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<td><strong>Author(s)</strong></td>
<td>Li, Qing; Zhang, Yicheng; Su, Rong.</td>
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A Flow-based Flight Scheduler for En-route Air Traffic Management

Qing Li*, Yicheng Zhang**, and Rong Su**

*Air Traffic Management Research Institute, Nanyang Technological University, Singapore 639798.
(e-mail: liqing@ntu.edu.sg)

**School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798.
(e-mails: yzhang088@e.ntu.edu.sg, rsu@ntu.edu.sg)

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.

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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. Tošić 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 decompose 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
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. Härry 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

\[ \{F_{ij} = (j_1, j_2, j_3, f_{ij})| i = 1,2, \ldots ,n; j = 1,2, \ldots ,m \}. \] (1)

It means that the value \( f_{ij} \) of aircrafts coming from node \( i \) will fly over node \( j \) toward node \( N_j \) 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 \( F_{ij} \) coming from the node \( i \), the system needs to dispatch \( f_{ij} \) aircrafts from the node \( N_j \) to the node \( N_k \). All aircrafts will experience three states, i.e. taking-off, flying and landing, to finish the dispatching:

- \( f_{1j} = -1 \) : aircrafts \( f_{ij} \) are generated from the node \( N_j \), and joint the queue on the node \( N_j \).
- \( f_{3j} = -1 \) : aircrafts \( f_{ij} \) are joining the queue on the node \( N_j \).
- \( f_{1j} \neq -1, f_{3j} \neq -1 \) : aircrafts \( f_{ij} \) are finalization as \( f_{ij} = j_2, f_k = j_2, F_k = \{ j_2 \} \), i.e. it starts at the node \( N_{f_k} \).

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 dispatch \( f_{ij} \) aircrafts from the node \( N_{j_2} \) to the node \( N_{j_3} \). All aircrafts will experience three states, i.e. taking-off, flying and landing, to finish the dispatching:

- \( f_{1j} = -1 \) : aircrafts \( f_{ij} \) are generated from the node \( N_j \), and joint the queue on the node \( N_j \).
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- \( f_{1j} \neq -1, f_{3j} \neq -1 \) : aircrafts \( f_{ij} \) are finalization as \( f_{ij} = j_2, f_k = j_2, F_k = \{ j_2 \} \), i.e. it starts at the node \( N_{f_k} \).

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\[ Q_{j_3} = \{P_k (o_k, d_k, f_k) \mid Q_{j_2}(f_k = j_1, d_k = D_{j_3})\}. \] (2)

\[ |Q_{j_3}| \] is the number of aircrafts in \( Q_{j_3} \). If \[ |Q_{j_3}| \geq f_{ij} \), the first \( f_{ij} \) aircrafts in \( Q_{j_3} \) will be dispatched from \( Q_{j_2} \) to \( Q_{j_3} \).
Else $j_3 = -1$, suppose that the subset $Q_{j_1,j_2,-1}$ denotes the aircrafts ($P_k(o_k,d_k,f_k) \subseteq Q_k$) that come from the node $N_{j_1}(f_k = j_1)$ with destination to the node $N_{j_2}(d_k = j_2)$:

$$Q_{j_1,j_2,-1} = \{P_k(o_k,d_k,f_k) \in Q_{j_1} | f_k = j_1, d_k = j_2 \}. \quad (3)$$

$$\|Q_{j_1,j_2,-1}\|$$ is the number of aircrafts in $Q_{j_1,j_2,-1}$. If $\|Q_{j_1,j_2,-1}\| \geq f_{ij}$, the first $f_{ij}$ aircrafts in $Q_{j_1,j_2,-1}$ will be removed from $Q_{j_2}$ and landed on the node $N_{j_2}$.

