Dynamic Airspace Management
- Models and Algorithms

Peng Cheng and Rui Geng
Department of Automation, Tsinghua University
P. R. China
chengp@tsinghua.edu.cn
gengrui@tsinghua.edu.cn

1. Introduction

Global air transport has been growing for decades and is expected to continue increasing in the future. The development of the air transport system has significantly increased the demands on airspace system resources. During the past several years, the operational concept of Dynamic Airspace Management has been developed to balance the mushrooming demands and limited airspace resources.

The Dynamic Airspace Management is an important approach to extend limited airspace resources by using them more efficiently and more flexibly. Under the Dynamic Airspace Management paradigm, the national airspace is administrated as a unified resource with temporary utilization clearances assigned to various airspace users on demand and reclaimed at the end of the utilization period. The structure of airspace can be changed as well if needed.

The airspace system typically has civil users and military users. In China, for example, most of the airspace is administrated by the military except for a few air routes reserved for civil aviation, that resemble a lot of tubes through the airspace. The air transport system is restricted not only by insufficient airport capacities (as in the United States) and sector capacities (as in Europe), but also by the structure and the management policy of air route networks. When there is a temporary increase of the air traffic demands or a decrease of airspace capacities, the civil air traffic controllers usually have to apply for additional routes from the military.

In the last two decades, the models and algorithms for Air Traffic Flow Management (ATFM) have been developed to provide better utilization of airspace resources to reduce flight delays(Vossen & Michael, 2006). Early ATFM models only considered airport capacity limitations(Richetta & Odoni, 1993; 1994). Bertsimas and Patterson(Bertsimas & Patterson, 1998; 2000), Lulli and Odoni(Lulli & Odoni, 2007) included airport capacity limitation and sector capacity limitation together. Cheng et al.(Cheng et al., 2001) and Ma et al.(Ma et al., 2004) investigated the ATFM problem in China and added air route capacity constraints into their models. In all these models, the airspace structure was treated as deterministic and unchangeable. These models follow the similar way that makes optimal schedules for a given set of flights passing through the airspace network by dynamically adjusting flight plans via airborne holding, rerouting, or ground holding to adapt to the possible decreases of the network capacity while minimizing the delays and costs.

Few studies have focused on how to reconstruct an efficient air traffic network and how to adjust the current network in a dynamic environment. In this chapter we discuss three problems of dynamically adjust air space resources including air routes and air traffic control sectors.

Firstly, an integer program model named Dynamic Air Route Open-Close Problem (DROP) is presented to facilitate the utilization of air routes. This model has a cost-based objective function and takes into account the constraints such as the shortest occupancy time of routes, which have not been considered in the past ATFM studies. The aim of the Dynamic Air Route Open-Close Problem is to determine what routes will be open for a certain user during a given time period. Considered as a simplified implementation of air traffic network reconstruction, it is the first step towards realizing the Dynamic Airspace Management.

Secondly, as a core procedure in Dynamic Airspace Management, the Dynamic Air Route Adjustment Problem is discussed. The model and algorithm of Dynamic Air Route Adjustment Problem is about making dynamic decisions on when and how to adjust the current air route network with the minimum cost. This model extends the formulation of the ATFM problem by integrating the consideration of dynamic opening and closing of air route segments and introducing several new constraints, such as the shortest occupancy time. The sensitivities of important coefficients of the model are analyzed to determine their proper values.

Thirdly, we discuss a set-partitioning-based model on the dynamic adjustment to air traffic control sectors to balance the workload of controllers and to increase the airspace capacity. By solving the optimization model, we get not only the optimal number of opened sectors but also the specific forms of sector combinations. To obtain the input parameters of the set-partitioning model, we also apply a method to evaluate controllers' workload through massive statistical analysis of historical radar data.

Several computational examples are also presented in this chapter to test the models and algorithms. All scenarios and data are extracted from Beijing Regional Air Traffic Control Center, which controls one of the most challenging airspaces of the world, in terms of either air traffic or airspace structure.

2. Dynamic Air Route Open-Close Problem

There are typically civil users and military users in the airspace system. When there is a temporal increase in air traffic demand or a decrease in airspace capacity, civil aviation user has to apply for additional routes from the military. The military may also "borrow" some air routes from the civil aviation system for training or combat. The Dynamic Air Route Open-Close Problem determines when additional routes should be opened or closed to the civil aviation system, and when the civilian routes can be used by the military. In this problem all air routes are considered to be independent. There is a special constraint named the Shortest Usage Time constraint. Since the airspace system does not allow air routes to be opened or closed arbitrarily, it has to be used for a shortest usage time once a route has been used.

2.1 Model Formulation

Consider a set of time intervals, $t \in \{1, ..., T\}$, a set of routes, $i \in \{1, ..., I\}$, and two users (civil aviation and military aviation), $k \in \{1, 2\}$. The notations for the problem are as follows.

$a_k(t)$ Cost coefficient for one unit of resource shortage of user k in time interval t

$b_{i,k}(t)$ Cost of user k using route i during time interval t

$o_{i,k}(t)$ Opening fee of user k borrowing route i from the other user in time interval t. If user k uses his own route, this coefficient will be zero

$C_{i,k}(t)$ Number of flights that can enter route i in time interval t when user k use this route

$P_k(t)$ Resource demand of user k in time interval t

$U_{i,k}$ Shortest occupancy time that user k uses a borrowed route i. If user k uses his own route, this coefficient will be zero

$d_k(t)$ Amount of resource shortage of user k in time interval t

The decision variables are defined as follows,

$$x_{i,k}(t) = \begin{cases} 1 & \text{if the route } i \text{ is occupied by the user } k \text{ in time interval } t. \\ 0 & \text{Otherwise.} \end{cases}$$

$$z_{i,k}(t) = \begin{cases} 1 & \text{if the route } i \text{ is opened to the user } k \text{ in time interval } t. \\ 0 & \text{Otherwise.} \end{cases}$$

The objective function can be written as

$$Min \sum_{k,t} a_k(t)d_k(t) + \sum_{i,k,t} o_{i,k}(t)z_{i,k}(t) + \sum_{i,k,t} b_{i,k}(t)x_{i,k}(t) \tag{1}$$

In Equation 1, the first term represents the cost of resource shortage which may cause flight delay or cancellation. The second term represents the cost of opening a route to users except the owner, since many things such as resource allocations, communications, and authorizations have to be done before the route can be opened to other users. The third term represents the cost of using another user's routes.

The constraints are given as below.

$$d_k(t) = max(0, P_k(t) - \sum_i C_{i,k}(t)x_{i,k}(t)) \qquad \forall t, k \tag{2}$$

$$\sum_k x_{i,k}(t) = 1 \qquad \forall i, t \tag{3}$$

$$z_{i,k}(t) = 0 \qquad \text{If } 1 \leq \sum_{\tau \in (t-U_{i,k},t)} x_{i,k}(\tau) \leq U_{i,k} \qquad \forall i, k, t \tag{4}$$

$$x_{i,k}(t) - x_{i,k}(t-1) \leq z_{i,k}(t) \qquad \forall i, k, t \tag{5}$$

$$x_{i,k}(t) \in \{0,1\}, \quad z_{i,k}(t) \in \{0,1\}, \quad d_k(t) \in \mathbb{Z}^+ \qquad \forall i, k, t \tag{6}$$

Constraint 2 gives the resource shortages $d_k(t)$. Constraint 3 shows that each route i is occupied by one specific user whether the route is actually used (there are flights using it) or not. Constraint 4 is the shortest occupancy time constraint. Any request to borrow a route for a planned occupancy time less than $U_{i,k}$ will be refused. This constraint ensures sufficient time for route switching between users. Constraint 5 describes the relationship between $x_{i,k}(t)$ and $z_{i,k}(t)$. Constraint 6 is the standard non-negativity and integral constraint.

