Departure Scheduling in a Multi-airport System

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Abstract—In this paper, we consider a scheduling problem for multi-airport departure flights. A mathematical model is presented for sequencing departure flights in different airports within one terminal area. Due to the traffic influences between airports, both airport runways and departure routes are considered in the model. Moreover, practical issues that affect the implementation of the schedule are also carried out by the Constraint Position Shifting (CPS). Then a tabu search algorithm is developed and implemented to obtain reasonable solutions within acceptable computation times. Finally, we apply the proposed model and algorithm to a real case study of Shanghai Terminal Area with departure flights from Shanghai HongQiao International Airport and Shanghai PuDong International Airport. The computational results validate the proposed model and show the advantage of the algorithm. Efficient scheduling flights for takeoff can fully utilize critical resources and reduce the impact of traffic interaction between airports.

Keywords- Air Traffic Flow Management, Multiairport System, Departure Scheduling, Tabu Search Algorithm.

I. INTRODUCTION

Tremendous growth in air transportation demand is challenging the existing Air Traffic Management (ATM) system. When ATM capacity can not meet the traffic demand, airspace congestion and flight delays occur. Great efforts have been made to ensure the safety and efficiency of the ATM system. Significant improvements have already been achieved in increasing airport capacity, such as construction of new airport and expansion of runway system. New operational methods and tools are applied in air traffic flow management (ATFM) field. The important aspects of ATFM are the management of departure flow and arrival flow in terminal area, which are known as departure management and arrival management.

There is considerable amount of literature on arrival scheduling problem (ASP). The earliest work in this field could be found in [1], where Dear studied the aircraft scheduling problem with position shift constraint. In [2] and [3], where Psaraftis and Bianco showed that the ASP is equivalent to the cumulative asymmetric traveling salesman problem. They used a dynamic programming formulation to attain lower bounds for the problem and then heuristic algorithms were applied to get solutions. Another wealth of information can be found in [4], in which an extensive literature overview on the arrival problem was made. Then Beasley et al. gave a mixed integer programming model for arrival sequencing problem. In the model, terminal area was treated as a single resource; different constraints (such as landing times or time windows) and different objective functions were adopted. However, these studies did not provide munch attention to the airspace restriction. In [5] and [6] Erzberger and Gilbo demonstrated that congestion might appear not only in the runway but also in the fixes. Papers relevant to arrival problems with airspace constrained were published in [7-10], Aircraft maneuver, a few airspace segments of final approach and holding patterns were considered in their work respectively.

Many researchers have recently turned to the departure scheduling problem (DSP). Bolender in [11] studied two major problems relating to the departure management. The first one is the scheduling of aircraft for departure and the second is merging departure flights onto their filed routes in a congested airspace environment. Greedy search algorithms and genetic algorithms were designed to minimize the total time to depart a set of aircraft. A brief summary of some of relevant work in departure scheduling is presented in [12], where Atkin et al. applied hybrid metaheuristics to aid runway scheduling at London Heathrow Airport. They developed a model based on the specific holding point structure and airspace environment in Heathrow, and proposed a hybrid metaheuristic system to enhance the throughput of runway. In [13], Balakrishnan et al. presented an efficient algorithm based on dynamic programming, to determine departure schedules that satisfy various upstream and downstream constraints.

Furthermore, decision support tools (DST) are developed and utilized to help terminal area controller deal with departure and arrival traffic. Arrival DSTs are Traffic Management Advisor (TMA), the Descent Advisor (DA) and the Final Approach Spacing Tool (FAST), Arrival Manager (AMAN) etc. Departure management tools could assist controller to enhance the departure performance by modification the departure sequence. Departure manager (DMAN) is the tactical controller assistance system, optimizing the air traffic flow form the gate to the departure runway. The Mantea Departure Sequencer (MADS) is a planning decision support tools for tower controller which was developed by the National Aerospace Laboratory NLR.

MADS can assist controller in the establishment of optimal departure sequences and the planning of initial climb phases and as such optimizes the use of runways[14].

However, the previous studies mainly focused on a single airport arrival scheduling (SAASP) or a single airport departure scheduling (SADSP). To the best of our knowledge, none of attempt has been given to scheduling arrival or departure flights in multi-airports within a terminal area. A study presented by Bonnefoy et al. showed that the transition from single-airport to multi-airport systems is and will remain a key mechanism by which the air transportation system scales and will meet growing demand in the future [15]. A geographical distribution of multi-airport systems is illustrated in Figure 1.
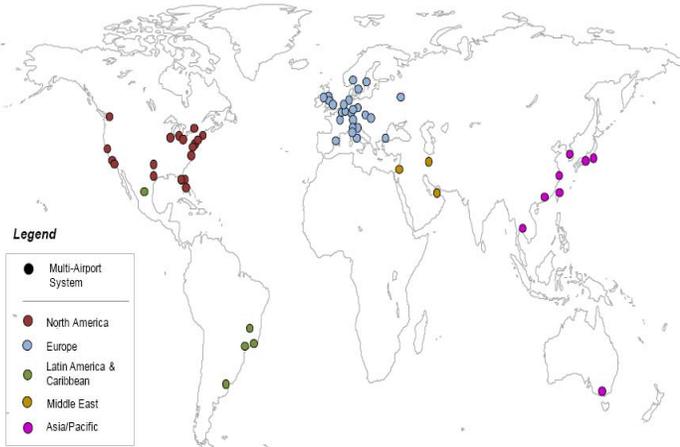

