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# A two-stage no-wait hybrid flow-shop model for the flight departure scheduling in a multi-airport system

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**Abstract**—To effectively alleviate the increasingly serious situation of airspace congestion and flight delays in a multi-airport system, we consider a scheduling problem for multi-airport departure flights in this paper. A mathematical model based on two-stage no-wait hybrid flow-shop is presented for sequencing departure flights in different airports within one terminal area. Moreover, some practical issues which affect the performance of the schedule are also carried out by the Constrained Position Shifting (CPS). Then a CPLEX program is developed and implemented to obtain reasonable solutions within acceptable computation time. 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 do prove the advantage of the proposed model and the algorithm. An efficient scheduling for departure flights can fully improve the utilization of critical resources and reduce the impact of traffic interaction between airports.

## I. INTRODUCTION

The existing Air Traffic Management (ATM) systems are facing great challenges because of the rapid growth in air transportation demand. When ATM capacity cannot meet the traffic demand, airspace congestion and flight delays occur. Great efforts have been made to ensure the efficiency of the ATM system and increase the capacity of airport, such as construction of new airports and expansion of runway system. But they cannot be achieved in a short term. Therefore, it is very necessary to schedule air traffic demand scientifically, optimize the allocation of time and space resources in the terminal area and improve the efficiency of a multi-airport system. New methods and tools are applied to work in the fields of Air Traffic Flow Management (ATFM), which is mainly focused on the management of departure flow and arrival flow in terminal area.

There is a number of literature on Arrival Scheduling Problem (ASP) and Departure Scheduling Problem (DSP). Aiming at minimizing the total delay cost, Tian et al. builds up dynamic optimizing models of the arrival flight scheduling, and use the simulated annealing algorithm to solve this problem, which could be found in [1]. In [2] Liu et al. put forwards a real-time decision support system, which provides air traffic controllers with optimized advisories on arrival sequence and schedule,

and can help improve efficiency and safety of arrival traffic flow ultimately. And Eun et al. based on a branch-and-bound algorithm with linear programming (LP) and Lagrangian dual decomposition, contributed an algorithm for optimal arrival flight sequencing and spacing in a near-terminal area, which could be found in [3]. In [4] considering the weather, air traffic control, route and other factors, Zhou et al. establish the model to make optimization of approach and departure flight scheduling, and a genetic algorithm was introduced to solve the model, which improves the runway throughput and reduces flight delay losses. In [5] to reduce system delay, a mixed integer linear program is presented by Gupta et al. for deterministic departure scheduling at runways, which is generic and can address various scenarios of departure queue handling. Through Compromise Immune Algorithm (CIA), optimization of departure and arrival flight is achieved to decrease delay cost, based on ensuring security and considering airport capacity limit, which could be found in [6]. However, we can see that these studies all focus on single-airport arrival and departure scheduling, ignoring to take the multi-airport scenario into consideration. That is to say, scheduling of arrival or departure flights in multi-airports system within a terminal area has been given a few attempt. In multi-airports system with dynamic sector capacity restriction, Wang et al. propose a new MAGHP dynamic model to minimize the total delay cost, and a heuristic optimal algorithm is used to solve it. By transforming anticipated airborne delays to the ground delay, they need to decide which flight should be delayed to take off and how long it is delayed, which could be found in [7]. However, it is only concerned about the delay cost and there is no exact algorithm. In [8], to minimize the total delay, Jiang et al. present a capacity allocation and flow assignment model for open multi-airport network, which help make decisions on the optimized arrival and departure time of every flight. However, they only take airport capacity restrictions into consideration, ignoring airspace sectors and en routes capacity. In [9], to solve the problem of the balance of traffic supply and demand in multi-airports terminal area, Chen et al. establish MOIPSO model, based on collaborative capability-flow allocation. Their objectives are to minimize the total delay time and cost, and maximize the fairness between

air companies. However, this model can be extended to a wider range of traffic network consisting of sector, air routes and others to promote the study.