Considering the model has nonlinear terms, which are usually difficult to handle, the formulation can be rewritten as follows.

$$P_k(t) - \sum_i C_{i,k}(t)x_{i,k}(t) \le d_k(t) \qquad \forall t, k \tag{7}$$

$$\sum_k x_{i,k}(t) = 1 \qquad \forall i, t \tag{8}$$

$$U_{i,k}(z_{i,k}(t) - (x_{i,k}(t) - x_{i,k}(t-1))) \le \sum_{\tau \in (t-U_{i,k},t)} x_{i,k}(\tau) \qquad \forall i, k, t \tag{9}$$

$$x_{i,k}(t) - x_{i,k}(t-1) \le z_{i,k}(t) \qquad \forall i, k, t \tag{10}$$

$$x_{i,k}(t) \in \{0,1\}, \quad z_{i,k}(t) \in \{0,1\}, \quad d_k(t) \in \mathbb{Z}^+ \qquad \forall i, k, t \tag{11}$$

Constraint 7 is derived from constraint 2. When $P_k(t) - \sum_i C_{i,k}(t)x_{i,k}(t) \le 0$, then $d_k(t) = 0$ according to constraint 11. When $P_k(t) - \sum_i C_{i,k}(t)x_{i,k}(t) \ge 0$, since the objective function has the term $\sum_{k,t} a_k(t)d_k(t)$, $d_k(t)$ will be equal to the minimum under constraint 7, and $d_k(t) = P_k(t) - \sum_i C_{i,k}(tx_{i,k}(t)$. Therefore, constraint 7 is equal to constraint 2 when combined with the objective function and constraint 11.

For the same reason, the relationship between $x_{i,k}(t)$ and $z_{i,k}(t)$ can be described as the combination of the object function and constraints 5 and 11. Figure 1 illustrates the relationship between $x_{i,k}(t)$ and $z_{i,k}(t)$.

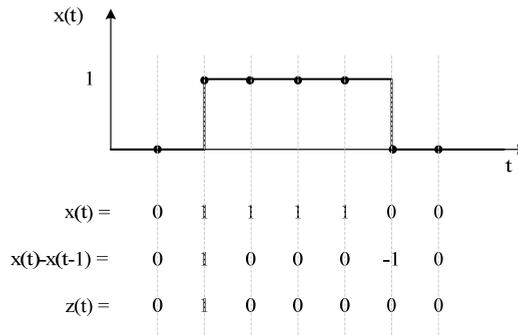Fig. 1. Typical relationship between $x_{i,k}(t)$ and $z_{i,k}(t)$

2.2 Simulations

Figure 2 shows an area with three civilian routes and a military training area through which an additional route can be opened to civilian users. All of these routes have different capacities, opening costs, usage costs. The military may borrow route 3 from the civil aviation authority when an additional area is needed.

Figure 3 shows the solution of a realistic instance of the Dynamic Air Route Open-Close Problem. In this case, the time horizon from 8:00 am to 11:00 pm is divided into many 15-minute time periods. The opening cost and the usage cost of route are set to be twice the cost of one unit of resource shortage. The shortest occupancy time is set to be 4 time intervals. The
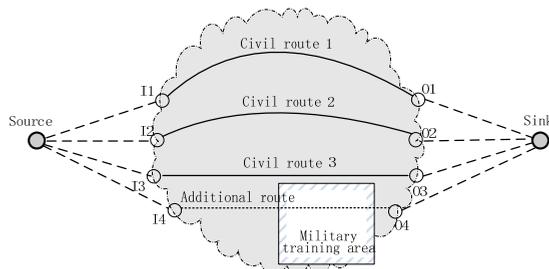
Fig. 2. Area with temporary additional routes

capacity of all three civilian routes, the capacity of the military area, and the demands of all users are shown in Figure 3(a). Note the capacity decrease of the civilian routes that lasts 6 time intervals, which is usually caused by severe weather.

Figure 3(b) to (e) show the value of $x_{i,k}(t)$ for the various routes. Routes 1 and 2 are exclusively used by the civilian users. Route 3 and the additional route (military training area) are opened or closed according to the total cost of all users' resource shortages, route opening, route usage, and the constraint of the shortest occupancy time.

The ratio of the resource shortage cost, route opening cost, and route usage cost significantly affects the result. If the cost of using an additional route is much higher than the cost of the resource shortage, for example due to a very complex route application procedure, the user may accept the shortage and change their flight plans.

Using the air space resources flexibly, the Dynamic Air Route Open-Close Problem is the first step towards the Dynamic Airspace Management. In this model all air routes are considered to be independent. But in more common situation, air routes are usually dependent. In next section we will focus our investigation onto the network of air routes and present the Dynamic Air Route Adjustment Problem.

3. Dynamic Air Route Adjustment Problem

Given an air traffic network composed of airports, way points, and routes, and a set of flights that are planned to fly through the network, the Dynamic Air Route Adjustment Problem makes dynamic decisions on when and how to adjust the current air traffic route network by applying for additional temporary air route segments (or arcs) to minimize the overall cost including opening cost, the usage cost for temporary arcs, and the flight and delay costs to all flights. The development of this model is partially motivated by the characteristics of the air route structure and the management policy in China.

3.1 Model Formulation

The model of the Dynamic Air Route Adjustment Problem is defined on a network, $\mathcal{G}$, having the node set $\mathcal{N}$ and the arc set $\mathcal{A}$. In $\mathcal{G}(\mathcal{N}, \mathcal{A})$, the nodes represent the airports and the way points while the arcs represent air route segments including the reserved routes for civil users as well as the dynamic routes, which can be temporarily used by civil users. The model can be
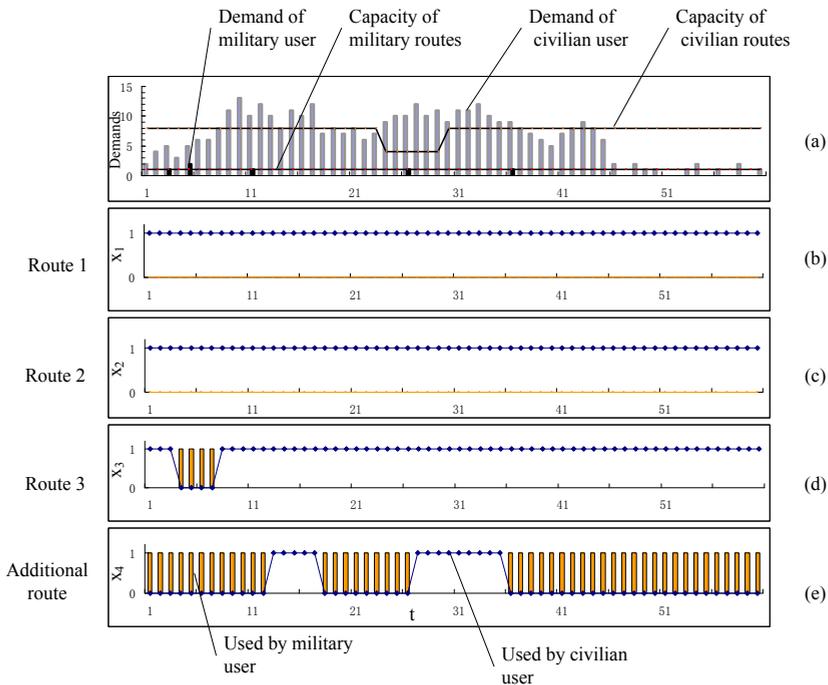
Fig. 3. A realistic instance of the Dynamic Air Route Open-Close Problem

described as a multi-commodity network flow model, where all flights with the same origin and destination belong to one commodity.