Figure 1. Geographical distribution of multi-airport systems worldwide (cite from [15])

In this research, the definition of multi-airport system is given as: a set of significant airports that serve commercial transport in a metropolitan region, without regard to ownership or political control of the individual airport [16]. In this paper, we develop a new model and an efficient algorithm for computing an optimal departure sequence in multi-airport that within a terminal area. The structure of the paper is as follows. Section II describes the multi-airport departure scheduling problem (MADSP) in detail. In section III we present a mixed integer program model of MADSP. A hybrid search algorithm to obtain reasonable solution is designed in section IV. The implementation of this approach to realistic scenarios draw from data of departure flow from Shanghai Terminal Area is given in section V. The paper ends with some conclusion in section VI.

II.   MULTI-AIRPORT DEPPARTURE SCHEDULING PROBLEM

A simplified operational scheme of terminal area with multi-airport system and the departure process at each airport and fixes is shown in Figure 2. The purpose of departure scheduling in multi-airport is to determine an optimal sequence and takeoff times under different objectives. These objectives include maximizing the runway throughput, minimizing the total delay, and ensuring airlines' or airports' equities in the departure sequence. To optimize the departure

sequence one needs to satisfy the following constraints that are imposed on the terminal area system.

A.   Minimum Takeoff Separation

A minimum takeoff separation between aircrafts from the same airport must be enforced for the consideration of departure safety. The required time separation S_{ij} for two consecutive aircraft i and j is determined by the wake types of two aircraft and the Standard Instrument Departure (SID) routes which they are using. Aircraft are divided into there types (Heavy, Medium, and Light) according to the maximum takeoff weight capacity. A wake vortex separation w_{ij} is required for aircraft j to prevent wake-vortex caused by the former aircraft i . Parallel runways may be used for independent instrument departures if the runway centre lines are spaced by the distance specified in Annex 14, Volume I and the departure tracks diverge by at least 15 degrees immediately after takeoff. Otherwise a segregated operation mode may be used. Additionally, to ensure that aircraft will not cause airspace congestion, the route spacing requirement r_{ij} for aircraft using different SIDs is defined. This depends on the SID group and aircraft speed group. Here a minimum takeoff separation $S_{ij} = \max(w_{ij}, r_{ij})$ is achieved.
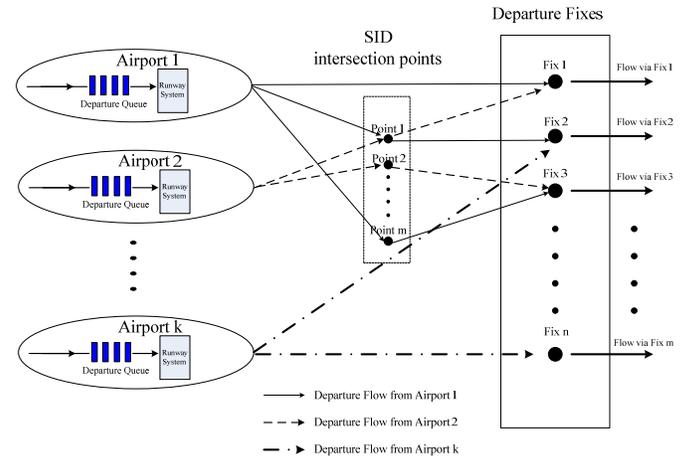

Figure 2. Scheme of departure in terminal area with multi-airport

B.   Departure Time Window

A departure time window will be assigned to a particular aircraft, to which the aircraft must adhere. It is possibly because of downstream traffic flow management to avoid congestion en route and at busy destination airports. These time windows impose an earliest and latest departure time for an aircraft. If any aircraft missed its time window, it will be delayed for another chance of allocating time window. This usually happens in U.S. airports or European airports. In China we impose a minimum takeoff separation between two consecutive aircraft which have the same destination instead of departure time window. For example, aircraft from Guangzhou to Beijing must meet a minimum of 10 minutes takeoff separation requirement. The earliest takeoff time of the later aircraft is 10 minutes late after the former aircraft

departure. No latest time is specified for the later aircraft.

