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Impact of Flight Speed Distribution on Efficiency of Urban Air Traffic Network

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***Abstract*—The emerging Urban Air Mobility (UAM) completes the current urban transportation landscape along with surface transport and relieves road traffic congestion significantly. This relief is not only to add one or more available ways in the air above each existing roadway, but to improve the operating efficiency of the entire traffic network by leveraging electric vertical take-off and landing (eVTOL) aircraft and exploiting advanced air traffic management technologies and procedures. The urban air traffic network is constructed in two different topological structures, namely generalized topology taking airway segments as edges and intersections between two airway segments as nodes, and dual topology considering airways as nodes and connection relationships between two airways as edges. Flight speed is assigned as weight to either airway segment or the entire airway in the two topology networks and network efficiencies are investigated with five common distributions of weight. A method of weight randomization is applied to further explore the impact of weight distribution on both networks, and the results demonstrate that the global and local network efficiencies of a regular network increase with various weight distributions to a certain degree, indicating that network efficiency can be improved by adjusting flight speed distribution while not changing the network structure. The comparison of the experiments on the two topology networks reveals that such adjustment is better-performed segment by segment instead of airway by airway, which provides a reference for stakeholders to manage the urban air traffic flow via better control of flight speed.**

***Keywords*—Urban air mobility, Network efficiency, Urban air traffic management, eVTOL aircraft**

I. Introduction

The process of global urbanization is still ongoing. The United Nations (UN) predicts that 68.4% of the world's population will live in cities by 2050 [1]. The mobility of the population will bring enormous strain to the urban transportation system. Such traffic growth cannot be satisfied by existing road traffic, railway traffic, etc., which will inevitably bring about serious traffic congestion problems. With the advent of innovative new aerial vehicles, such as electric vertical take-off and landing (eVTOL) aircraft and unmanned aerial vehicles (UAV), the Urban Air Mobility (UAM) concept emerges for safe and efficient flight operation at a high automation level in metropolitan airspace. These eVTOLs and UAVs play an important role in low-altitude UAM operation in missions such as parcel delivery, passenger transportation, medical emergency, and surveillance, to name a few [2], which introduces new challenges for air navigation service providers (ANSP) to manage an already convoluted airspace.

UAM operations are designed to achieve high-level autonomous operations in high-density airspace, and Unmanned Aircraft System (UAS) is expected to perform beyond-visual-line-of-sight (BVLOS) operations, which have brought great challenges to the conventional Air Traffic Management (ATM) system. To this end, a new concept of UAS Traffic Management (UTM) was proposed by NASA in 2014 [3] and several preliminary projects have been carried out to explore low-altitude UAS operation requirements and technical capabilities [4]–[7]. The UTM concept envisages providing a complementary infrastructure to the current ATM system by creating dedicated airspace and procedures for UAS operations, as well as facilitating information sharing among different stakeholders [8]. The European Aviation Safety Agency (EASA) also developed a concept of U-space in which a set of services and procedures were defined relying on a high level of digitalization and automation of functions to manage UAS traffic [9], [10]. The regulation of U-space created a new type of airspace, U-space airspace, which is a dedicated geographical zone for UAS where UAS operations are only allowed to take place with the support of U-space services [11]. At this stage, all UAS flights are required to operate in segregated airspace which means separated from crewed aircraft to ensure safety. Bauranov and Rakas [12] reviewed several state-of-the-art abstract airspace networks idealized from literature with emphasis on various aspects and found that the airspace structure has a great influence on the level of safety, efficiency, and capacity of airspace. Jang et al. [13] designed three airspace structures for UAS traffic flows for urban areas namely Sky-lane, Sky-tube, Sky-corridor with different level of freedom for flight trajectory. Several varieties of each airspace structure were compared in terms of space use, simplicity, performance, and robustness and each of the designs showed both pros and cons in different aspects. Labib et al. [14] introduced a multi-layer network airspace structure based on the Erdős – Rényi random graph model and optimized the traffic for minimizing total travel time and minimizing total energy consumption respectively. With a focus on the UTM airspace structure, Sacharny et al designed a lane-based air route layout for UAS operations and proposed a corresponding

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flight strategic deconfliction method based on the lane-based structure [15]. Their subsequent research investigated the lane-network performance and tactical deconfliction protocol to handle dynamic contingencies [16]. Pang et al. [17] proposed an AirMatrix airspace configuration with different resolutions together with UAV operational rules. The airspace structures and adapted operating rules proposed by these scholars further make UAS operation possible. However, different airspace structure designs require different infrastructure and operating procedures, which will also correspond to different operating efficiencies. Changing the airspace structure to improve operational efficiency means huge construction costs. Therefore, this paper proposes a general operational model that can improve the operational efficiency of airspace without changing the structure from a network perspective.