The model is based on the following assumptions.

1. Since the quantity of each commodity is the number of flights, it must be a nonnegative integer.

2. All flights must land at their destination nodes eventually.

3. The time period T is sampled into discrete time slots with equal intervals.

4. All flights have identical mechanical characteristics and fly at the same speed. So the travel time through one arc is identical for every flight. But it may differ at different instances.

5. The arc capacities are known and given in this model but they may differ at different times.

6. All flights have the same fuel consumption rate and the same delay fees, which are constants in this model.

7. If a temporary arc opens, it should be kept open for at least the shortest occupancy time so that the air traffic controllers have enough time to switch access to the arc between different users.

The notations for the model are as follows.

$\mathcal{A}$	set of arcs
$\mathcal{A}_{tmp}$	set of arcs that can be temporarily opened, $\mathcal{A}_{tmp} \subset \mathcal{A}$,
$\mathcal{K}$	set of flight commodities
$\mathcal{N}$	set of nodes
$\mathcal{N}_{orig}$	set of origin nodes, $\mathcal{N}_{orig} \subset \mathcal{N}$,
$\mathcal{N}_{dest}$	set of destination nodes, $\mathcal{N}_{dest} \subset \mathcal{N}$;
$\mathcal{N}_{mid}$	set of nodes other than origin and destination nodes, $\mathcal{N}_{mid} \subset \mathcal{N}$
i	node index, $i \in \mathcal{N}$
(i,j)	arc index, $(i,j) \in \mathcal{A}$
t	time interval index, $t \in \mathcal{T}$
k	flight commodity index
$dis_{i,j}$	Length of arc (i,j)
$a_{i,j}$	Travel time along arc (i,j)
$c_{i,j}(t)$	Maximum number of flights that can enter arc (i,j) during time interval t
$U_{i,j}$	The shortest occupancy time of arc (i,j)
$P_i^k(t)$	Number of commodity k flights scheduled to take off from origin node i during time interval t
$w_{in}(i)$	The maximum indegree of node i
$w_{out}(i)$	The maximum outdegree of node i
r	Cost of flying one kilometer
$d_i(t)$	Cost of holding a flight at origin node i during time interval t
$o_{i,j}(t)$	Opening fee of temporary arc (i,j) during time interval t
$m_{i,j}(t)$	Usage cost of temporary arc (i,j) during time interval t

The decision variables are defined as follows.

$$x_{i,j}(t) = \begin{cases} 1 & \text{if the arc } (i,j) \text{ is in use during time interval } t. \\ 0 & \text{Otherwise.} \end{cases}$$

$$z_{i,j}(t) = \begin{cases} 1 & \text{if the arc } (i,j) \text{ is opened during time interval } t. \\ 0 & \text{Otherwise.} \end{cases}$$

$f_{i,j}^k(t)$ is the number of flights of commodity k entering arc(i,j) during time interval t. The objective function can be written as

$$
\begin{aligned}
minZ \quad = \quad & \sum_{t,k,i\in\mathcal{N}_{orig}} d_i(t) \cdot f_{i,i}^k(t) + \sum_{t,k,(i,j)\in\mathcal{A}} r \cdot dis_{i,j} \cdot f_{i,j}^k(t) \\
& + \sum_{t,(i,j)\in\mathcal{A}_s} o_{i,j}(t) \cdot z_{i,j}(t) \\
& + \sum_{t,(i,j)\in\mathcal{A}_s} m_{i,j}(t) \cdot x_{i,j}(t)
\end{aligned}
\tag{12}
$$

The first term represents the cost of flight delay at origin nodes. Here, $\sum_k f_{i,i}^k(t)$ is the number of all kinds of flights on the self-loop arc (i, i) at time t. The arc (i, i) begins and ends at the same origin node i, which has a travel time equal to 1 and a length equal to 0. The flight on arc (i, i) is delayed and waiting on node i. The second term represents the flight costs bases on the flying distance. Since the lengths of self-loop arcs are 0, their flying distance is zero. The third term represents the cost of opening all temporary arcs. The last term represents the cost of using the temporary arcs.

The constraints are given as below.

$$\sum_{j:(i,j)\in\mathcal{A}} f_{i,j}^k(t) - \sum_{j:(j,i)\in\mathcal{A}} f_{j,i}^k(t - a_{j,i}) = P_i^k(t) \qquad \forall i \in \mathcal{N}_{orig}, \, t \in \mathcal{T}, \, k \in \mathcal{K} \qquad (13)$$

$$\sum_{j:(i,j)\in\mathcal{A}} f_{i,j}^k(t) - \sum_{j:(j,i)\in\mathcal{A}} f_{j,i}^k(t - a_{j,i}) = 0 \qquad \forall i \in \mathcal{N}_{mid}, \, t \in \mathcal{T}, \, k \in \mathcal{K} \qquad (14)$$

$$\sum_{t,j:(j,i)\in\mathcal{A}} f_{j,i}^k(t) - \sum_{t,q\in\mathcal{N}_{orig}} P_q^k(t) = 0 \qquad \forall i \in \mathcal{N}_{dest}, \, k \in \mathcal{K} \qquad (15)$$

$$\sum_{k\in\mathcal{K}} f_{i,j}^k(t) \leq c_{i,j}(t) \cdot x_{i,j}(t) \qquad \forall (i,j) \in \mathcal{A}, \, t \in \mathcal{T} \qquad (16)$$

$$U_{i,j}[z_{i,j}(t) - (x_{i,j}(t) - x_{i,j}(t-1))] \leq \sum_{\tau\in(t-U_{i,j},t)} x_{i,j}(\tau) \qquad \forall (i,j) \in \mathcal{A}_s, \, t \in \mathcal{T} \qquad (17)$$

$$x_{i,j}(t) - x_{i,j}(t-1) \leq z_{i,j}(t) \qquad \forall (i,j) \in \mathcal{A}_s, \, t \in \mathcal{T} \qquad (18)$$

$$\sum_j x_{j,i}(t) \leq w_{in}(i) \qquad \forall i \in \mathcal{N}_{mid}, \, t \in \mathcal{T} \qquad (19)$$

$$\sum_j x_{i,j}(t) \leq w_{out}(i) \qquad \forall i \in \mathcal{N}_{mid}, t \in \mathcal{T} \qquad (20)$$

$$x_{i,j}(t) \in \{0,1\}, \quad z_{i,j}(t) \in \{0,1\}, \quad f_{i,j}^k(t) \in Z^+$$
$$\forall t \in \mathcal{T}, \, k \in \mathcal{K}, \, (i,j) \in \mathcal{A} \qquad (21)$$