In this paper, we creatively develop a new scheduling model, based on a two-stage no-wait hybrid flow-shop theory, and apply CPLEX algorithm for computing an optimal departure sequence in a multi-airport system within a terminal area. A two-stage no-wait hybrid flow-shop consists of two stages and stage  $j$  has  $m_j$  identical parallel machines ( $j = 1, 2$ ).  $N$  given jobs  $J_i$  are to be processed on the two stages in the same technological order, first on stage 1 and second on stage 2. An operation of any job consists of three phases: setup, processing and removal. Applying it to this paper, we regard the aircrafts, airports, and points as jobs, machines on stage 1 and machines on stage 2, respectively. But there are also some differences between them. For example, job  $j$  requires a processing time on each stage, which is not needed by aircrafts. By modeling like this, we can independently analyze the departure process and utilization of resources of time and space of aircrafts from different airports, and analysis the interactions between them systematically. And the algorithm can produce an exact solution within reasonable computation time, which help the airport managers decide departure scheduling scheme satisfying no-wait constraint, and minimize the total weighted delay cost. The contribution of this paper may include: (i) we creatively apply a two-stage no-wait hybrid flow-shop model to the multi-airport scheduling problem, to minimize the total weighted delay cost. (ii) A CPLEX algorithm is developed and implemented to obtain exact solutions within acceptable computation time, which help to sequence departure flights in different airports without waiting in the air. The paper is organized as follows. Section 2 describes the Multi-Airport Departure Scheduling Problem (MADSP) in details. In Section 3 we present an integer program model and CPLEX to obtain reasonable solutions. The implementation of this approach to realistic scenarios needs data of departure flights from Shanghai Terminal Area, which is given in Section 4. Finally we conclude the main contribution in Section 5.

## II. PROBLEM DESCRIPTION

When making departure scheduling in a multi-airport system, the key issues we have to determine are optimal sequences and takeoff times under different objectives. These objectives are diverse, including improving the runway throughput, reducing the total delay and total cost, ensuring airlines or airports equities in the departure sequence and so on. In this paper, the objective is to minimize the total weighted delay. To optimize the departure sequence one needs to satisfy the following constraints that are imposed on the terminal area system.

### A. Take-off Separation

For the sake of departure safety, when two aircrafts departure from the same airport, a takeoff separation time must be imposed. The required separation time  $S_{ij}$  for two successive aircraft  $i$  and  $j$  is determined by the wake types of two aircrafts and the SID routes they are using. According to the maximum

takeoff weight capacity, aircrafts are divided into three types, they are, heavy, medium, and light. In order to avoid the wake-vortex caused by the former aircraft  $i$ , it is very necessary for us to arrange a wake-vortex separation  $w_{ij}$  for aircraft  $j$ . In addition, to prevent the airspace congestion caused by aircraft, we need to define the route spacing requirement  $r_{ij}$ . Thus a minimum takeoff separation  $S_{ij} = \max(w_{ij}, r_{ij})$  is obtained.

### B. Departure Time Window

To avoid congestion en route and at busy destination in downstream traffic flow management, aircrafts must have their own departure time window respectively, which they have to comply with. These time windows give an earliest and latest departure time for an aircraft. Once an aircraft missed its time window, it will be delayed and have to wait for another chance to be allocated time window. This phenomenon often appeared in the US or European airports, while in China a minimum takeoff separation time is used to solve the scruple, instead.

### C. Position Shifting Constraints

With the advantage of operating easily, as well as obtaining a sense of fairness to some degree, the First-Come-First-Served (FCFS) order is considered as the most pervasive method to sequence departure flights. However, under the requirement of wide spacing, it is apparent that the runway throughput may be limited by using the FCFS schedule. Based on the previous conclusion, that the takeoff separation is closely related to the aircraft type and the SID group, obviously heavy aircraft requires a larger separation than light one. Hence, the makespan of departure queue can be reduced by grouping heavy aircrafts and arranging the light ones before them. Nevertheless, it is infeasible to carry out such strategy for disobeying the principle of fairness among airlines, which motivate the concept of Constrained Position Shifting (CPS) to come into being. According to the conception of CPS, the number of positions an aircraft can transfer from its FCFS order is limited. To restrict the maximum feasible numbers, the Maximum Position Shifting (MPS) is adopted as a control parameter. Thus, CPS is an efficient method to improve the throughput of runway with a decent fairness among airlines.