The main contribution of this work is to address the traffic efficiency problem of UAS operation in specified airspace which is modeled as a weighted network of nodes and edges named Urban Air Traffic Network (UATN). Both global efficiency and local efficiency of the UATN are investigated under several common flight speed distributions assigned to airways. To further explore the optimal flight speed distribution of the network, we set the initial weights of airways equal and introduced a method to randomize the distribution of network weights to observe the change of network efficiency with the degree of randomization.

The remainder of this paper is as follows. In Section II, two types of UATN structures are described as the generalized topology network and the dual topology network. The efficiency between a pair of nodes in both topology networks is defined and the weight redistribution process is introduced. The setup of experiments is presented in Section III as well as the discussion of results. Section IV resumes the contribution of this paper and the future research perspectives.

II. Urban Air Traffic Network Efficiency

A. Urban Air Traffic Network Model

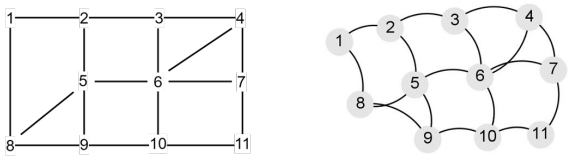
UAM is expected to conduct high-density autonomous flight operations which makes it impractical for ANSPs to provide tactical air traffic control services to every eVTOL aircraft. Therefore, it is particularly important to design airways and determine the flight speed of each flight segment in advance to ensure safety and efficiency. Inspired by common urban road construction designs of grid layout and circular radial layout, most airspace configurations in the literature are designed as regular structures to reduce complexity [12], [13], [15], [17]. There are two ways to abstract the road structure into a complex network graph structure. The most commonly used network topology method is to directly abstract the physical network, that is, to build a generalized topology network graph with airways as edges and intersections as nodes. This method is quite straightforward and less complicated as shown in Fig. 1, taking airway segments as edges with speed weights assigned to each segment. Since the edge is extracted in units of airway segments instead of the whole airway with the same name, the aircraft need to adjust speed along with the edge weight when traveling on the same airway. The other method is to establish a dual graph of the original physical network as shown in Fig. 2, where airways are taken as nodes and the cross-connection relationship of airways as edges. Compared with the generalized topology network topology, the dual topology can be used to analyze the network structure and its influence on the network function, and can further be used to analyze the connection relationship between airways, the traffic characteristics of the flight routes, the connectivity, reliability, and importance of the airways in the entire network. In the dual topology network, the weight of an airway keeps constant regardless of its length and number of intersections with other airways. We explore the network efficiency with different weight distributions on both network constructions. A weighted urban air traffic network with *n* nodes and *m* edges can be expressed as follows:

$$G = (V, E, W) \tag{1}$$

Where $V = \{v_1, v_2, \cdots, v_n\}$ is the node set representing intersections in the generalized topology network and airways in the dual topology network, and $E = \{e_1, e_2, \cdots, e_m\}$ is edge set representing airway segments in the generalized topology network and intersections of airways in the dual topology network. The network is designed as an undirected network assuming each airway goes in both directions and a pair of airways are connected in both ways. $W = \{w_1, w_2, \cdots, w_m\}$ is the weight set of each edge.