C. Position Shift Constraints

The most common way to sequencing departure flights has been to maintain the First-Come-First-Served (FCFS) order. A FCFS schedule is easy to implement, and it also maintains a sense of fairness. Obviously a drawback of the FCFS schedule is that it may limit the throughput of runway due to large spacing requirement. As discussed previously, the required takeoff separation is based on the types of aircraft and the SIDs group. Heavy aircraft usually cause a large separation while light aircraft have a smaller one. One can obtain a departure queue with the smallest makespan by grouping heavy aircraft and placing them after light aircraft. However, such practice should be given up because it may raise the disapproval of fairness among airliners. The Constrained Position Shifting (CPS) concept was first addressed in[1] by Dear (1976). In the CPS framework, there has a certain degree of flexibility to shift an aircraft in the FCFS sequence by a small number of positions. The Maximum Position Shifting (MPS) as an important parameter is introduced to specify the maximum number of positions an aircraft can shift from its FCFS order. Consequently CPS may increase runway throughput while ensuring some degree of fairness.

D. Multi-runway Operation

For the airport with multiple runways used for departure, the relative magnitude of the delays experienced at each runway can directly affect the capacity and efficiency. Due to the nature of departure demand, aircraft taxi restriction, and controller actions, runway imbalances may occur. Although the global objective is to reduce departure delay, we don't expect the situation that there is a long queue existing at one runway while another runway is idle. The primary sources of departure runway imbalances are the homogeneity in direction of flight during a departure push and the procedures for runway assignments[17]. Assign aircraft to the runway near its apron is a common strategy used by tower controller which can reduce additional taxi time. Runway balancing is complicate and difficult. Scheduling in a multi-runway operational environment is a very difficult problem. Bolender et al. conducted a study to evaluate scheduling strategies for multiple runways[18]. However, scheduling methods for multi-runway is out of the scope of this study. In this paper we discuss the departure scheduling problem that each airport has only one runway used for departure.

E. Traffic Interaction between Airports

The significant difference between SADSP and MADSP is the rule of using the shared and critical departure resources, such as departure fixes and SID segments. In a multi-airport terminal area, departure routes of each airport are stacked in the limited airspace. They may intersect at a fix (including a departure fix) or even have a same route segment. Controller will keep a safe separation for aircraft flying over intersection point. Therefore departure traffic from one airport may have impact on flights from other airports. With intersection limitation, departure scheduling must take the whole flow into consideration; otherwise it will cause airspace congestion and increase controller workload.

III. MODEL OF MULTI-AIRPORT DEPARTURE SCHEDULING

In this section we present a scheduling model for multi-airport to determine departure sequence and departure times for a given set of flights, complying with separation rules. Let $AD = \{1, 2, ..., A\}$ be the set of airports' indices, where A is the number of airports under consideration. Let $PT = \{0, 1, 2, ..., P\}$ be the set of intersection points' indices, where P is the number of the points. Let $FL = \{1, 2, ..., N\}$ be the set of departure flights indices, where N is the total number of flights under consideration. Let $a_i \in AD$ be the airport that flight i departs from. Let $p_i \in PT$ to represent the intersection point in the route of flight i. Particularly, $p_i = 0$ stands for there is no intersection point of flight i. Other variables are defined as follows:

e_i : Earliest take off time of flight i

o_i^j : Position of flight i in the FCFS schedule of airport j

k : A predetermined number of MPS

b_i : Earliest time of Departure Time Window for flight i

l_i : Latest time of Departure Time Window for flight i

F^c : Set of flights with departure time window, $F^C \subset FL$

F_j^a : Set of departure flights from airport j , $F_j^a \subset FL$

N_j^a : Number of flights in the set F_j^a

t_i^p : Flying time of flight i between its origin airport and route point p

τ^p : Required time separation imposed on two consecutive flights that pass route point p

Here we have decision variables:

c_i^j : An integer that represents the position of flight i in the departure order of airport j , $i \in F_j^a$

d_i : The calculated take off time of flight i

When scheduling flights in multi-airport, the sequences of flights passing intersection points have great impact on the entire terminal operating effectively and efficiently. If we swap the positions of two flights i and j that depart from different airports in the sequence, all the flights in the airport a_i that take off after flight i may be delayed. This is one of the major constraints in the multi-airport departure scheduling. So we introduce another decision variable to determine the departure sequence of entire terminal area:

c_i : An integer that represents the position of flight i in the departure order of entire terminal area, $i \in FL$