### D. Traffic Interaction between Airports

Multi-airport Departure Scheduling Problem (MADSP) is much more complicated than Single-airport Departure Scheduling Problem (SADSP), because of the effect of shared and critical departure resources, including departure fixes and intersection points. Various departure routes are aggregated in a restricted airspace. Therefore, it is very important for the controller to make an appropriate safe separation between aircrafts flying through the intersection point, which may cause the aircraft from different airport have an effect on each other. Under the restriction of intersections, the departure scheduling of a multi-airport system is supposed to be considered comprehensively, in order to avoid airspace chaos and burden the controller with unnecessary work.

### III. MATHEMATICAL FORMULATION

In this section, we present an integer programming formulation for the considered problem. We view all the airports as the first stage machines and all the intersection points as the second stage machines. Suppose the number of all physical intersection points is  $|B| - 1$ , and for the flights not passing intersection points, we virtually formulate a  $|B|$ -th intersection point, in which all these flights pass it. Notice that through the  $|B|$ -th intersection point, all flights passing it do not required to keep a setup time in between two flights. In the first stage, we have  $|A|$  airports. As each flight is previously assigned an airport, we do not need decision variables to describe the airport assignment decisions. As each flight is also previously assigned an (physical or virtual) intersection point we do not need decision variables to describe the intersection point assignment decisions. As once flights depart, they cannot wait in line before the intersection points in the air, we model this phenomenon as so-called *no-wait* constraints. That is, the departure time from intersection points  $S^B$  is equal to the departure time of a flight  $C^A$  plus a certain given flying time  $\tau$  from airports to intersection points, i.e.,  $C^B = C^A + \tau$ . On an airport in the first stage, the departure times of two consecutive flights must keep a certain difference, to guarantee safety. We model this separation time as setup time  $S^A$ . Similarly, the certain separation time  $S^B$  between two consecutive flights passing the same intersection point must be respected, to maintain flight safety.

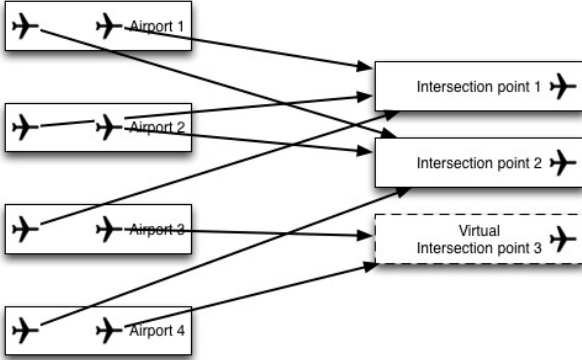


Fig. 1. An example of Multi-airport system

#### Indices:

- $i, j$ : flight indices;
- $a$ : airport index;
- $b$ : intersection point index;

#### Problem parameters:

- $N$ : set of flights;
- $A$ : set of airports (at the first stage);
- $B$ : set of intersection points (at the second stage);
- $X_{ia}^A$ : 0-1 parameter, equals to 1 means flight  $i$  departs from airport  $a$ , 0 otherwise;
- $X_{ib}^B$ : 0-1 parameter, equals to 1 means flight  $i$  passes intersection point  $b$ , 0 otherwise;

- $q_i$ : position of flight  $i$  in the FCFS schedule at its departure airport;
- $Q$ : a number of maximum position shifting, and in this work we set  $Q = 4$ ;
- $e_i$ : the expected departure time of flight  $i$ , which is also the earliest time it can take off;
- $l_i$ : the latest departure time of flight  $i$ ;
- $\tau_{ab}$ : the flying time from airport  $a$  to intersection point  $p$ ;
- $S_{ija}^A$ : setup time between flight  $i$  and  $j$  if they consecutively depart from the same airport  $a$ ;
- $S_{ijb}^B$ : setup time between flight  $i$  and  $j$  if they consecutively pass the same intersection point  $b$  (note that the setup time is zero if the intersection point is the virtual one);
- $w_i$ : weight of flight  $i$ ;
- $M$ : a very large integer.