Constraints 13 to 15 are flow-conservation constraints. Constraint 13 shows that all flights departing from an origin node in time interval t are either flights scheduled to take off from this node in time interval t or flights which were delayed and waiting at this node. Constraint 15 states that all flights taking off from origin nodes must land at destination nodes. Constraint 16 is the capacity constraint. Constraint 17 is the shortest occupancy time constraint. Constraint 18 describes the relationship between $x_{i,j}(t)$ and $z_{i,j}(t)$. This constraint combined with the objective function ensures that $z_{i,j}(t)$ is equal to 1 when $x_{i,j}(t)$ changes from 0 to 1. Constraint 19 and 20 limit the number of arcs entering or leaving a node so that the situation will not be too complex to be handled by the air traffic controllers. Constraint 21 is the standard non-negativity and integrality constraint.

3.2 Analysis and Evaluation

This section gives several examples of the Dynamic Air Route Adjustment Problem. These examples model possible scenarios in the southern part of the Beijing ATC Region, one of the busiest air traffic control regions in China. Figure 4 shows the air-route network model for this region with 5 origin nodes, 1 destination node, 17 reserved arcs, and 26 temporary arcs. The time horizon from 8:00 am to 11:00 pm is divided into 90 time slots with the flight plans

of 473 flights generated based on real air traffic in this region. The solution uses $r = 0.0025$, $d_i(t) = 1$, $o_{i,j}(t) = 5.5$, and $m_{i,j}(t) = 0.3$.
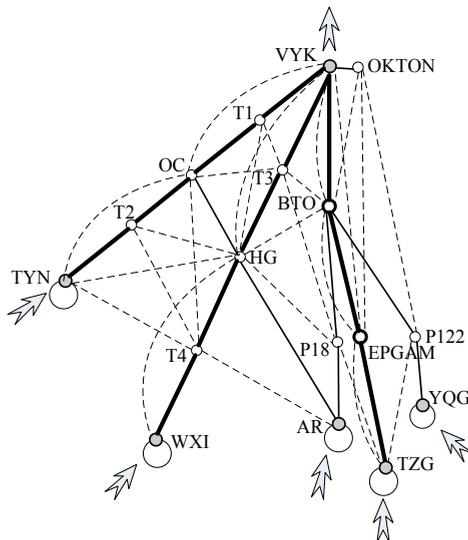

Fig. 4. Network with temporary additional route segments

Table 1 lists six scenarios with different arc capacities to simulate capacity decreases caused by severe weather or other incidents. Scenario I has normal conditions with the normal capacity of arc "EPGAM-BTO" as 4. This capacity decreases from 4 to 3 in scenario II, to 2 in III, to 1 in IV, and to 0 in V. In scenario VI, the capacity of arc "EPGAM-BTO" decreases to 2 only between 9:00 am to 11:00 am.

Figure 5 shows some details of the result for scenario VI which shows the demands of flights entering from TZG. The normal condition (scenario I) does not experience delays. In scenario VI, if no temporary arcs can be used, flights will be delayed for 125 slots. If the temporary arcs can be used, the temporary arc 5 will open and only 3 slots delays will occur in total. Figure 5 also shows the number of delays on TZG and the opening and closing schedule of the temporary arc "EPGAM-VYK."

3.3 Sensitivity Analysis

In the model, the opening fee, $o_{i,j}(t)$, and the usage fee, $m_{i,j}(t)$, of temporary arc (i, j) at time t significantly affect the opening and closing schedules of the temporary arcs and the flight arrangements. This section describes several analyses to show the sensitivity of $o_{i,j}(t)$ and $m_{i,j}(t)$.

The flight delay cost has been estimated from the experience of air traffic management experts and the statistical data from the FAA, Eurocontrol, and various airlines (Eurocontrol, 2008), (Dubai, 2008) to be €72 per minute in Europe and $123.08 per minute in the Unite States. The fuel consumption of a flight is related to its type, load, and route. According to Shenzhen

Table 1. Computational Results of Dynamic Air Route Adjustment Problem

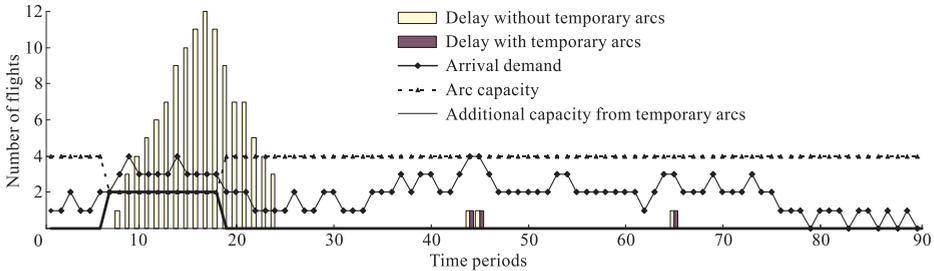| Scenario	Without temporary arcs		With temporary arcs			
	Total costs	Delay time (slots)	Total costs	Delay time (slots)	Temporary arcs used	Usage time (slots)
I	392.4	0	392.4	0	0	0
II	412.3	24	403.3	8	1	6
III	1290.2	903	412.5	0	1	66
IV	5517.5	5131	429.0	6	2	79
V	10172.5	9786	447.2	0	2	155
VI	513.3	125	400.6	3	2	10

Fig. 5. Solution of scenario VI with and without temporary arcs

Airline's operational data for 2006, the fuel consumption per thousand kilometers for their aircraft is 3.7 to 3.8 tons on average and the price of aviation fuel is about $900 per ton. Therefore, $r : d_i(t)$ is about 1:400, and the scenarios assume $r = 0.0025$ and $d_i(t) = 1$.

Four scenarios were considered to test the effect of changing $o_{i,j}(t)$ and $m_{i,j}(t)$. Scenario 1 simulates operations with little overload. In scenario 2, the capacities of arcs EPGAM-BTO and BTO-VYK are reduced to half of their normal level. In scenario 3, arcs EPGAM-BTO and BTO-VYK are closed for two hours because of severe weather. In scenario 4, EPGAM-BTO and BTO-VYK are closed throughout the simulation time.

In these comparisons, $o_{i,j}(t) \in [1, 10]$ and is increased from 1 with step size 0.5, $m_{i,j}(t) \in [0.1, 1.4]$ and is increased from 0.1 with step size 0.1.