The departure flight will request to startup when it is ready. No punishment will be assigned to a flight for it takes off before its scheduled departure time. While in an arrival scheduling problem, an additional cost will be produced for a flight landing before its preference time. Since no flight can

take off before it's ready. We have:

$$d_i \geq e_i \quad \text{for all } i \in FL. \tag{1}$$

In this model, the first flight is assumed to take off at its earliest take off time:

$$d_i = e_i \quad \text{if } c_i = 1, \ i \in FL. \tag{2}$$

To alleviate the controllers' workload, rescheduling flights in an airport should satisfy the CPS constraint:

$$|c_i^j - o_i^j| \leq k \quad \text{for all } i \in F_j^a, j \in AD. \tag{3}$$

Flights with departure time window have to take off within the assigned slot or it will be delayed,

$$b_i \leq d_i \leq l_i \quad i \in F^c. \tag{4}$$

Most important aspect of scheduling departure flights is that all flights must comply with the required separation rules. Flights from the same airport should fulfill the minimum takeoff separation requirement. Flights overflying a same route point should maintain a predefined separation. Here we have:

$$d_j \geq \max_{i \in FL | c_i < c_j, a_i = a_j} (d_i + S_{ij}) \tag{5}$$

and

$$\begin{cases} \left| (d_i + t_i^p) - (d_j + t_j^p) \right| \geq \tau^p \\ i, j \in FL, p \in PT \mid c_i > c_j, p_i = p_j = p \end{cases} \tag{6}$$

The terms from (1) to (6) make up the basic constraints of multi-airport departure scheduling model.

The major objective of departure scheduling is to reduce aircraft delay. Here we use the average delay of total flights in the terminal area as the objective function of Model I :

$$J^I(d_i) = \frac{\sum_{i \in FL}(d_i - t_i)}{N} \tag{7}$$

In the model, the average delay suffered by airport j is computed as:

$$D_j^a = \frac{\sum_{i \in F_j^a}(d_i - t_i)}{N_j^a} \tag{8}$$

We aim to minimize the average delay of terminal area while taking each airport's average delay under consideration. The objective function of Model II is introduced as following:

$$J^{II}(d_i) = J^I(d_i) + \sum_{j \in AD} \left| D_j^a - J^I(d_i) \right|^{\alpha_j} \tag{9}$$

The coefficient α^j works as the weight of airport j. It allows us to achieve different objective by adjusting α^j under different situation.

IV. TABU SEARCH APPROACH

Tabu search (TS) algorithm in [19, 20] is a metaheuristic approach designed to find a near-optimal solution of combinatorial optimization problem. The basic idea of TS is to explore the search space of all feasible scheduling solution by a sequence of moves. Vaessens showed that TS methods are superior over other approaches (in specific job scheduling cases) such as simulated annealing, genetic algorithms, and neural networks[21]. The algorithm can be sketched as follows: TS starts with an initial feasible solution x_0, and replace x_0 by the best neighbor solution $x^.$ which is determined by means of the measuring function and a tabu list. In each iteration step, a tabu list is used to remember the local optimal solution and the recent moves in order to prevent repeating these processes in next few steps. If the neighborhood set is connected, then the global optimal solution will be found by using the TS algorithm. There are total five key essentials of TS algorithm: (1) Initial solution; (2) Neighborhood searching; (3) Tabu list; (4) Measuring function; (5) Stop condition.

(1) Initial Solution

In order to be applied, the TS algorithm requires an initial solution. FCFS policy may be used to get the initial solution. For all flights under consideration, a sequence x_0 in order of ascending ETD with several adjustments will be the starting point for TS. The principle of adjustments is that try to scatter the aircraft that using the same route points in the sequence while under the CPS constraint. For example, the origin departure sequence is shown in the Figure 3. Flight 3 from airport 1 and flight 11 from airport 2 use the same route point 3. Although swap the poisons of flight 3 and 4 in the sequence of airport 1 can cause a bigger wake separation, it will avoid the route point conflict which could evoke the huge traffic delay. The initial departure sequence for TS algorithm after adjustment is shown in Figure 4.
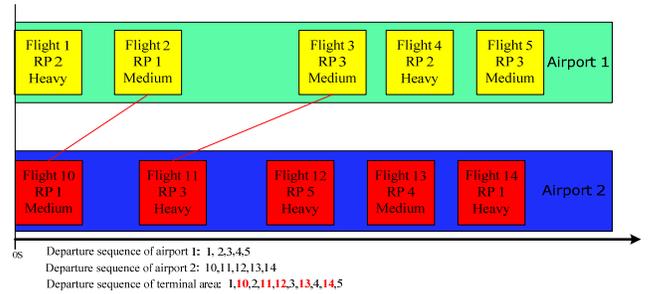

