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A Flow-based Flight Scheduler for En-route Air Traffic Management

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Abstract: This paper addresses a network-wide scheduling problem for generating, adjusting and optimizing flight schedules in en-route airspace. The aim of scheduling is twofold: to support flight plans by providing flight schedules reliable on optimal flow restrictions; and to assist en-route traffic control by ensuring safe and ordered trajectory of traffic. Firstly, we design an algorithm to generate continuous-time flight schedules based on discrete-time flow assignments of aircrafts. This algorithm is further enhanced with consideration of sequence optimization for merging traffic. A flight scheduling system has been developed in a simulation environment.

Keywords: air traffic flow management; scheduling; sequencing; en-route traffic control; simulation

1. INTRODUCTION

With trade liberalization and globalization of air services, air traffic is boosted by strong growth of air transport over the past decades. The demand for use of limited resources in Air Traffic System (ATS) spurred by frequent airborne movements may increase beyond acceptable range. In the case that traffic volume exceeds capacity of the traffic system, delays and traffic congestion would arise (C. Gwiggner and S. Nagaoka, 2010). Air Traffic Flow Management (ATFM) is a problem of optimization of resource allocation to manage capacity-demand imbalances in airspace and airports (V. Tošic et al., 1995). Recently, the ATFM related research is focusing on: the optimization problem for the multiple airports network (D. Sun and A.M. Bayen, 2008, D. Bertsimas et al., 2011); and the predictive models with regards to stochastic capacity profiles, e.g. weather conditions (S. Wang, 2009, D. Bertsimas and S.S. Patterson, 2000). Such research at present reflects the capability of ATFM to handle complexity and uncertainty in a large-scale system. At the same time, the network-wide ATFM become more significant. The International Civil Aviation Organization (ICAO) encourages ATFM to establish collaborative decision-making between multiple operators (airports, airlines, air service provider and manufacturer) and multiple operational levels (local, regional and global) (ICAO, 2014). Flow management is strongly required to collaborate with flight plan from both strategic and operational perspectives (C. Gwiggner and S. Nagaoka, 2010). An example of the collaboration is flight scheduling, which is to decide when and where aircrafts will fly. This gives rise to a research problem: how the flow management strategies assist air traffic managers to plan and operate flight schedules?

Fight scheduling using traffic flow techniques has been developed in past research, which refers to the topic of "traffic flow scheduling". Such research on the optimal scheduling problem employs different approaches to formula the scheduling model, e.g. integer linear programming (J. Rios and K. Ross, 2010), mixed integer linear programming (A.D. Aspremont and L.E. Ghaoui, 2007), and mixed non-linear integer programming (S. Yan et al., 2007). On the other hand, the flow model have a common feature: the flow variables are discrete space–discrete time aggregated (D. Sun and A.M. Bayen, 2008). The scheduling is inherently to assign flows for the number of aircrafts that can fly within a certain link/sector at a given time. Such flows obtained cannot directly be applied in practice for flight planner. We need a method to discompose the aggregated flows into individual, time-spatial continued flights.

The disaggregation problem is solved by an algorithm that decomposes the flows into arc chains, each of which represents an aircraft's route (R. Ahujanti and J. Orlin, 1993). The idea is essentially to do a routing which generates paths for individual flights in accordance with flow assignments. This algorithm is also adapted by other researchers to solve the flow disaggregation problem (S. Yan and H.F. Young, 1996, C.H. Tang et al., 2008). At the same time, a study for rerouting management proposes a random heuristic method combined with Integer Programming Packing Formulation to generate non-aggregated individual flight paths (D. Bertsimas and S.S. Patterson, 2000). There is not a routing but also a scheduling process, so that the routes generated meet scheduling constraints, e.g. departure time is less than or equal to scheduled departure time. Although the target of disaggregation is achieved, these two methods mentioned above have limitations: 1. the solution is not unique due to the randomness of routing: it may result in different routes; 2. the solution may not be reliable because it merely considers the flow and OD constrains, where the operational aspects of aircrafts, e.g. separation, speed and sequence, are ignored.

Against the background, this paper is motivated. Here we focus on a flight scheduling problem for generating, adjusting and optimizing flight schedules in en-route space, which is implemented into two phases. Firstly, a scheduling algorithm is developed to generate a set of time-spatial continuous individual flights from aggregated aircraft flows. The second phase is concerned with schedule adjustment and optimization, for a special case: merging sequence. En-route traffic control

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is to maintain safe and ordered trajectory of aircrafts. In this sense, this paper is meaningful for providing flight planner optimal flow-based flight schedules, as well as assisting en-route traffic controller to maintain safe and ordered trajectory of traffic.

Compared with the mentioned methods for flow disaggregation, our scheduling method is enhanced with operational feasibility, i.e. how to allocate time separations and how to order the sequence for aircrafts flying within a link. Technological contributions include: solve the randomness resulted from path dispatching; and avoid the solution not unique through optimal techniques for merge sequencing.

The rest of this paper is organized as follows. Section 2 describes the scheduling algorithms for generating the flow-based schedules. Section 3 presents the part of scheduling adjustment and optimization, especially for merging sequence. Section 4 includes a simulation case with a series of scenarios for illustrating the effect of scheduling. Finally, conclusions are drawn in Section 5.