Figures 6(a) to 6(f) show the relationships between the number of opened arcs, the occupancy time for all the temporary arcs, the total delay and the opening fee, $o_{i,j}(t)$, or the usage fee, $m_{i,j}(t)$. The symbols are the calculated results with the curves drawn to connect the average values of the results for same opening fee or usage fee. Each curve shows one scenario's result and the curve noted by "S1" shows the result of scenario 1.
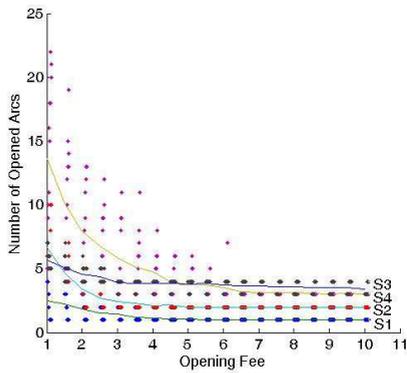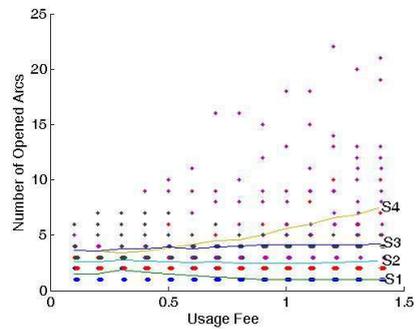
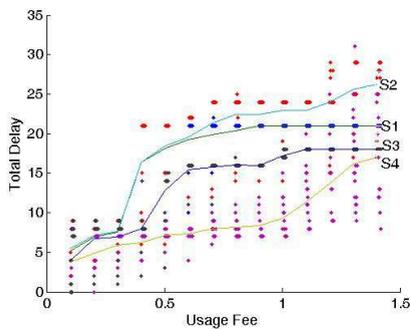(a) Opening fee and no. of opened arcs
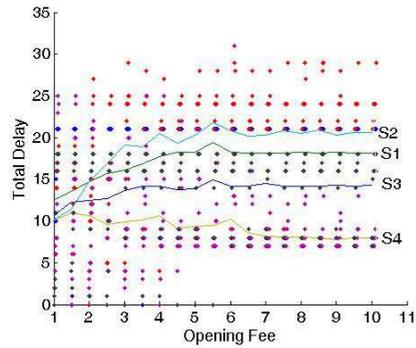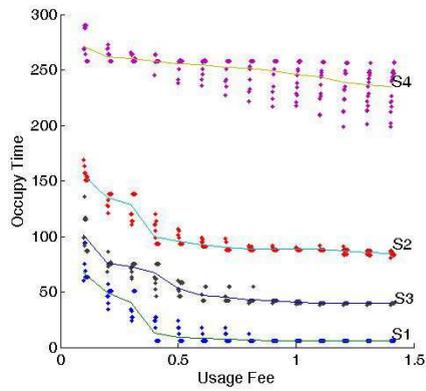
(b) Opening fee and total delay
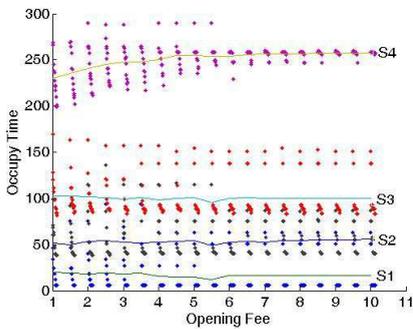
(c) Opening fee and occupying time

(d) Using fee and no. of opened arcs

(e) Using fee and total Delay

(f) Using fee and occupying Time

Fig. 6. Sensitivity analysis of factors

Figures 6(a) shows that the number of opened temporary arcs decreases as the opening fee, $o_{i,j}(t)$, increases. When the opening fee is larger than 5, the number does not change much. As in Figure 6(c), when the opening fee increases, the occupancy times remain steady because the temporary arcs are well used so they will not be opened and closed frequently. They will keep open after they are opened so that the opening fee has little effect on the occupancy time. Figure 6(b) shows that in scenario I to III, the total delays increase as $o_{i,j}(t)$ increases until $o_{i,j}(t) = 6$ and keep steady after that. The curve in scenario 4 is a little different since the occupancy time for temporary arcs is very large which means more temporary arcs are used. Figure 6(f) and 6(e) show that as the usage fee, $m_{i,j}(t)$, increases, the occupancy times for all the scenarios decrease and the total delays increase. Figure 6(d) shows that in scenario I to III, the number of opened arcs almost keeps steady. In scenario IV, it decreases a little for $m_{i,j}(t) < 0.5$ and then increases from then on. Two arcs were closed during this scenario, so some temporary arcs have to remain open no matter how expensive the usage fee is to prevent severe delays.

The values of $o_{i,j}(t)$ and $m_{i,j}(t)$ balance the military and civil users. These results provide a good reference for pricing the temporary arcs to balance these two needs.

4. Dynamic Sector Adjustment Problem

It is critical to explore how to utilize limited airspace resource via more flexible approaches in order to meet the increasing demand of air traffic. Since 1990 United States has planned the future National Airspace System (NAS) and introduced the concept of Free Flight, the object of which is using emerging technology, procedures, and concept to implement the transition from the modernization of NAS to air flight freerization, and then to satisfy the requirement of users and service providers of National Airspace System(Bai, 2006). In 1992, Europe presented a new concept of Flexible Use of Airspace (FUA), the main content of which is to abandon the method of simply partitioning airspace into two fixed types - civil airspace and military airspace, and to investigate and establish a new method of airspace use, i.e. flexibly using airspace on demand based on coordination between civil users and military users. Recently China has also started the attempt of developing new airspace planning method and technology considering the characteristics of its airspace structure and the features of its air traffic.

Dynamic adjustment to air traffic control sectors is to make reasonable sector configurations to meet all of following criteria: 1) satisfying the requirement of air traffic control service; 2) keeping the controller's workload not beyond a bearable range; and 3) taking up the least resource of air traffic control.

4.1 Dynamic Adjustment to Air Traffic Control Sectors

An aircraft is usually under the control of several different control units, including the tower control, the terminal control and the en-route control during the whole flight process(Wang et al., 2004). Considering the air traffic control is one kind of heavy brainwork, the workload of on-duty air traffic controllers is kept under a limited level to ensure the flight safety. A controlled airspace is usually divided into several sectors, each of which is under the control of an air traffic control seat, usually consisting of a group of two air traffic controllers. Air traffic controllers are responsible for surveilling flight activity, commanding aircrafts to avoid conflicts, and communicating with neighbor sectors for control handover according to flight plan.

Daily fluctuation of air traffic flow causes the unbalance of controller's workload in different hours or between different sectors. During peak hours more sectors are required to open to increase the airspace capacity and to ensure the flight safety. But when air traffic flow is low some sectors are allowed to merge to avoid unnecessary waste of resources of air traffic control.

One of the difficulties of dynamic sector adjustment is how to evaluate the controller's workload of each sector. The aim of sector adjustment is, on one side, to open enough control sectors to satisfy the air traffic requirement, and on the other side, to open as few as possible control sectors to avoid unnecessary waste of control resources. Therefore the control workload is the direct basis to implement dynamic sector adjustment and the criterion of evaluating the sector adjustment results as well.