Figure 3. Origin departure sequences of flights in terminal area
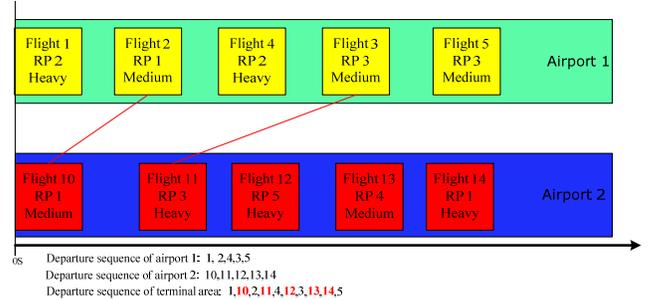

Figure 4. Initial departure sequence of flights for TS algorithm

(2) Neighborhood Searching

Our neighborhood $N(x)$ is defined as a constrained 2-opt. A neighbor is generated by swapping the positions of two aircraft in x while complying with the CPS. It must be noted that the CPS constraint is imposed on the departure sequence of each airport. Simply swap two positions of aircraft in the terminal sequence with predefined MPS will reduce the solution-space. We use the following way to generate the neighborhood. First, randomly select two aircraft in the terminal sequence and swap their position without consideration of CPS constraint. Second, validate the new sequence by checking whether every departure sequence of each airport is satisfying the CPS constraint. If this neighbor is an effective move, then add the neighbor in the $N(x)$; otherwise abandon the sequence and generate a next neighbor.

A candidate set $V(x)$ is used to alleviate the computational burden. If $n(N(x)) > 100$, we randomly generate 100 new neighbors to make up $V(x)$; else we select the whole neighborhood $N(x)$ as candidate set $V(x)$.

(3) Tabu List

A tabu list is built up from the history of moves used to explore search space until the old solution area is left behind. The last 20 moves of each aircraft are stored in the tabu list. Any moves that place the aircraft back to its initial position remembered in the list is rejected.

Two aspiration criteria will be used in the process of iteration. One criteria is that when all solutions in candidate set are forbidden, then the solution with minimal objective value is chosen to unbind. The other is that although one solution is forbidden but its measuring function value is better than the value of the current best solution, then this solution can be unbound and return to the candidate set.

(4) Measuring Function

A new starting point will be selected from candidate set through the measuring function. Here we take the objective function $J^{II}(d_i)$ as the measuring function.

(5) Stop Condition

As a heuristic algorithm, the TS algorithm is designed to find a satisfactory solution of the problem within an acceptable time-span. The TS algorithm stops after it has run for a predetermined number of iterative steps MAX_ITER. Another condition that algorithm terminated is when the objective value does not decrease in limited steps MAX_OPT. In our implementation, MAX_ITER=1000 , MAX_OPT=200.

(6) The algorithm procedure

Step 1. Get an initial solution x^{now} as described in (1). Let the iteration number $N_{iter}=0$, the number of optimal solution occurs $N_{opt}=1$, the current optimal solution $x^* = x^{now}$, and set tabu list $T = \Phi$.

Step 2. (a) If $N_{iter}=$MAX_ITER ,or $N_{opt}=$MAX_OPT, terminate the algorithm and output the optimized solution.

(b) Else randomly select 100 new solutions in $N(x^{now})$ or the whole $N(x^{now})$ to form the candidate set $V(x^{now})$. These solutions are not forbidden or unbound formed under aspiration criteria.

Step 3. For all solutions in $V(x^{now})$, get the optimal one and denote it by x^{next}, and let $x^{now} = x^{next}$, $N_{iter}=N_{iter}+1$.

Step 4. (a) If $F(x^{now}) < F(x^*)$, let $x^* = x^{now}$, $N_{opt}=1$; (b) Else let $N_{opt}=N_{opt}+1$.

Step 5. Update T, then goes to step 2

V. CASE STUDY

A. Scenario

In this section, we apply our model and algorithm to assess the potential benefits. Here we use departure data on 11th December 2006 in Shanghai Terminal Area based on the flight data from Operations Management Centre of Air Traffic Management Bureau, CAAC. Shanghai Terminal Area is one of the busiest terminal areas in China which covers two hub airports, namely Shanghai HongQiao International Airport (ZSSS) and Shanghai PuDong International Airport (ZSPD). A simplified terminal airspace is shown in Figure 5. There are a total of 567 flights that are scheduled to depart from Shanghai Terminal Area (252 from ZSSS and 315 from ZSPD) during that day. The departure demand at the airports distributed for each hour is shown in Figure 6. We select the flights from 15:00 to 16:00 as the input in our experiment. Table 1 shows the statistics result of departure flights for each airport through different fixes during the period.
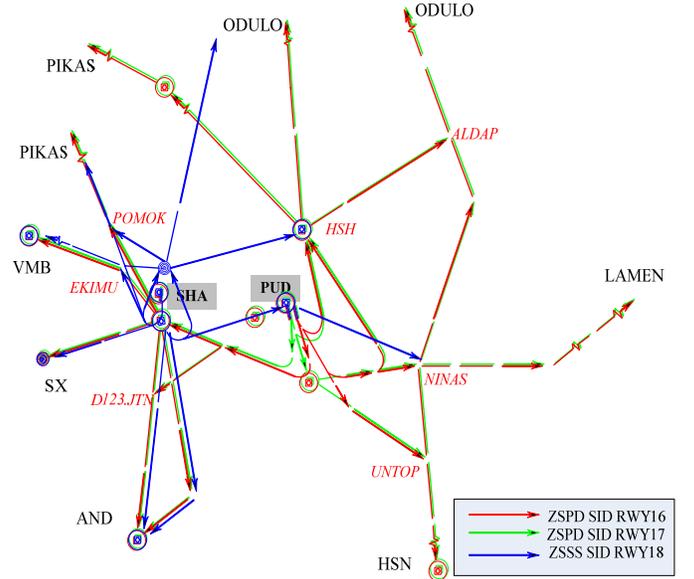