#### Decision variables:

- $y_{ija}^A$ : equals to 1 if flight  $i \in N$  is arranged before flight  $j \in N$  and they both departs from airport  $a \in A$ , 0 otherwise;
- $y_{ijb}^B$ : equals to 1 if flight  $i \in N$  is arranged before flight  $j \in N$  and they both pass intersection point  $b \in B$ , 0 otherwise;
- $C_{ia}^A$ : departure time of flight  $i \in N$  at airport  $a \in A$ ;
- $C_i^A$ : departure time of flight  $i \in N$  from airports;
- $C_{ib}^B$ : departure time of flight  $i \in N$  from intersection point  $b \in B$ ;
- $C_i^B$ : departure time of flight  $i \in N$  from intersection points;
- $T_i^A$ : delay time of flight  $i \in N$  departing from airports, which is calculated by  $T_i^A = C_i^A - e_i$ .
- $p_i$ : the position of flight  $i \in N$  in the final departure sequence at its corresponding airport;

Now we are ready to present the mixed integer linear programming formulation as follows:

$$(\text{MILP}) \quad \min \sum_{i \in N} w_i T_i^A \quad (1)$$

where the objective function is to minimize the total weighted delay of all flights.

$$T_i^A = C_i^A - e_i, \quad i \in N \quad (2)$$

where this constraint defines the delay time of a flight.

$$C_{ia}^A \leq X_{ia}^A M, \quad i \in N, a \in A \quad (3)$$

where this constraint imply that if a flight  $i$  is not assigned to airport  $a$ , then its departure time at this airport is  $C_{ia}^A = 0$ .

$$C_{ib}^B \leq X_{ib}^B M, \quad i \in N, b \in B \quad (4)$$

where this constraint imply that if a flight  $i$  do not pass intersection point  $b$ , then its departure time at this intersection point is  $C_{ib}^B = 0$ .

$$C_i^A = \sum_{a \in A} C_{ia}^A, \quad i \in N \quad (5)$$

where this constraint means that the departure of flight  $i$  from airports is the one at which it departs from its assigned airport

a. Notice that among all departures of flight  $i$  (i.e.,  $C_{ia}^A$  for all  $a \in A$ ), at lease  $|A| - 1$  values are zeros.

$$C_i^B = \sum_{b \in B} C_{ib}^B, \quad i \in N \quad (6)$$

where this constraint implies that the departure of flight  $i$  from intersection points is the one at which it passes its assigned intersection point  $b$ .

$$y_{ija}^A \leq X_{ia}^A, \quad \{i \neq j\} \in N, a \in A \quad (7)$$

$$y_{ija}^A \leq X_{ja}^A, \quad \{i \neq j\} \in N, a \in A \quad (8)$$

where these two constraints guarantee that either if flight  $i$  does not depart from airport  $a$ , or if flight  $j$  does not depart from airport  $a$ , then  $y_{ija}^A = 0$ .

$$y_{ija}^A + y_{jia}^A \leq 1, \quad \{i \neq j\} \in N, a \in A \quad (9)$$

$$y_{ija}^A + y_{jia}^A \geq 1 - (2 - X_{ia}^A - X_{ja}^A)M, \quad \{i \neq j\} \in N, a \in A \quad (10)$$

where these two constraints mean if both flights  $i$  and  $j$  depart from the same airport  $a$  (i.e.,  $X_{ia}^A = 1$  and  $X_{ja}^A = 1$ ), there must exist a precedence relation, i.e.,  $y_{ija}^A + y_{jia}^A = 1$ .

$$y_{ijb}^B \leq X_{ib}^B, \quad \{i \neq j\} \in N, b \in B \quad (11)$$

$$y_{ijb}^B \leq X_{jb}^B, \quad \{i \neq j\} \in N, b \in B \quad (12)$$

where these two constraints guarantee that either if flight  $i$  does not pass intersection point  $b$ , or if flight  $j$  does not pass intersection  $b$ , then  $y_{ijb}^B = 0$ .