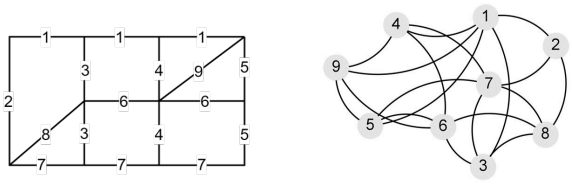
B. Network Efficiency

In traditional network research, the average shortest path length and clustering coefficient are used to describe the global properties and local characteristics of the network, but these two parameters require the network to be unweighted and sparsely connected. Latora et al. [18] proposed a new characteristic parameter, network efficiency, to describe the effectiveness of information dissemination on the network. Network efficiency applies not only to weighted networks but also does not require the network to meet the necessary conditions of connectivity and sparsity. In the study of network efficiency of different network topologies, Latora et al. found that regular networks have higher local efficiency and lower global efficiency, random networks have higher global efficiency and lower local efficiency, while small-world networks are both globally and locally efficient. This shows that the parameter of network efficiency can be a good substitute for



(a) Original network (b) Generalized topology network

Fig. 1. Generalized topology network: intersections are numbered as nodes.



(a) Original network (b) Dual topology network

Fig. 2. Dual topology network: airways are numbered as nodes.

the average path length and clustering coefficient in measuring the properties and functions of the weighted network. Network efficiency e_{ij} between two nodes $\{v_i, v_j\}$ is defined as the reciprocal of the distance d_{ij} between them, and the distance depends on the weight of the edge between the two nodes [18].

$$e_{ij} = \frac{1}{d_{ij}} \tag{2}$$

In an unweighted network, the distance d_{ij} between two nodes refers to the number of edges from v_i to v_j which measures the shortest path length between these two nodes. If two nodes are directly connected, the distance between them is 1. If the two nodes are not directly connected, but are connected with one intermediate node between them, then the distance is increased by 1. If two nodes are not connected by a path, then the distance is infinite. For weighted networks, there are two types of weights according to their physical meaning: similarity weight and dissimilarity weight. The difference between dissimilarity weight and similarity weight directly affects the definition of the shortest path length of the network. For dissimilarity weight, the greater the weight, the farther the distance between two nodes is, and the distance is proportional to the weight, so the distance can thus be measured directly by the sum of the weights of the edges connecting these two nodes. Suppose v_i and v_j are connected through v_k, and the path through v_k from v_i to v_j is considered as the shortest one, then the distance between v_i and v_j with dissimilarity weight is defined as:

$$d_{ij}^{dis} = w_{ik} + w_{kj} \tag{3}$$

However, the similarity weight is just the opposite. A larger similarity weight means a closer relationship between the two nodes and easier to reach each other. The distance between v_i and v_j through v_k with similarity weight is defined as [19]:

$$d_{ij}^{sim} = \frac{w_{ik}w_{kj}}{w_{ik} + w_{kj}} \tag{4}$$

Where w_{ik} is the weight of the edge between v_i and v_k. In UATN, we are more concerned about the time it takes for an eVTOL or UAV to travel from one location to another. The shorter the time, the higher the efficiency of the path. Under the condition that the flight performance is satisfied and the airspace resources allow, the aircraft prefer to choose the shortest path to fly. If the airspace resources are not sufficient, the shortest path may not be the best choice. This needs to be addressed as a path optimization problem which is out of the scope of this work. We assume that all aircraft follow the shortest path in UATN operation. As the path length between two geographical locations is fixed, the flight time is determined by flight speed. In the generalized topology network, the flight speed on each airway segment is assigned to the corresponding edge as a weight, and greater weight comes with lower flight time and higher efficiency between the pair of nodes connected by that edge. In the dual topology network, the flight speed on each airway is assigned to the corresponding node as a weight, and the weight of the edge between two connected nodes reflects the average speed from one airway to the other, so the weight of the edge is calculated as the harmonic mean of the weights of the two nodes:

$$w_{ik} = \frac{2w_i w_k}{w_i + w_k} \tag{5}$$

Where w_i and w_k represent the weight assigned to node v_i and v_k respectively. It is easy to see that the weight of the edge is positively correlated with the efficiency of the path through this edge, however, the weight can not be treated as similarity weight directly as in [19]. Because it is believed in the literature that in the case of similarity weights, assuming that all edge weights are positive, the more edges the path passes, the smaller the distance of the path, which is inconsistent with the network model in this paper. In UATN, the distance between two nodes represents the time it takes to travel from one node to another in the generalized topology network and to transfer from one airway to another in the dual topology network. In both cases, when the weight on a route increases, the distance will of course decrease. However, if the number of edges that the shortest path needs to pass through increases, even if the weights on these edges are positive, the distance between the two nodes will increase accordingly. Hence the distance of a path between v_i and v_j connected through v_k is defined as:

$$d_{ij} = \frac{w_{ik} + w_{kj}}{w_{ik}w_{kj}} \tag{6}$$

The efficiency of a path between two nodes in the generalized topology network is the multiplicative inverse of the travel time of an aircraft from one location to another location in the network:

$$e_{ij} = \frac{w_{ik}w_{kj}}{w_{ik} + w_{kj}} \tag{7}$$

And the efficiency of a path between two nodes in the dual topology network represents the ability of an aircraft to perform transitions from a location on one airway to a location on another airway:

$$e_{ij}^{*} = \frac{2w_i w_j w_k}{(w_i + w_j)w_k + 2w_i w_j} \tag{8}$$

As e_{ij} represents the efficiency between a pair of nodes, the global efficiency of the network is obtained by averaging the efficiency of all node pairs in the network:

$$E_G = \frac{1}{n(n-1)} \sum_{i \neq j} e_{ij} \tag{9}$$

The local efficiency of a node v_i is the average global efficiency of the subnetwork induced by the neighbors of the node denoted as E_{G_i}, and the average local efficiency is the average of the local efficiencies of each node which can be given as:

$$E_L = \frac{1}{n} \sum_{i \in G} E_{G_i} \tag{10}$$

The local efficiency quantifies the resistance of the network to small-scale faults. If the local efficiency of the network is high, it means that it is not sensitive to small-scale faults and the network has compensatory capabilities. The global efficiency is an approximation of the average path length of the network, while the local efficiency is an approximation of the clustering coefficient, and the average local efficiency is the first-order approximation of the average clustering coefficient.

C. Weight Distribution

Regular networks have higher local efficiency and lower global efficiency, random networks have higher global efficiency and lower local efficiency, while small-world networks are globally and locally efficient. The problem addressed here is how to make the urban airspace designed according to the regular network show a small-world effect while keeping the original topological structure unchanged, that is, have a large global efficiency and a large local efficiency at the same time. When the network structure of a weighted network is determined, the efficiency of the network is affected by the weights in the network, and the efficiency of the network will change with different weight distributions. We experimented with five common weight distribution forms on regular networks while keeping the total weight of the network unchanged, namely uniform distribution, normal distribution, Poisson distribution, power-law distribution, and exponential distribution.

D. Weight Randomization

In order to further explore the impact of weight distribution on network efficiency, we assign the same initial weight to all edges in the generalized topology network (nodes in the dual topology network) and generate different weight probability distributions by dynamically adjusting the randomization probability. A weight randomizing method was introduced in [20] in which two edges with different weights are selected randomly and then their weights are exchanged with each other. The process is repeated multiple times until termination is triggered. The weight exchange converted the mapping of edges and edge weights, however did not change the overall distribution of weights all over the network, so we need to find another way to distribute the weights differently. We apply a similar method of constructing a WS small-world network [21] to randomly distribute weights. The specific process in the generalized topology network is as follows:

- Assign the same initial weight to all edges as w;
- Divide the weight of each edge into $w/\triangle w$ equal parts;
- Each unit of weight $\triangle w$ is removed with probability p from an original edge and reallocated randomly to an edge chosen from the network which is possible to be the same edge as the original one;
- Repeat the previous step to traverse all edges in the entire network;
- The randomization process is continued until each unit of weight has been considered once. To be noted, if the unit of weight is the only unit of weight on an edge, it will be skipped to avoid disconnecting the edge.