Figure 5. Standard Instrument Departure of Shanghai Terminal Area (From AIP)
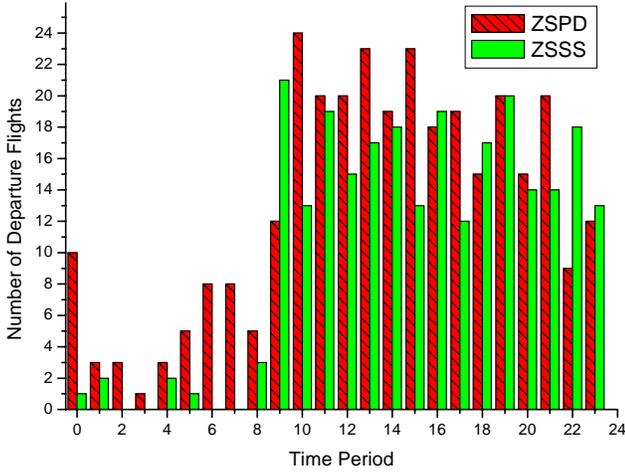
Figure 6. Histogram of departure rates at Shanghai terminal area on Dec.11, 2006

Table 1. Statistics result on number of departure flights from 15:00 to 16:00

Fix / Airport	HSN	LAMEN	ODULO	PIKAS	SX	Total
ZSPD	8	2	4	3	3	20
ZSSS	0	0	0	9	9	18
Total	8	2	4	12	12	38

In this experiment, the minimum runway separation is 2 minutes as all aircraft types in experiment are either heavy or medium. The required time separations at different fixes according to flight destination are listed in table 2. Based on the model and algorithm described in previous sections, we developed a prototype system to schedule departure flights in multi-airport with Microsoft Visual C++ 6.0. The computing time is in order of 1 – 2 minutes run on a PC with 1.4 GHz processor speed. Below we present the computational results using above data under three different cases. Case A is that ZSPD is open while ZSSS is closed. Case B is that ZSSS is open while ZSPD is closed. Case C is that both ZSPD and ZSSS are open during the period.

Table 2. Minute-In-Trail requirement at departure fixes

Fix	Minute-In-Trail Separation
HSN	Flights to Hong Kong and Macao require an 8 minutes distance; others 5 minutes
PIKAS	7 minutes
SX	Flights which depart from the same airport require a 7 minutes distance；otherwise 3 minutes
ODULO	8 minutes
LAMEN	5 minutes

B. FCFS Schedule and Model I Schedule

To illustrate the traffic interaction between airports, a departure delay result under different cases is summarized in table 3. As expected, the average delay at each fix (even HSN, LAMEN, and ODULO) and airport under Case C is much higher than that of Case A or Case B, no matter in a FCFS policy or in an optimal policy. It must be pointed out that the amount of flights departing through PIKAS and SX exceeds the total flights of entire terminal area by 60%, which includes

all the flights from ZSSS and 25% of the flights from ZSPD. Therefore, a conclusion may be made that the interaction of traffic through the PIKAS and SX has a great impact on the whole departure flow. Hence, smoothing the traffic through PIKAS and SX is the key element to reduce the average delay.