2. SCHEDULE GENERATION

2.1 Preliminaries and scheduling solution

The en-route traffic network can be represented by basic elements, i.e. nodes (airports and waypoints) and links (J. Härri et al., 2009). The flight schedule is scoped in the en-route airspace, excluding departure/arrival time slots on ground. Thus, the airports are simplified as nodes, referring to the origin/destination of a flight route.

The input for scheduling is traffic flow rate, which is assumed from a general flow model. Each flow rate represents the number of aircrafts that can fly within a link at a given time. The flow is directional, and defined as

$$\{F_{ij} = (j_1, j_2, j_3, f_{ij}) | i = 1,2,\cdots,n, j = 1,2,\cdots,m\}. \quad (1)$$

It means that the value f_{ij} of aircrafts coming from node , will fly over node N_{j_2} toward node N_{j_3} at time step T_i. Fig.1. gives an example for illustration: the left table lists the directions of all flow rates each with a format "from…via…to…", where the number in the table refers to the node ID, and the node with ID -1 refers to the airport; and the right table is a matrix of values of flow rates, where *j* is flow ID and *i* is time step ID.

F_{ij}; $i = 1,2,\cdots,n$ →; ↓ $j = 1,2,\cdots,m$

j_1	j_2	j_3	f_{ij}				
-1	1	3	2	0	0	0	0
-1	2	3	3	0	0	0	0
1	3	4	0	2	0	0	0
2	3	4	0	3	0	0	0
3	4	5	0	0	2	0	0
3	4	6	0	0	3	0	0
			T_1	T_2	T_3	T_4	T_5

Fig. 1.Input flows.

The output is flight schedules, each of which includes the sequence of nodes along the aircraft's path also the time stamps at which the aircraft reaches these nodes. The scheduling is executed by two steps: firstly, an algorithm is used to dispatch aircrafts, i.e. to discompose aggregated flows into individual aircraft routes; and then another algorithm is used to allocate times for each aircraft passing its route, where schedules are achieved and time-separation between flying aircrafts is near-uniform distribution.

2.2 Algorithm for route dispatching

For each aircraft, it departs from its origin, flies over the air traffic network via certain waypoints and finally reaches the destination. Route dispatching is to pick up available aircrafts from aggregated flows, meanwhile dispatching them to corresponding routes, until all flow restrictions are satisfied. The key notations are listed as below:

- $P_k(o_k, d_k, f_k)$: The aircraft with origino_k, destination d_k, and the last node it flies over is f_k.
- $R_k = \{R_{k,1}, R_{k,2}, R_{k,3}, \cdots\}$: The route of P_k, where $R_{k,l}$ is a node it passes.
- Q_{j_2}: The queue on the node N_{j_2}, i.e. a waiting list to record the aircrafts available to be dispatched.
- D_{j_3}: the destinations of flights passing node N_{j_3}.

The flowchart for algorithm is described in Fig.2. The algorithm iteratively executes a dispatching process beginning from T_1 and moving forward to end of time steps. In the flowchart, a part high-lighted by dish lines refers to the one-time dispatching at T_i . To satisfy the flow rate $F_{ij} = (j_1, j_2, j_3, f_{ij})$, the system needs to dispatchf_{ij}aircrafts from the node N_{j_2} to the nodeN_{j_3}. All aircrafts will experience three states, i.e. taking-off, flying and landing, to finish the dispatching:

- $j_1 = -1$: aircrafts (f_{ij}) are generated from the node N_{j_2} , and joint the queue on the node N_{j_3} . Each aircrafts$P_k(o_k, d_k, f_k)$is initialized as $o_k = j_2, f_k = j_2, R_k = \{j_2\}$, i.e. it starts at the nodeN_{j_2}.
- $j_3 = -1$: aircrafts (f_{ij}) coming from the node N_{j_1} land on the node N_{j_2}. Each aircrafts$P_k(o_k, d_k, f_k)$is finalized as $R_k = R_k \cup \{d_k\}$, i.e. it reaches the destination N_{j_2}.
- $j_1 \neq -1, j_3 \neq -1$: aircrafts (f_{ij}) coming from the node N_{j_1} joint the queue on the node N_{j_3} . Each aircrafts $P_k(o_k, d_k, f_k)$ is updated as $f_k = j_2, R_k = R_k \cup \{j_2\}$, i.e. it passes the node N_{j_2}.

If $j_1 \neq -1, j_3 \neq -1$, suppose that the subset Q_{j_1,j_2,j_3} denotes the aircrafts $\{P_k(o_k, d_k, f_k)\} \subseteq Q_{j_2}$ that come from the node $N_{j_1}(f_k = j_1)$ and can fly to the node $N_{j_3}(d_k \in D_{j_3})$:

$$Q_{j_1,j_2,j_3} = \{P_k(o_k, d_k, f_k) \in Q_{j_2} | f_k = j_1, d_k \in D_{j_3}\}. (2)$$

$\|Q_{j_1,j_2,j_3}\|$ is the number of aircrafts in Q_{j_1,j_2,j_3}. If $\|Q_{j_1,j_2,j_3}\| \geq f_{ij}$, the first f_{ij}aircrafts in Q_{j_1,j_2,j_3} will be dispatched from Q_{j_2} to Q_{j_3}.