of routes, and \( c \) signifies the number of nodes on a particular route.

### 4. The Experimental Demonstration

#### 4.1. Experimental Parameters

The experimental parameters are set as follows in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>0.1</td>
<td>Maximum iteration times</td>
<td>100</td>
</tr>
<tr>
<td>( q_0 )</td>
<td>0.8</td>
<td>Heuristic function factor</td>
<td>1</td>
</tr>
<tr>
<td>( a )</td>
<td>10</td>
<td>Pheromone constants</td>
<td>0.14</td>
</tr>
<tr>
<td>( n )</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 4.2. The Method for Constructing Urban Air Mobility Route Network Based on Flight Routes

This study selects a specific area in Shanghai as the environment for simulation experiments in Figure 7. This area is characterized by a high concentration of tall buildings, making it well-suited for simulating no-fly zones. During the experiment, the altitude of the air route network is set at 200 m, with a safety margin of 20 m. This designates buildings with a height of 180 m or above as no-fly zones. In the diagram below, red
buildings represent areas with heights exceeding the specified limit, while green buildings represent areas that meet the safety flying requirements.

Figure 7. Real view, top view, and section view.

Although certain buildings do not meet the requirements for flight, they occupy a significant area, with low-rise buildings surrounding their bases. Additionally, some neighboring high-rise buildings are in close proximity. Flying in between these two sets of buildings does not meet safety requirements. Therefore, considering these factors, the red polygon in the diagram below designates the no-fly zone.

Assume there are air routes from the left side of the designated area to this area, ultimately flying into the area. The diagram shows the starting point for the flight, indicated by the red arrow in Figure 8, and the destination, represented by the airport icon.

Figure 8. Airspace environment.
During the early stages of urban air mobility development, with a limited number of aircraft, tasks could be managed by controllers alone. However, as the user demand increases, more routes need to be planned to meet the growing needs. This puts immense pressure on controllers. To address the challenge of managing a large number of routes, this study aims to draw inspiration from the concept of ‘ground road networks’ and proposes the design of an air route network.

In order to alleviate complexity and improve manageability, the design includes 12 specific routes as depicted in the diagram below in Figure 9. These routes traverse through complex airspace conditions, making them difficult to manage individually. Therefore, the aim is to integrate these routes into an organized air route network.

![Figure 9. Flight routes.](image)

To process the airspace environment as described in the second section, blue auxiliary lines and orange auxiliary points are generated, as shown in Figure 10.

![Figure 10. Airspace environment handling.](image)

The auxiliary points on each auxiliary line are subjected to clustering to form hub points. Following the sequence of the routes passing through the auxiliary lines, the hub points are connected one after another to form the air route network, as shown in Figure 11. The blue dots represent the hub points, while the blue line segments represent the air route network.

Based on the experimental results mentioned above, it is evident that this approach can effectively establish a route network based on pre-planned flight paths. In addition, the initial lengths of the 12 routes were compared with their lengths after the route network was constructed, and the magnitude of the change was calculated, as shown in Figure 12.
Based on the above figure, it can be observed that the route network constructed using the method proposed in this paper resulted in minimal changes in the lengths of the 12 routes, with a variation rate of less than 4%. This indicates that the modifications made to the original flight paths were overall minimal, thereby validating the scientific nature of the method. However, it should be noted that during the construction process, the direct connection of hub points was done without considering airspace conflicts. Therefore, further improvements will be made during the optimization phase.

4.3. The Global Optimization Method for Urban Air Mobility Route Network Based on Node Movement

After inputting the parameters, the constructed route network was optimized, and the results are shown in Figure 13. Due to the interconnectivity of various nodes in the route network, new conflicts arose during the optimization process. Subsequently, conflict detection was performed on the optimized results, revealing conflict areas as indicated by the purple lines in the figure.

According to the optimization method described in Section 3.2, a secondary optimization was performed on the conflicting areas, as depicted in Figure 14. In the figure, all route networks have successfully established connectivity between their respective starting and ending points, while also avoiding conflicts with airspaces.
Figure 13. Global optimization and conflict detection.

Figure 14. Local optimization.

When there is a low node sampling density within the node space, even if three consecutive nodes do not experience spatial conflicts, they are still subject to restrictions on optional node positions, resulting in the existence of turning points. Therefore, it is necessary to assess the nodes in the final result. If three or more adjacent nodes simultaneously satisfy the condition that the middle node is not adjacent to any other nodes except those mentioned above, and there is no spatial usage conflict between the first and last nodes directly connected, then update the segment path to connect the first and last nodes, as shown in Figure 15.

Figure 15. The final air route network.
For the analysis of the final experimental results, this study examines the iterative effect, changes in path length, and spatial usage rate. As depicted in Figure 16, it can be observed that by applying the optimization method proposed in this study, the total length of the final path converges to 2312.6.

![Figure 16. Iterative diagram.](image)

As shown in Figure 17, for different flight routes, the rate of change in the initially constructed air route network is within 4% compared to the previous state. However, there are multiple areas with spatial conflicts at this stage. In the optimization process, the method proposed in this study aims for global optimality while avoiding spatial conflicts. Therefore, some flight routes may experience substantial changes compared to the previous routes, while still maintaining an overall change rate within 6%.

![Figure 17. The comparison of flight route length.](image)

The spatial usage rate refers to the proportion of airspace occupied by flight routes compared to the available airspace. Assuming that a 20 km exclusion zone is enforced on both sides of the flight routes to prevent other aircraft from flying, this exclusion zone is considered part of the airspace used by the flight routes. For flight routes that do not utilize the air route network, the spatial usage rate is 0.067%. However, for flight routes that utilize the air route network, the spatial usage rate is reduced to 0.053%, resulting in a decrease of 20.8% compared to the previous state. This reduction indicates a more regulated and clear airspace environment.

5. Summary

The future has arrived, and with consecutive test flights of various aircraft, urban aerial transportation has become a hot area for addressing urban traffic issues. This
study, targeting the characteristics of future urban aerial traffic management, proposes an operational model for air route networks and develops a set of air route network planning methods for this model. Through experimental validation, the method is shown to be capable of constructing air route networks in complex airspace environments, achieving the expected results, and offering some insights into air route network planning and the development of urban aerial transportation. However, this method only provides a macro-level design of air route networks and does not elaborate in detail on aspects such as the airspace structure at intersections and the flight and management rules within the air route network. Furthermore, in future research, it is necessary to address the flight capacity as well as the selection of ground and air travel modes using multinomial logit. Therefore, future work will focus on researching and continuously contributing to the development of urban aerial transportation by addressing these detailed aspects.

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