Table 3. Comparative results on aircraft delay under different cases and policies (in minute per aircraft)

Fix/Airport	Case A		Case B		Case C	
	FCFS	Model I.	FCFS	Model I.	FCFS	Model I.
HSN	7	1	—	—	18.375	8
LAMEN	4	4	—	—	14.5	7
ODULO	7	10.5	—	—	14.5	11.75
PIKAS	5.67	1.33	20	5.44	27.17	12.92
SX	4.33	1.67	19.44	12.56	23.58	15.5
ZSPD	6.1	2.95	—	—	15.95	10.25
ZSSS	—	—	19.72	9	29.11	14.5
Terminal	6.1	2.95	19.72	9	22.18	12.26

Table 4 shows the statistics result of separation between every two consecutive flights at different fixes. We note that the average departure separation of each airport under Case C is greater than they open separately. This result clearly indicates that the runway capacity is no longer the primary cause of flight delay. At the same time, in an optimal policy, the separation at PIKAS and SX drops to the lowest, 7.09 minutes (7 minutes is the lower bound) and 5.82 minutes respectively (see Table 5.). The capacities of these two fixes are fully utilized. This is in accordance with the conclusion discussed previously and supports that making best use of shared and critical departure resources is of significance in scheduling aircraft departure at airports.

Table 4. Average time intervals between aircraft at fixes (in minute)

Fix/Airport	Case A		Case B		Case C	
	FCFS	Model I.	FCFS	Model I.	FCFS	Model I.
HSN	8.43	8.43	—	—	9.43	8.57
LAMEN	41	35	—	—	25	24.5
ODULO	9	15	—	—	12.33	14
PIKAS	**27**	**23**	**9.75**	**7.25**	**8**	**7.09**
SX	**22.5**	**21**	**9.75**	**7.75**	**8.09**	**5.82**
ZSPD	3.42	3.42	—	—	4.26	3.78
ZSSS	—	—	4.71	3.65	5.53	4.18

Table 5. Time intervals between aircraft at PIKAS and SX, Case C (in minute)

	PIKAS		SX	
	FCFS	Model I	FCFS	Model I
1	7	8	7	3
2	**18**	7	8	4
3	7	7	3	8

4	7	7	4	7
5	7	7	7	8
6	7	7	**18**	6
7	7	7	7	7
8	7	7	**16**	7
9	7	7	5	7
10	7	7	7	3
11	7	7	7	4
Average	**8**	**7.09**	**8.09**	**5.82**

Figure 7 depicts the departure sequence and departure time of each flight. As can be seen, the departure time with optimal sequence are much better distributed than a FCFS sequence in the entire time-span. In the optimal sequence, flights from ZSSS and ZSPD take off alternately, and the average delay reduces from 22.18 minute per aircraft to 12.26 minute per aircraft.
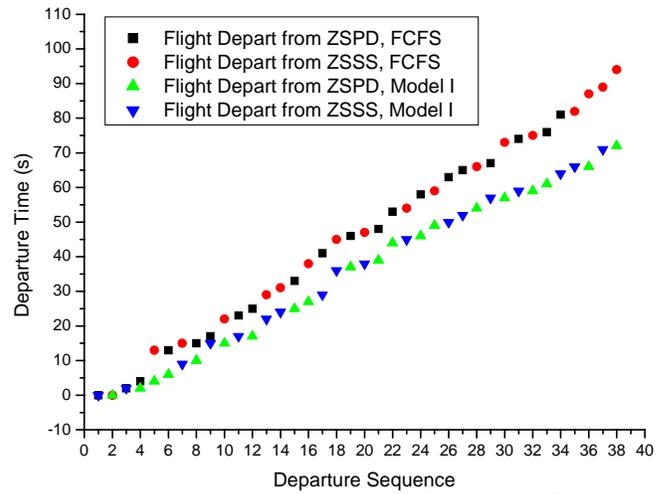