$$y_{ijb}^B + y_{jib}^B \leq 1, \quad \{i \neq j\} \in N, b \in B \quad (13)$$

$$y_{ijb}^B + y_{jib}^B \geq 1 - (2 - X_{ib}^B - X_{jb}^B)M, \quad \{i \neq j\} \in N, b \in B \quad (14)$$

where these two constraints mean if both flights  $i$  and  $j$  pass the same intersection point  $b$  (i.e.,  $X_{ib}^B = 1$  and  $X_{jb}^B = 1$ ), then there must exist a precedence relation, i.e.,  $y_{ijb}^B + y_{jib}^B = 1$ .

$$C_i^A \geq e_i, \quad i \in N \quad (15)$$

$$C_i^A \leq l_i, \quad i \in N \quad (16)$$

where these two constraints require that the departure time windows of all flights must be respected.

$$C_{ia}^A + S_{ija}^A \leq C_{ja}^A + (1 - y_{ija}^A)M, \quad \{i \neq j\} \in N, a \in A \quad (17)$$

where this constraint implies that if flights  $i$  and  $j$  at airport  $a$  have precedence relation, then the departure time of the later flight  $j$  (i.e.,  $C_{ja}^A$ ) is not smaller than the departure time of the earlier flight  $i$  (i.e.,  $C_{ia}^A$ ) plus a setup time  $S_{ija}^A$ .

$$C_{ib}^B + S_{ijb}^B \leq C_{jb}^B + (1 - y_{ijb}^B)M, \quad \{i \neq j\} \in N, b \in B \quad (18)$$

where this constraint implies that if flights  $i$  and  $j$  passing the same intersection point  $b$  have precedence relations, then the departure time of the later flight  $j$  (i.e.,  $C_{jb}^B$ ) is not smaller than the departure time of the earlier flight  $i$  (i.e.,  $C_{ib}^B$ ) plus a setup time  $S_{ijb}^B$ .

$$C_{ia}^A + \tau_{ab} \leq C_{ib}^B + (2 - X_{ia}^A - X_{ib}^B)M, \quad i \in N, a \in A, b \in B \quad (19)$$

$$C_{ia}^A + \tau_{ab} \geq C_{ib}^B - (2 - X_{ia}^A - X_{ib}^B)M, \quad i \in N, a \in A, b \in B \quad (20)$$

where these two constraints mean that if flight  $i$  departs from airport  $a$  (i.e.,  $X_{ia}^A = 1$ ) and passes intersection point  $b$  ( $X_{ib}^B = 1$ ) then the departure time at intersection point  $b$  (i.e.,  $C_{ib}^B$ ) is equal to the departure time at airport  $a$  (i.e.,  $C_{ia}^A$ ) plus the flying time between  $a$  and  $b$  (i.e.,  $\tau_{ab}$ ). These constraints express the so-called no-wait requirement.

$$p_i = \sum_{a \in A} \sum_{j \in N, j \neq i} y_{ija}^A, \quad i \in N \quad (21)$$

where this constraint calculates the final position of flight  $i$  at its departure airport.

$$p_i - q_i \leq Q, \quad i \in N \quad (22)$$

$$p_i - q_i \geq -Q, \quad i \in N \quad (23)$$

where these two constraints require that the position shifting of flight  $i$  cannot exceed the given boundary  $Q$ .

$$y_{ija}^A, y_{ijb}^B \in \{0, 1\} \quad \{i \neq j\} \in N, a \in A, b \in B \quad (24)$$

$$C_{ia}^A, C_i^A, C_{ib}^B, C_i^B, T_i^A \geq 0, \quad i \in N, a \in A, b \in B \quad (25)$$

$$p_i \in \mathcal{Z}^+, \quad i \in N \quad (26)$$

where these constraints give the domains of decision variables.

#### IV. SOLUTION EXAMPLE

In order to apply the model above, we design a multi-airport system with two airports, three intersection points and twelve flights, and the most common way to sequencing departure flights is to maintain the FCFS order. So there is no doubt that the values of a lot of parameters are known in this model, for example, the departure airports, time windows and sequencing order in FCFS of every flight. In our solution example, we generate these values randomly like TABLE I to TABLE III.