Another difficulty of dynamic sector adjustment is how to choose the best scheme of sector configurations, i.e. how to assign n sectors to $k(1 \leq k \leq n)$ air traffic control seats reasonably. The complexity of the problem consists in too many possible assignments of n sectors. Suppose the number of possible assignments of n sectors to k control seats is $P(n,k)$. The computation rule is shown in equation 22. Also suppose the total number of means of grouping n sector is $P(n)$. The computation rule is shown in equation 23(Gianazza & Alliot, 2002). For example, if the number of total sectors is 13, there exists 27,644,437 possible means of assignments and the computation of searching optimal scheme of sector configurations by traversing will be enormous.

$$P(n,1) = 1, \quad P(n,n) = 1$$
$$P(n,k) = kP(n-1,k) + P(n-1,k-1) \tag{22}$$

$$P(n) = \sum_{k=1}^{n} P(n,k) \tag{23}$$

4.2 Evaluation of Controller's Workload

The workload of an air traffic controller refers to the objective requirement of tasks assigned to him(or her), his objective efforts to fulfill the requirements, his working performance, his physiological and psychological states, and his subjective perception to the efforts he ever made.

Many studies have been done on the evaluation of controller's workload and a lot of models and algorithms have been presented. Meckiff et al.(Meckiff et al., 1998) introduced the concept of air traffic complexity in order to evaluate controller's workload. Air traffic complexity refers to the level of complexity of air traffic controller's work caused by a certain air traffic situation. It doesn't consider the difference of control procedures of different airspace, nor the difference of of controller's responses to the same traffic situation. Therefore the air traffic complexity is easier to evaluate than the controller's workload(Schaefer et al., 2001). But no matter what the definition of air traffic complexity or the definition of controller's workload is, it is important to distinguish the degree of requirement of air traffic control under different traffic situations. It seems it is a better way to combine these two concept together, i.e. , to compute the air traffic complexity using the classification of controller's workload, and to quantify controller's workload using air traffic complexity.

The factors that influence the air traffic complexity and the controller's workload include the space structure of sectors, the features of in-sector flight activities, and the types and numbers of conflicts occurred inside the sector. Different sectors have different traffic demands

due to their specific geographic locations. The sectors near an airport, usually spanning the climbing or descending phase of flight, have more workloads of adjusting headings, altitudes and speeds. Furthermore, the more percentage of climbing and descending flights there is, the more possibly the flight conflicts could happen, and the more controller's workloads there are. Also, the more complex the airspace structure is, the more complex the fight activities are. The types and numbers of in-sector conflicts largely depend on the complexity of flight activities inside. The more complex the flight activities are, the more probably the conflicts could occur.

In order to objectively quantify the evaluation of controller's workload, we build an evaluation model based on the features of flight activities. Table 2 lists all feature variables of flight activities. We count 22,000 flights in 15 days and analyze the features of these flights' activities inside each sector in each hour. According to this we evaluate the controller's workload of each sector in different hours.

Table 2. Feature Variables of Flight Activities in the Airspace

Feature Variables	Meanings
$\bar{T}$	average service time
α_{al_up}	percentage of climbing flights
α_{al_down}	percentage of descending flights
α_{al_keep}	percentage of traversing flights
α_{sp_up}	percentage of accelerating flights
α_{sp_down}	percentage of decelerating flights
α_{sp_keep}	percentage of flights with constant speed
α_{hd}	percentage of flights changing their headings
N_{al_up}	average time of climbs for the climbing flights
N_{al_down}	average time of descents for the descending flights
N_{sp_up}	average time of accelerations for the accelerating flights
N_{sp_down}	average time of decelerations for the decelerating flights
N_{hd}	average time of changes for the heading-changing flights

Normally the controller's workload can be classified into three types: 1) surveillance workload, i.e., the workload of inspecting each aircraft's trajectory and its flight state inside the sector; 2) conflict-resolution workload, i.e., the workload of any actions for resolving flight conflicts inside the sector; 3) coordination workload, i.e., the workload of information exchange between pilots and air traffic controllers, or between air traffic controllers of different sectors when aircrafts fly across the border of sectors.

We build an evaluation model of controller's workload by analyzing all kinds of influence factors, as shown in Equation 24. The meanings of variables and parameters are shown in Table 3. In Equation 24, λ, γ, β represent respectively the influence factors related to each feature of flight activities and a, b, c are coordination factors among three kinds of controller's workload.

$$
\begin{aligned}
W_{total} &= CI \times F \\
&= W_{mo} + W_{cf} + W_{co} \\
&= F \times \{ a\bar{T}(\lambda_{al}\partial_{al} + \lambda_{sp}\partial_{sp} + \lambda_{hd}\partial_{hd} + \lambda_{al\_keep}\partial_{al\_keep}) \\
&\quad + b\bar{T}\left[\frac{\min(\alpha_{al\_up}, \alpha_{al\_down}, \alpha_{al\_keep})}{\max(\alpha_{al\_up}, \alpha_{al\_down}, \alpha_{al\_keep})} + \frac{\min(\alpha_{sp\_up}, \alpha_{sp\_down}, \alpha_{sp\_keep})}{\max(\alpha_{sp\_up}, \alpha_{sp\_down}, \alpha_{sp\_keep})} \right] \\
&\quad \cdot (\gamma_{al}\partial_{al} + \gamma_{sp}\partial_{sp} + \gamma_{hd}\partial_{hd} + \gamma_{al\_keep}\partial_{al\_keep}) + c \cdot 2\beta \}
\end{aligned} \quad (24)
$$

where

$$
\begin{aligned}
\partial_{al} &= \alpha_{al\_up}N_{al\_up} + \alpha_{al\_down}N_{al\_down} \\
\partial_{sp} &= \alpha_{sp\_up}N_{sp\_up} + \alpha_{sp\_down}N_{sp\_down} \\
\partial_{hd} &= \alpha_{hd}N_{hd}
\end{aligned}
$$

Table 3. Feature Variables in the Evaluation Model of Controller's Workload

Feature Variables	Meanings
W_{total}	controller's workload
F	traffic flow
CI	coefficient of air traffic complexity
W_{mo}	surveillance workload
W_{cf}	conflict-resolution workload
W_{co}	coordination workload

Considering the Beijing Air Traffic Control Region as our investigation object, the sector division scheme is shown in Figure 7. Figure 8 shows the percentage of climbing flights in each hour. The 15 curves in the upper part of Figure 8 show the daily changes of percentage of climbing flight since Jan 1, 2008 to Jan 15, 2008. The lower part of Figure 8 presents the average value of percentage of climbing flights in each hour. We can see the variation tendencies of daily percentage of climbing flight are basically identical, that shows the daily in-sector flight activities have some regularity.