Similar process in the dual topology network is shown as follows:

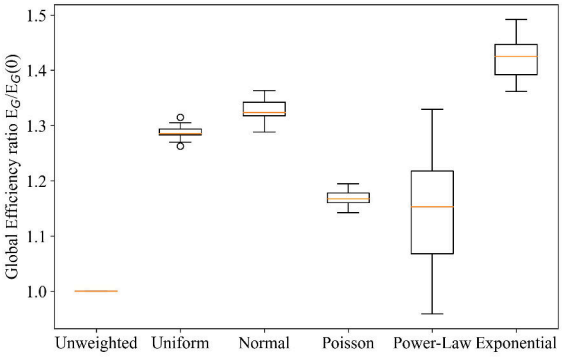
- Assign the same initial weight to all nodes as w;
- Divide the weight of each node into $w/\triangle w$ equal parts;
- Each unit of weight $\triangle w$ is removed with probability p from an original node and reallocated randomly to a node chosen from the network which is possible to be the same node as the original one;
- Repeat the previous step to traverse all nodes in the entire network;
- The randomization process is continued until each unit of weight has been considered once. To be noted, if the unit of weight is the only unit of weight on a node, it will be skipped to avoid turning the node into a senseless one.

In the process of randomizing the weights, the connections of the nodes do not change, but the distribution of weights in the network does. The efficiency of the network changes with the weight distribution, which allows us to improve the network efficiency by adjusting the weight distribution while maintaining the topology of the network.

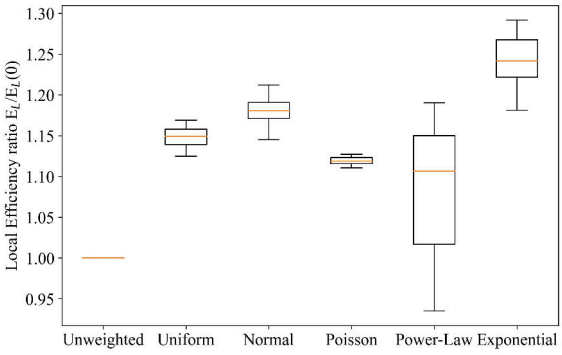
III. Experiments and Analyses

A. Scenario construction

The UATN is constructed with both generalized topology and dual topology to experiment with the impact on network efficiency of edge weight and node weight respectively. In the generalized topology network, five different distributions of flight speed values are generated, namely, uniform distribution, normal distribution, Poisson distribution, power law distribution, and exponential distribution. Each speed value is assigned to each edge as a weight, which is used to calculate the efficiency between each pair of nodes. Then we calculate the network global efficiency and average local efficiency and compare them with the equal-weighted network in which the weight of each edge is set to the same value. The equal-weighted network can be converted to an unweighted network after weight normalization and the efficiency is equivalent to that in an unweighted network. Same scenario is applied when experimenting with the dual topology network in which the flight speed value is assigned to each node as node weight, and the weight of an edge connecting a pair of nodes is derived from the weight of both nodes. Then we started with the equal-weighted network and adopted the weight randomization method to explore more weight distribution probabilities.

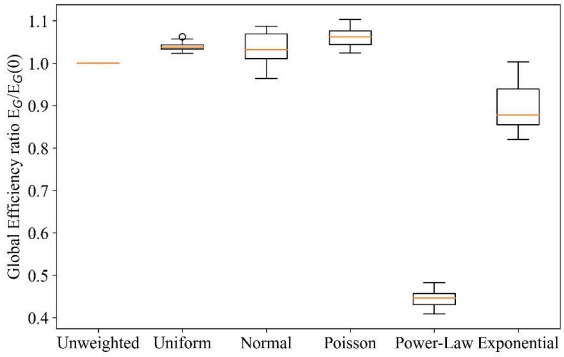


(a) Global efficiency

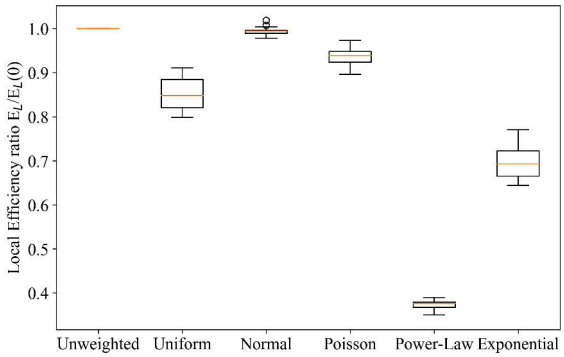


(b) Local efficiency

Fig. 3. Network efficiency of the generalized topology network with edge weight redistribution: E_G and $E_G(0)$ represent the global efficiency of weight distributed network and equivalent unweighted network respectively; E_L and $E_L(0)$ represent the average local efficiency of weight distributed network and equivalent unweighted network respectively.