And we suppose the maximum position shifting is 4, and weights of different flights are produced by the weight of this flight in its departure airport multiplied by the weight of its departure airport, and the result are as TABLE IV.

Through these tables, we can easily obtain some information, including the departure airport of every flight, their departure time window and sequencing order in respective airport under FCFS. At the same time, we know the time and order when different flights pass different intersection points.

TABLE I  
AIRPORTS EVERY FLIGHTS DEPARTURE FROM

$X_{ia}^A$	Airport 1	Airport 2
Flight 1	1	0
Flight 2	0	1
Flight 3	1	0
Flight 4	1	0
Flight 5	1	0
Flight 6	1	0
Flight 7	1	0
Flight 8	1	0
Flight 9	1	0
Flight 10	0	1
Flight 11	1	0
Flight 12	0	1

TABLE II  
INTERSECTION POINTS EVERY FLIGHTS PASSED BY

$X_{ib}^B$	Point 1	Point 2	Point 3
Flight 1	1	0	0
Flight 2	0	0	1
Flight 3	1	0	0
Flight 4	0	0	1
Flight 5	0	1	0
Flight 6	0	1	0
Flight 7	1	0	0
Flight 8	1	0	0
Flight 9	0	0	1
Flight 10	0	0	1
Flight 11	1	0	0
Flight 12	0	0	1

Let's take airport two for example, from the data above, we can conclude that there are three flights departure from airport two, flight 2, flight 10 and flight 12, and their departure order is flight 12 followed by flight 2 follows flight 10.

Using CPLEX to search for the solutions on personal computer, we can get the optimal value of 1621 after a few seconds, and the optimal solutions are shown in TABLE V and TABLE VI.

These two tables reveal the optimal departure scheduling of every airport and the optimal passing order of every point. For example, the optimal departure order in airport 1, in turn, is flight 3, flight 9, flight 7, flight 1, flight 4, flight 8, flight 11, flight 5 and flight 6, which is different from the order in FCFS, and their optimal take off time can also be found in the table.

## V. CONCLUSION

By conducting a whole optimization research to the resources of airports, intersection points and flights in the multi-airport system, this paper first establish a model based on two-stage no-wait hybrid flow-shop with the objective of minimizing the total delay, then we can get the accurate solution by using the theory of mathematical programming and CPLEX. The proposed model and solving method in this paper contribute to helping airports to optimize its flight resource allocation and scheduling, and it is obvious that compare with FCFS, the readjust flight sequence after optimizing can effectively reduce the total weighted delay.

TABLE III  
DEPARTURE ORDER IN FCFS

	Flight 1	Flight 2	Flight 3	Flight 4
Order	4	3	3	7
	Flight 5	Flight 6	Flight 7	Flight 8
Order	5	8	1	6
	Flight 9	Flight 10	Flight 11	Flight 12
Order	2	1	9	2

TABLE IV  
WEIGHT OF FLIGHTS

	Flight 1	Flight 2	Flight 3	Flight 4
Weight	4	4	6	4
	Flight 5	Flight 6	Flight 7	Flight 8
Weight	6	1	1	5
	Flight 9	Flight 10	Flight 11	Flight 12
Weight	3	1	6	3

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TABLE V  
OPTIMIZED DEPARTURE ORDER AND TIME

$C_{ia}^A$	Airport 1	Airport 2
Flight 1	742	0
Flight 2	0	902
Flight 3	19	0
Flight 4	832	0
Flight 5	1132	0
Flight 6	1252	0
Flight 7	303	0
Flight 8	922	0
Flight 9	111	0
Flight 10	0	484
Flight 11	1042	0
Flight 12	0	317

TABLE VI  
OPTIMIZED ORDER AND TIME ON INTERSECTION POINTS

$C_{ib}^B$	Point 1	Point 2	Point 3
Flight 1	1000	0	0
Flight 2	0	0	1149
Flight 3	277	0	0
Flight 4	0	0	1053
Flight 5	0	1261	0
Flight 6	0	1381	0
Flight 7	561	0	0
Flight 8	1180	0	0
Flight 9	0	0	332
Flight 10	0	0	731
Flight 11	1300	0	0
Flight 12	0	0	564