We input the feature variables of flight activities into Equation 24 and obtain the variation tendencies of air traffic complexity in each hour as shown in Figure 11(a). It is perceptible that the no.1, no.3, and no.13 sector, which are the nearest ones to Beijing Terminal Control Area, have the largest air traffic complexity, above 1.2 during peak hours. The no.4, no. 6, no.9, and no.10 sector also have fairly large air traffic complexity, above 1.0 during peak hours, because the structure of air route networks in no.9 and no.10 sector are comparatively complex while no.4 and no.6 sector are quite close to Beijing Terminal. Those that are far from Beijing Terminal, such as no.5, no.7, no.8, no.11, and no.12 sector, have relatively small air traffic complexity, basically around 0.8. The computational results tally with the analysis of influence factors to air traffic complexity and show the validity of the evaluation model of controller's workload.
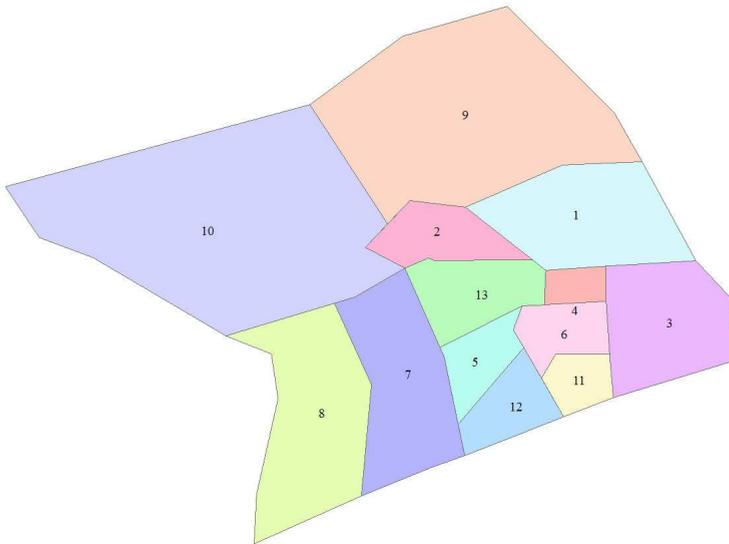
Fig. 7. The Current sector configuration of Beijing Regional ATC Center

4.3 Set-Partitioning Based Model

As what we have discussed, if we seek optimal sector configuration scheme by traversing directly, the amount of calculation will be enormous because many sector combinations dissatisfy the constraint of sector structure features. Therefore we firstly determine all feasible sector combinations and then search optimal sector configuration scheme from the feasible sector combinations using an optimization model based on set partitioning.

4.3.1 Finding Feasible Sector Combinations

We define a sector combination as the mergence of several sectors. Only those sector combinations that satisfy the constraints of sector structure features are feasible sector combinations. A feasible sector combination can be assigned to an air traffic control seat.

The constraints of sector structure features include the continuity constraint and the convexity constraint(Trandac et al., 2003) (Han & Zhang, 2004). According to the principle of air traffic control, a controller's working airspace should be inside a comparatively concentrated airspace for favoring the smoothness of the control work. Otherwise the controller's attention could be distracted due to the dispersion of controlled airspace(Han & Zhang, 2004). Therefore any feasible sector combination must be a continuous airspace. The convexity constraint of sector combination's shape is for avoiding the same aircraft flying across the sector borders twice when executing a flight plan. In fact it is difficult to ensure every sector's shape to be absolutely convex. So we consider a sector combination to satisfy the convexity constraint if the situation that an aircraft flies across the sector borders twice during a single flight activity will not happen.

To obtain all feasible sector combinations, we firstly find out all interconnected sector combinations by setting the prerequisite of interconnection of all participated sectors. Secondly,
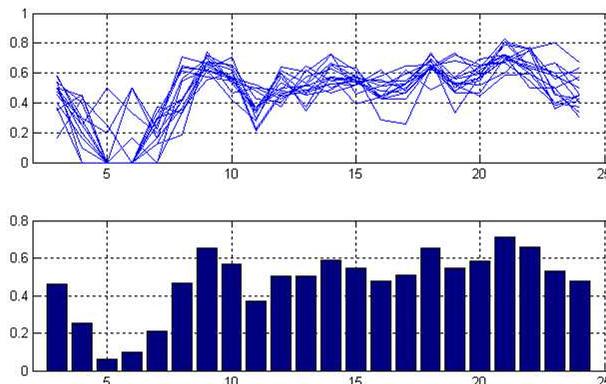
Fig. 8. Hourly percentage variations of climbing flights

we find out all sector combinations that are in accord with the convexity constraint of sector's shape.
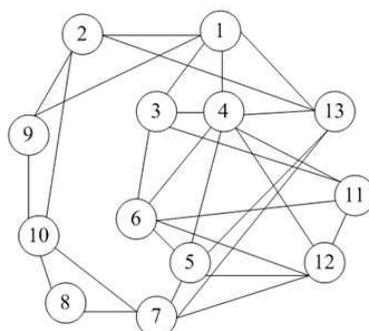
Fig. 9. The Neighborhood Network of Beijing Regional ATC Center

There are 13 sectors in total among the Beijing Regional ATC Center as shown in Figure 7 .So there are $2^{13} = 8192$ possible sector combinations in all. We firstly filter all these sector combinations according to interconnection. Figure 9 is the neighborhood network of each sector of the Beijing ATC Region. Filtering out the sector combinations satisfying the interconnection feature is equal to finding out all interconnected subnets from the network. According to the computation, we know that there are 1368 interconnected sector combinations in all within this network structure.

Basically we have two ways to filter out the sector combinations that satisfy the convexity constraint. One way is by analyzing historical flight data. After screening historical radar data to count the times of each flight flying in or out the sector, we can get all flights passing each sector combinations. If a flight occurs several times and the adjacent two occurring times are discontinuous, it is can be determined that the current sector combination fails to satisfy the convexity constraint. The other way is by human experiences. It is can be distinguished

whether the sector combination satisfies the convexity constraint through analyzing the detailed shape of each sector combination and the spacial distribution of historical radar trace points. Finally 438 feasible sector combinations are determined by the above two ways.

4.3.2 Model's Formulation

Suppose that the set of sectors is S, the set of all feasible sector combinations is R, and the set of sampling points in time period t is I. The optimal sector configuration problem can be described as shown in Equation 25, 26, 27, and 28, where c_r represents the cost efficient of choosing sector combination r and decision variable x_r represents whether to choose the sector combination r. The objective function is to minimize the total costs of choosing opened sector combinations. a_{sr} represents the mapping coefficient of sector combination r and sector s. If sector s is contained by sector combination r, $a_{sr} = 1$; otherwise $a_{ar} = 0$. The constraint 26 shows that each sector must be attached to one and only one opened sector combination. The constraint 27 shows that the instantaneous traffic flow at each sampling point inside the chosen sector combination at time t must be within the limited range.

$$\min \quad \sum_{r \in R} c_r x_r \tag{25}$$

$$s.t. \quad \sum_{r \in R} a_{sr} x_r = 1 \quad \forall s \in S \tag{26}$$

$$f_{ri} x_r \leq f_0 \qquad \forall r \in R, \forall i \in I \tag{27}$$

$$x_r \in \{0, 1\} \qquad \forall r \in R \tag{28}$$

where $a_{sr} = 1$ when $s \in r$ or $a_{sr} = 0$ otherwise. As shown in equation 29, the instantaneous traffic flow within the sector combination r is equal to the sum of the instantaneous traffic flow of all sectors constructing the sector combination.

$$f_{ri} = \sum_{s \in S} a_{sr} f_{si} \tag{29}$$

$$
\begin{aligned}
c_r &= a \cdot C_r^{++} + b \cdot C_r^{--} + c \cdot (C_r^+ + C_r^-) \\
&= a \cdot (\Delta W_r^{++})^2 + b \cdot (\Delta W_r^{--})^2 + c \cdot (\Delta W_r^+ + \Delta W_r^-)
\end{aligned} \tag{30}
$$

$$\Delta W_r = W_r - W_0 \tag{31}$$

$$\Delta W_r^+ = \begin{cases} \Delta W_r & 0 \leq \Delta W_r \leq u \\ 0 & otherwise \end{cases} \tag{32}$$

$$\Delta W_r^{++} = \begin{cases} \Delta W_r & \Delta W_r > u \\ 0 & otherwise \end{cases} \tag{33}$$

$$\Delta W_r^- = \begin{cases} |\Delta W_r| & l \leq \Delta W_r \leq 0 \\ 0 & otherwise \end{cases} \tag{34}$$

$$\Delta W_r^{--} = \begin{cases} |\Delta W_r| & \Delta W_r \leq l \\ 0 & otherwise \end{cases} \tag{35}$$