Figure 7. Departure time and sequence for flights under different policies

C. Comparison of Model I and Model II

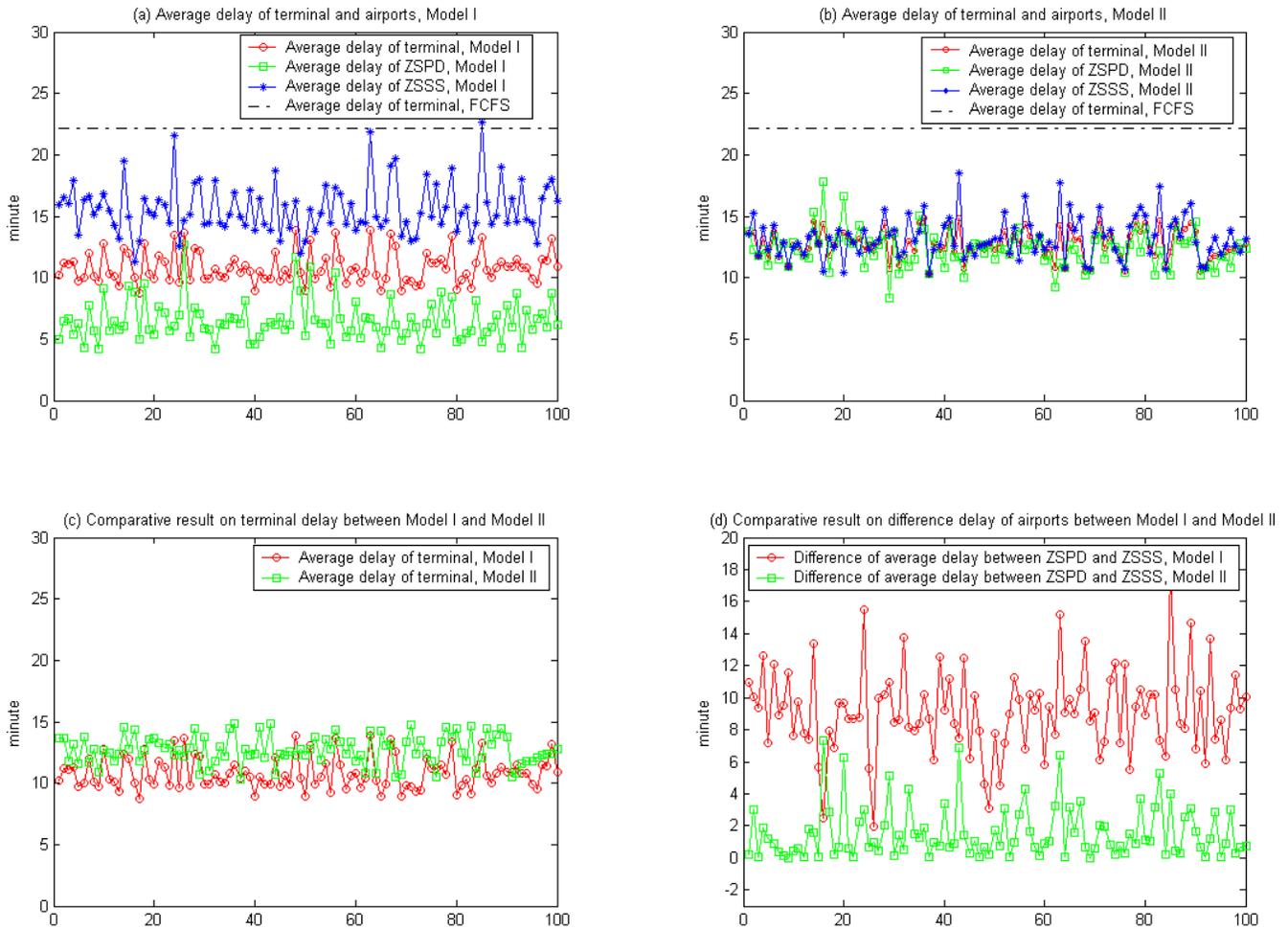A comparison of Model I and Model II was carried under

Figure 8. Computational results on average delay of Model I and Model II

Case C to show the influence between airports. The graphical representation of the terminal delay and airport delays is shown in Figure 8. As expected, there is a little fluctuation of terminal delay during the 100 computational tests both in Model I and Model II (see Fig. 8(a) and Fig. 8(b)). This could be explained by the nature of the TS algorithm. As one kind of heuristic algorithm, TS algorithm could not guarantee find the global optimal solution. However it provides you a satisfactory solution within an acceptable time horizon. Attention should be paid to that there always exist about 10 minute differences of average delay between ZSSS and ZSPD in Model I. This is probably due to the objective of Model I, which is to minimize the average delay of terminal area rather than minimize average delay of every single airport. Although the entire terminal delay of Model II is 2 minutes higher than that of Model I (see Fig. 8(c)), the differences of delays between the two airports decreased to 1 minute by setting coefficient $\alpha_1 = \alpha_2 = 2$ (see Fig. 8(d)). All of flights depart from ZSSS use only two departure fixes, which are PIKAS and SX. Without the competition of ZSPD, the lower bound of ZSSS delay is about 9 minute per aircraft (see Table 3.). That is the main reason ZSSS always has a higher delay than ZSPD.

VI. CONCLUSION

In this paper, we proposed a new model for solving departure scheduling problem in multi-airport system. In the model, both runways and departure fixes were considered as the critical resources of terminal area. The fairness among airliners was guaranteed by the CPS. Additionally, a tabu search algorithm has been built and realized in order to get a global optimal solution of the problem. The presented model and algorithm were validated through the operational flight data of Shanghai Terminal Area. From the above discussion, it seems that the limited capacity of departure fixes is the main factor confining the growth of departure flow in multi-airport system. Optimize utilizing the shared departure fixes will result in an enhancement of terminal capacity. Departure traffic interaction between airports can bring the unfairness among airports. Fortunately this can be eliminated by a reasonable departure control strategy. Some improvement to the departure scheduling may be including the airliners' preferences in the model. Integral scheduling departure and arrival flow in terminal area will be another challenging aspect in ATFM field.

AUTHOR BIOGRAPHY

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