(a) Global efficiency



(b) Local efficiency

Fig. 4. Network efficiency of the dual topology network with node weight redistribution: E_G and $E_G(0)$ represent the global efficiency of weight distributed network and equivalent unweighted network respectively; E_L and $E_L(0)$ represent the average local efficiency of weight distributed network and equivalent unweighted network respectively.

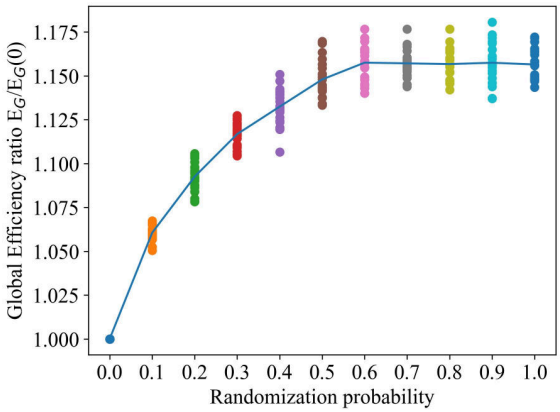
B. Parameters setting

The UATN is considered as a regular network with a network size of 500 nodes, each node is connected with 10 other nodes, hence there are a total of 2500 edges in the network. In the generalized topology network, the average edge weight is set to 5, and the different edge weight distributions of 12500 in total over 2500 edges are investigated. Then the weight randomization method is applied to the equal-weighted network in which each edge weight is set as 5. The randomization probabilities range from 0.1 to 1 in 0.1 intervals so that ten weight distributions of different randomization probabilities are explored. As the total edge weight changes with the node weight distribution in the dual topology network, we take the total node weight as the network weight to be consistent within each node weight distribution. The average node weight is set to 5 and different node weight distributions of 2500 in total over 500 nodes are studied. The weight randomization processes are the same as in the generalized topology network except that the initial weight of 5 is set to each node.

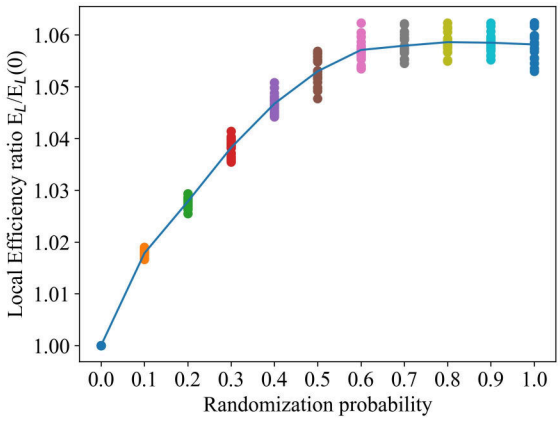
C. Analyses of results

In this experiment, each trial is performed 20 times randomly, and the global efficiency and average local efficiency of the network are recorded for each trial. Fig. 3 reveals that in the generalized topology network, both global and local network efficiency are improved with all the five weight distributions among which the exponential distribution of edge weights performs the best. The power-law distribution has a positive impact on the efficiency however performs not as stable as the other four distributions because the edge weights of the power-law distribution change significantly with each random weight redistribution trial. Although different weight distributions bring notable improvements in the efficiency of the generalized topology network, it is not obvious in the dual topology network. In the dual topology network, the uniform distribution, normal distribution, and Poisson distribution have a small improvement in global efficiency, while the power-law distribution greatly reduces network efficiency both globally and locally. The reason is that the power-law weight distribution leads to most slow airways and a few very fast airways which prevents the aircraft from traveling smoothly. Fig. 4 also shows all distributions have a negative influence on the network local efficiency, further illustrating that it is better to set different flight speeds segment by segment than to maintain the same speed for the entire airway.