It is known that $P_k$ passes $N_{R_k,l}$ due to a flow rate $F_{ij} = (j_1,R_{k,l},j_3,f_{ij})$ at time $T_i$. Denote $\lambda_{i,R_{k,l}}$ as the summary of all flow rates via $N_{R_{k,l}}$ during the time interval $[T_i,T_{i+1}]$ as

$$\lambda_{i,R_{k,l}} = \sum_{(j_1,R_{k,l},j_3,f_{ij})} f_{ij}. \quad (6)$$

Thus, there are $\lambda_{i,R_{k,l}}$ aircrafts pass the node $N_{R_{k,l}}$ during the time interval $[T_i,T_{i+1}]$, and all these $\lambda_{i,R_{k,l}}$ aircrafts are in the queue $Q_{R_{k,l}}$ at the time $T_i$. The target of the scheduling is to control these $\lambda_{i,R_{k,l}}$ aircrafts passing the node $N_{R_{k,l}}$ with a uniform time separation. In that way, the aircrafts of same type flying on the same level can keep uniform distribution with each other. Such separation is good for safety control, as well as to avoid traffic congestion. However, this is a quite ideal situation and is hardly achieved in reality. Alternatively, a near-uniform separation calculation is proposed as follows.

A time separation is determined as

$$S_{i,R_{k,l}} = \frac{T_{i+1} - T_i}{2\lambda_{i,R_{k,l}}} \quad (7)$$

The $x$-th aircraft passes the node $N_{R_{k,l}}$ at time

$$T_i + (2x - 1)S_{i,R_{k,l}} \quad (8)$$

Referring to Fig.3, we have

- A time separation $S_{i,R_{k,l}}$ is added between the first aircraft and the aircraft ahead,
- A time separation $S_{i,R_{k,l}}$ is added between the last aircraft and the aircraft behind, and
- A time separation $2S_{i,R_{k,l}}$ is set between two aircrafts.

Notice that in Fig.3

- During time interval $[T_{i-1}, T_i]$, $\lambda_{i-1,R_{k,l}}$ aircrafts pass the node $N_{R_{k,l}}$, and the last time separation is $S_{i-1,R_{k,l}}$.
- During time interval $[T_i, T_{i+1}]$, $\lambda_{i,R_{k,l}}$ aircrafts pass the node $N_{R_{k,l}}$, and the first time separation is $S_{i,R_{k,l}}$.
- During time interval $[T_{i+1}, T_{i+2}]$, $\lambda_{i+1,R_{k,l}}$ aircrafts pass the node $N_{R_{k,l}}$, and the first time separation is $S_{i+1,R_{k,l}}$.

As such, during time interval $[T_i, T_{i+1}]$,

- The time separation between the first aircraft and the aircraft ahead is $S_{i-1,R_{k,l}} + S_{i,R_{k,l}}$ and
- The time separation between the last aircraft and the aircraft behind is $S_{i,R_{k,l}} + S_{i+1,R_{k,l}}$.

Considering a special case, where $\lambda_{i-1,R_{k,l}} = \lambda_{i,R_{k,l}} = \lambda_{i+1,R_{k,l}}$, we have $S_{i-1,R_{k,l}} = S_{i,R_{k,l}} = S_{i+1,R_{k,l}}$. It means that all aircrafts

Fig. 2 Flowchart of dispatching algorithm.

Notice that, an initialization for Origin-Destination (OD) is needed, after an aircrafts $P_k$ is generated (i.e. taking-off),

$$f_k = o_k, R_k = \{o_k\}. \quad (4)$$

Node $N_{j_1}$ has a list of destinations $D_{j_1}$, each of which refers to the destination of a flight passing this node. In the flowchart, $D_{j_1}$ is used for enabling aircrafts satisfy their OD constraints. For example, an aircrafts $P_k(o_k,d_k)$ can fly to the node $N_{j_1}$ if and only if its destination is in $D_{j_1}$, i.e. $d_k \in D_{j_1}$. Using this way, the dispatching algorithm, compared with the previous method (D. Bertsimas and S.S. Patterson, 2000), eliminates the randomness of routing.