Referring to the research result by Gianazza et al.(Gianazza & Alliot, 2002), we define the opening cost of sector combination r as shown in Equation 30 and Equation 31, 32, 33, 34, and

35 where ΔW_r represents the difference of controller's workload W_r and the average workload W_0. The purpose of defining such cost function is to make the controller's workload of opened sector combination r as close as possible to the average working ability.

$$CI_r = \frac{\sum_{s \in S} a_{sr} \cdot F_s \cdot CI_s}{\sum_{s \in S} a_{sr} \cdot F_s} \qquad (36)$$

As shown in Equation 36, the air traffic complexity of sector combination r is derived from the weighted sum of the air traffic complexity of the constituent sectors. The weighted coefficient is the current traffic flow inside the sector.

4.4 Computational Example

We calculate the hourly optimal sector configuration schemes of Beijing Regional ATC Center in a typical day - Jan 4, 2008. The curves of the hourly variations of air traffic complexity of each sector are shown in Figure 11(a). The curves of the hourly variations of controller's workload are shown in Figure 11(b). Figure 10 shows the optimal sector configuration scheme during the time period from 8:00am to 9:00am. Eight sector combinations are chosen to open for the whole ATC region. Figure 11(c) shows the optimal sector configuration in each hour, each grid of which represents an opened sector combination. The first number in a grid indicates the serial number of opened sector combination and the second number represents the controller's workload of the sector combination during current time period. It shows that the controller's workloads are kept balanced, i.e. basically around 25, among all opened sector combinations after adjustment.
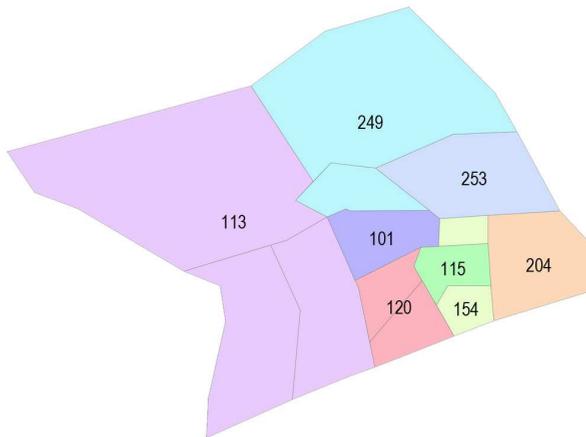

Fig. 10. Optimal Sector Configuration of Beijing ATC Region (8:00-9:00 Jan 4, 2008)

(a) Hourly Variations of Air Traffic Complexity of Each Sector

(b) Hourly Variations of Controller's Workload of Each Sector

	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
9														102 24	101 35	101 32							
8								101 33	101 29	101 27		101 25	102 25	106 28	102 30	102 24	101 32						
7								113 19	113 24	102 23	114 27	113 28	113 22	111 22	113 24	113 19	102 24	102 24	112 29				
6								115 20	115 36	126 23	115 28	115 39	115 41	115 38	115 60	115 36	115 25	113 22	115 35	113 25	102 25		
5								120 20	120 28	126 23	120 27	119 24	118 21	118 24	118 25	115 37	115 38	120 25	115 35	115 36			
4								154 23	154 26	154 25	154 26	154 28	154 23	154 26	154 28	154 28	118 23	119 26	154 21	120 28	126 25		
3	132 21							204 35	204 27	204 30	204 36	204 30	204 34	204 47	204 36	204 29	154 24	154 27	204 21	205 31	154 28	115 25	
2	249 24	202 20					252 24	249 21	249 17	251 28	249 27	249 24	249 26	247 22	249 23	249 25	204 23	204 18	251 15	247 28	252 29	133 28	202 23
1	305 24	443 18	538 11	538 15	538 19	344 27	253 26	253 27	253 30	253 28	253 32	253 18	253 25	253 40	253 25	351 28	351 27	253 21	258 21	286 29	454 28	443 23	

(c) Hourly Optimal Sector Configurations

Fig. 11. Computational Results (Jan 4, 2008)

5. Conclusion

This chapter investigates the models and algorithms for implementing the concept of Dynamic Airspace Management. Three models are discussed. First two models are about how to use or adjust air route dynamically in order to speed up air traffic flow and reduce delay. The third model gives a way to dynamically generate the optimal sector configuration for an air traffic control center to both balance the controller's workload and save control resources. The first model, called the Dynamic Air Route Open-Close Problem, is the first step toward the realization of Dynamic Airspace Management. It designs a pricing mechanism for civil users and military users once they need to use each other's resources and decides what routes will be open and for how long the routes keep open for a certain user during a given time period. The second model, called the Dynamic Air Route Adjustment Problem, provides a new approach to optimize air traffic flow with the option to adjust or reconstruct the air route

network. This model extends the formulation of the ATFM problem by integrating the consideration of dynamic opening and closing of air route segments and introducing several new constraints, such as the shortest occupancy time constraint and the indegree and outdegree constraints, which have not been considered in previous research. The algorithm provides management insight for improving the current airspace management strategy from static to dynamic, from restricted to flexible, and from policy-based to market-based. The sensitivity analysis provides useful reference for pricing temporary arcs in the new flexible market-based airspace management system. The third model, called the Dynamic Sector Adjustment Problem, tries to dynamically utilize airspace resources from another viewpoint. Dynamic adjustment to air traffic control sectors according to the traffic demand is an important means of increasing the efficiency of airspace utilization. We present an empirical model of evaluating controller's workload and build a set-partitioning based mixed integer programming model searching optimal sector configurations. Several examples are solved based on the data from Beijing Regional Air Traffic Control Center. The computational results show that our models on Dynamic Airspace Management are suitable to solve actual-sized problems quickly using current optimization software tools. The work of model validations and implementations are to be completed in the future.

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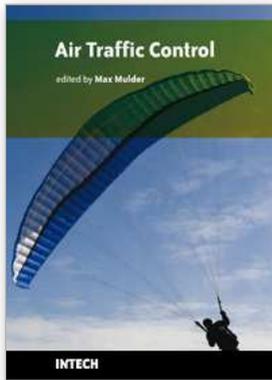
Air Traffic Control

Edited by Max Mulder

Improving air traffic control and air traffic management is currently one of the top priorities of the global research and development agenda. Massive, multi-billion euro programs like SESAR (Single European Sky ATM Research) in Europe and NextGen (Next Generation Air Transportation System) in the United States are on their way to create an air transportation system that meets the demands of the future. Air traffic control is a multi-disciplinary field that attracts the attention of many researchers, ranging from pure mathematicians to human factors specialists, and even in the legal and financial domains the optimization and control of air transport is extensively studied. This book, by no means intended to be a basic, formal introduction to the field, for which other textbooks are available, includes nine chapters that demonstrate the multi-disciplinary character of the air traffic control domain.

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