The results of the weight randomization experiments show that the global network efficiency is improved for both the

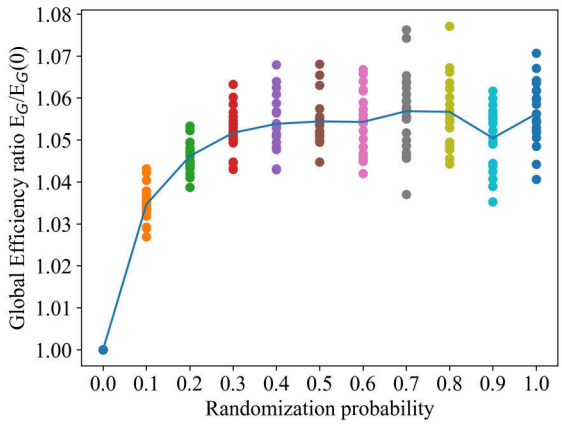


(a) Global efficiency

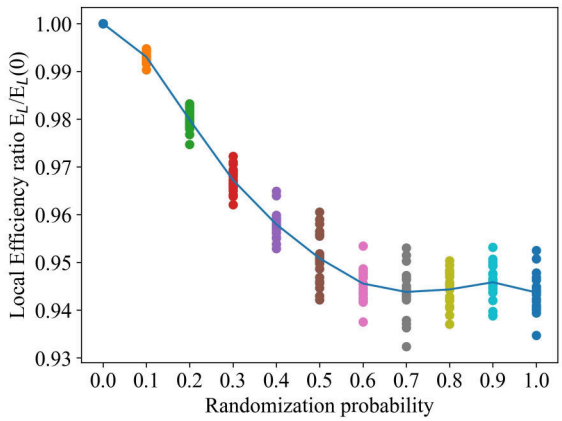


(b) Local efficiency

Fig. 5. Network efficiency of the generalized topology network with edge weight randomization: $E_G(0)$ and E_G represent the global efficiency of the network before and after weight randomization respectively; $E_L(0)$ and E_L represent the average local efficiency of the network before and after weight randomization respectively.



(a) Global efficiency



(b) Local efficiency

Fig. 6. Network efficiency of the dual topology network with node weight randomization: $E_G(0)$ and E_G represent the global efficiency of the network before and after weight randomization respectively; $E_L(0)$ and E_L represent the average local efficiency of the network before and after weight randomization respectively.

generalized topology network and the dual topology network, but the local efficiency shows the opposite effect as is shown in Fig. 5 and Fig. 6. In the generalized topological network, the global efficiency and local efficiency increase with increasing randomization probability, reaching a steady state around the probability of 0.6 and randomized weights improve global efficiency more than local efficiency. This is because the global efficiency of the UATN as a regular network is relatively small and has much room for improvement, while the local efficiency is already large. Fig. 6 indicates that in the dual topological network, as the probability of randomization increases, the global efficiency shows an increasing trend, while the local efficiency shows the opposite. Improvement in global efficiency comes at the expense of local efficiency indicating that the randomization of node weights cannot improve global efficiency and local efficiency at the same time, that is, the flight speed of the segments on both sides of the airway intersection needs to be adjusted separately to obtain the maximum benefit of the entire network. Additionally, even though randomizing the weights in the dual topology network can improve the global network efficiency, the improvement is not as significant as that of the generalized topology network, and in 20 random experiments, the improvements in the dual topology network are unstable and have a large variance.

IV. Conclusions

This paper investigated the impact of flight speed distribution on global and local efficiency in both generalized and dual topology network models. The experimental results show that the flight speed redistribution on edges in the generalized topology network performs a great improvement on the network efficiency which provides an idea of optimizing the network operation while keeping the network structure unchanged and no extra cost of airspace resources introduced. Comparison of weight randomization between the generalized topology network and the dual topology network illustrates that the adjustment of flight speed should be carried out segment by segment instead of airway by airway. This provides a reference for stakeholders to utilize advanced aircraft

maneuverability to control flight speeds, with potential benefits in reducing energy consumption and noise pollution.

The urban air traffic network considered in this work is a regular network model. However, the actual network may not reach the ideal regular state and the impact of flight speed distribution in networks with different physical structures on efficiency needs to be further explored. In addition, by combining different flight speed distributions and launch and landing locations of aircraft, the optimal flight path planning problem for the aircraft is to be addressed in the following research.

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