2.3 Algorithm for scheduling

After dispatched, each aircraft $P_k$ has a route $R_k = \{R_{k,1}, R_{k,2}, R_{k,3}, \ldots, R_{k,n_k}\}$ representing $n_k$ nodes the flight passed. The time for $P_k$ passes the $l$-th node $N_{R_{k,l}}$ on its route is $\tau_{R_{k,l}}$. Scheduling is to decide the a time sequence $\tau_{R_{k,l}}$, which is assigned with

$$\tau_{R_{k,l}} = \{\tau_{R_{k,1}}, \tau_{R_{k,2}}, \tau_{R_{k,3}}, \ldots, \tau_{R_{k,n_k}}\}. \quad (5)$$
during time interval \( [T_{i-1}, T_{i+2}] \) have the same time separation. In this case, the uniform distribution is achieved.

Thus, the time for \( P_k \) passes the \( l \)-th node \( N_{R_k,l} \) on its route depends on the order of aircraft \( P_k \) in \( O_{l,R_k,l} \).

The order \( O_{i,R_k,l} \) can be set as flight priority. For example, an aircraft \( P_k \) with the highest flight priority, i.e. \( O_{i,R_k,l}(k) = 1 \), then

\[
\tau_{k,l} = T_i + S_{l,R_k,l}.
\]  

During the scheduling process, this aircraft will always be the first one to pass a merging node. Obviously, its travelling time will be the minimal.

3.2 Optimization for multiple aircrafts

The travelling time for a aircraft \( P_k \) in the system is denoted as \( \tau_k = \tau_{k,n_k} - \tau_{k,1} \). Suppose \( K = \{k_1, k_2, \ldots \} \) are indices for aircrafts with higher priorities. Here we aim to reduce the average travelling time of those aircrafts. It can be achieved by solving the following objective function,

\[
\min_{O_{l,j}} \sum_{k \in K} \| \tau_k \|,
\]  

Where \( O_{l,j} \) are aircrafts’ queue order on the merging node \( N_j \) at time step \( T_i \).

In practice, aircrafts may be required to fly over a certain region as fast as possible, e.g. military zones. Under this consideration, we attempt to further optimize the average flight within a certain region. Suppose \( L \) is a local area, and \( N_j \) are indices for all the merging nodes in this local regions, and \( K = \{k_1, k_2, \ldots \} \) are indices for aircrafts with higher priorities. We aim to reduce the travelling time for passing this region.

The time for \( P_k \) passes the \( l \)-th node \( N_{R_k,l} \) on its route is \( \tau_{k,l} \). Thus, its travelling time in the local region is \( \tau_{k,l_1} - \tau_{k,l_2} \), with \( R_{k,l_1}, R_{k,l_2} \in N_l, R_{k,l_1+1}, R_{k,l_2-1} \notin N_l \).

The local optimization can be achieved by solving the following objective function,

\[
\min_{O_{l,j}} \sum_{j \in N_L} \left( \tau_{k,l_1} - \tau_{k,l_2} \right) \cdot \left( \tau_{k,l_1} \right).
\]  

4. SIMULATION

We have developed a simulation system to implement flight scheduling, using Microsoft Visual Studio 2008 under Windows 7 environment. It is an integrated multi-functional simulation platform, consisting of the graphic display module, the data processing module, the simulation control module, the algorithm module. The system supports real-time simulation which can be run on advanced microcomputers or graphic workstations. Currently, we are utilizing this system for air traffic simulation for the Association of Southeast Asian Nations (ASEAN).
In this section, we give a simulation case for an en-route traffic space (10 airports with 26 waypoints) for a region of ASEAN. All flights take off from Changi Airport in Singapore, and fly to other 9 airports, i.e. Kuala Lumpur, Penang, Phuket, Bangkok, Ho Chi Minh City, Kota Kinabalu, Kuching, Jakarta and Surabaya. The scheduling method is demonstrated in the following three scenarios.

4.1 Scenario 1: visualized individual flights

This scenario is to present a normal scheduling process, i.e. how to obtain individual flights from aggregated flows. Input flows are generated from a flow model established by our research team. Based on those data, the scheduling algorithm takes 120 milliseconds to generate 381 flights for 4 hours’ simulation time. Table 1 lists the configuration of the computer and the scheduling performance.

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<td>Computer</td>
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<td>Operation system</td>
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<tr>
<td>CPU</td>
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<tr>
<td>RAM</td>
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<tr>
<td>Scheduling time</td>
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The inputs and outputs are visualized in the terms of 3D chart in Fig.5. We select data based on a partial map (26 nodes) within 39 time steps for illustration, considering the complete time-space data is huge. As shown in Fig.5(a), flows are aggregated in discrete space (x-axis) discrete time (y-axis), where z-axis refers to the value of flow rates. After scheduling, the disaggregation problem is effectively solved. As shown in Fig.5(b), each line represents an individual flight (z-axis) which is continued time (x-axis) and continued space (y-axis).

4.2 Scenario 2: rescheduling with capacity change

This scenario is to present a rescheduling process under a stochastic capacity profile. Due to weather conditions, the capacity of a link is reduced to 50%. Table 2 lists a summary of simulation results. In total 231 aircrafts are affected with either delay or route change. As shown Fig.6, there is an overview of changed trajectories after rescheduling. The aircraft highlighted in purple colour refer to the rerouted aircrafts; and the ones in red colour are delayed. A more detailed picture is shown at the lower left corner. We can see that all aircrafts can be tracked, and moves with near-uniform separations with each other.

The system executes the rescheduling calculations in the background, paralleling with display of dynamic scene. The high efficiency provides the capability to real-time analyse of the impact of flow management actions.

Fig. 6.Changes in flight trajectories after rescheduling.

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<tr>
<td>Simulation time period</td>
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<tr>
<td>Total number of aircrafts generated</td>
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<tr>
<td>Number of aircrafts changed route</td>
</tr>
<tr>
<td>Number of delayed aircrafts</td>
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<tr>
<td>Average delay for delayed aircrafts</td>
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4.3 Scenario 3: sensitively analyses for flight priority

This scenario is to present a reasonable change of merging sequence when the priority of a certain flight is changed during the rescheduling process. An example is show in Fig.7. In Scenario 2, the aircraft (ID 62 in red) was delayed due to its low priority during rescheduling (Fig.7(a)). After merged into the downstream link, the aircraft is sequenced at last end of other aircrafts, with the merging sequence: 62-7-72 (Fig.7(b)). Now the aircraft is assigned with a higher priority. It is not delayed (Fig.7(c)), and sequenced in the head of others with the new merging sequence is 7-72-62 (Fig.7(d)).
Fig. 7. Merging sequencing with flight priority.

5. CONCLUSIONS

A systematic scheduling framework is provided with capability of generating, adjusting and optimizing flight schedules in en-route airspace. It enhanced collaboration on en-route traffic control problems with flow-based flight planning. On one hand, it assists flight planner by providing flight schedules reliable on optimal flow restrictions; On the other hand, it ensures en-route air traffic controller by maintaining safe and ordered trajectory of traffic. This paper addresses an attempt to link strategic flow management with operational traffic control, which is encouraged by current ATFM in Collaborative Decision Making (CDM) process where multiple levels participate in flight decisions in the strategic, pre-tactical, and tactical phases (C.L. Wu and R.E. Caves, 2002).

The key achievement is to design algorithms to generate individual flights from aggregated flows, while enabling aircrafts keep reasonable separations and sequence. Despite flow-based, this scheduling method is independent of patterns of flow models, and thus supports a general problem of flow disaggregation. The sequencing problem is simply discussed and keeps some potential for further study. Simulation experiments demonstrate feasibility and reliability of the scheduling method, also proves a capacity of high-efficient computing, with fast response for real-time rescheduling.

REFERENCES