

Airport Gate Reassignment Based on the Optimization of Transfer Passenger Connections

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Abstract—Disruptions occur frequently in airport operations and affecting the original schedule of flights' gate assignment. For international hub airports, the implication on the connection of flights and passengers is obvious. In this paper, we develop a reassignment model that focuses on transfer passengers' satisfaction level and heuristically solve this model to meet real-time solution requirement. The computational results show the competitive performance of our methods.

Index Terms—gate reassignment, transfer passenger, network model

I. INTRODUCTION

In recent years, market demand of air transportation grows significantly all over the world. Most airlines adopt the structure of hub-and-spoke, which makes those hub airports even more crowded. Although these hub airports usually have more infrastructure resources such as several runways and multiple terminals, they are still insufficient due to the participation of new airlines, more aircrafts and higher frequency of flights. Whereas, these scarce resources cannot be expended in a short timeframe as redesign and construction of new terminal buildings requires government permission as well as huge investments. As a result, current schedule of the gate assignment for flights tend to be tight with each other, in another word, has less separation time between successive flights in the airports which have insufficient gates. Such schedules are usually not robust when faced with disruptions. In fact, there are many factors that will affect gate assignments during real operations, including: flight or gate breakdown, flight earliness or tardiness, emergency flights, severe weather conditions, errors made by staff and many others [1]. If any of these disruptions lead to gate conflict, knock-on-effect may affect the following schedules not only related to one gate, but also many airlines' following connections. Flight delay or cancel, transfer passenger missing connection are all among the events it may bring out. Therefore, gate reassignment is urgent especially for large disruptions such as arrival delay for too long time, gate breakdown or airport temporary closure. Most of the previous researches of gate reassignment problems mainly focus on minimizing the deviation of new schedules from original ones such as total flight delay time or gate

differences of total aircrafts. However, we found for major airlines in hub airports, the transfer passengers take up more than 30% of total passengers, and they are much more sensitive to the delay time than departing or destination passengers, as transfer passenger may miss their second connection if their arrival flight arrives too late.

There are amount of research on airport gate assignment problems. Gate assignment problem (GAP) is to assign a gate for each of the flight for a set of flights. The common objectives include maximizing one-day throughput of the airport, maximizing airline preference, minimizing towing time, etc. A comprehensive review was written by Dorndorf, U., *et al.* [2]. Dorndorf *et al.* [3] considered a gate assignment problem which include weighting sum of three objectives: airline preferences, tows, and robustness. They transformed this problem for the special case with no shadow restrictions into an equivalent Clique Partitioning Problem and solves it using an ejection chain algorithm. Based on this work, Dorndorf *et al.* [4] further incorporated a forth objective that minimize the deviation from a given reference schedule and shown that it could be easily integrated into their previous existing model. Ding *et al* [5]-[7] focused on the over-constrained gate assignment problem which aimed to minimizing the number of ungated flights and total walking distances for transfer passengers. Tabu search and simulated annealing are used to solve their problems. Kim *et al.* [8]-[10] considered three objectives in the gate assignment problem: passenger transit time, aircraft taxiing time, and expected gate conflict time. Tabu search is adopted for solving this problem. There are two main methods to deal with the disruptions. One is to proactively predict the possible disruptions and make robust schedules based on the forecast information. Examples are found in [3], [4], [8]-[11], the major objective is to distribute the buffer time among flights assigned to the same gate in expectation of less overlapping occurrence. As robust scheduling is conducted at the plan stage, it could still be regarded as the gate assignment process.

The other measure to deal with disruption is to reassign the flights. This measure is usually done when the disruption is large and the delay cannot be absorbed by pre-scheduled buffer time. The major differences between gate assignment problem (GAP) and gate reassignment problem (GRP) include: (1) GRP should be solved in real

time and thus need efficient algorithm; (2) in GRP, resources like gate time slot are insufficient for all flights to use at their previous assigned time, some of the flight may even need to be cancelled; (3) the objectives of GRP are minimizing the deviation from original schedules, which is planned in GAP. There are several papers related to this topic. In [12], Yan and Tang integrated planned stage and re-assignment stage into one framework, which is solved iteratively by adjusting the penalty values in each iteration. However, they only used a simple manual reassignment rule to perform their reassignment problems. Tang *et al.* [13] put forward a gate reassignment framework with mathematical model and the objective is to minimize delay time and gate difference. Yan *et al.* [14] built a network model to solve the GRP after temporary airport closures, but no delay options are allowed in this reassignment problem. Based on their own work, they [15], [16] further proposed to solve GRP which incorporated the stochastic issues. Maharjan and Binod [17] aimed to minimizing the walking distance of passengers whose flight is re-assigned in their GRP. A zoning strategy is adopted to make the problem smaller. To the best of our knowledge, no one explicitly considered the transfer passenger connection in the reassignment problems. However, transfer connections are usually interrupted due to the flight disruptions. Moreover, passengers' satisfaction level affects a lot to the profit of both airlines and airports.

In this paper, we consider a reassignment problem which mainly focuses on the transfer passengers' profit. We propose a model to formulate the airport gate reassignment which considered two aspects of transfer passenger service satisfaction: minimize the number of passenger who will miss their connection and minimize transfer walking distance. To more efficiently solve this problem, we further put forward a network model, which make the model easier to solve. A heuristic method is also developed based on this model to meet the real-time operation requirement.

II. THE PROBLEM DESCRIPTION

When disruptions occur, we quickly collect the following information:

- The time frame that we need to optimize
- The earliest available time of each gate at the airport
- The information of the flights that have not started occupying a gate, including the earliest starting time, occupation duration, compatible gates, following flight flown by the same aircraft (if any)
- The transfer passenger number between each arrival flight and departure flight

That means, we do not consider those flights which already berth at a gate. We also should have the information of the terminal building about the walking distance between the gates and transfer service counter.

Our model is built based on the following assumptions:

- Each flight must be assigned to a gate, with the specific delay copy that indicates its starting time for occupying the gate

- No time overlapping occurs at any gate
- Arrival and departure flight of the same aircraft can be assigned to different gates, but the starting time of departure flight must be later than the ending time of arrival flight flown by the same aircraft
- Buffer time is included in the gate occupation duration of each flight
- The flight cannot be delayed more than the maximum delay time (e.g. 30 minutes)
- Each flight has 6 possible delay copies successively with 5 minutes gap
- Some aircrafts of the specific type cannot be assigned to two neighbor gates at the same time (shadow constraint / adjacency constraint)

In this study, we focus on the inconvenience the GRP brings to the transfer passengers. Due to the flight time variations, the arrival flight of some transfer passengers will be later than the departure flight and cause the miss-connections. Furthermore, the transfer distance may be much longer than the original walking distance due to the gate deviation of new schedule from original one. Therefore, we consider two aspects of transfer passenger service satisfaction: firstly we try to minimize the walking distance of all the transfer passengers in the terminal; secondly, we try to minimize the number of transfer passengers who will miss their departure flight.

III. MODELS DEVELOPMENT

In this section, we proposed two models to describe our GRP problem. The first one is an integer programming model and the second is network model. The first model is adapted from the one proposed in [13], while the other is our original work.

A. The Integer Programming Model (Model 1)

1) Parameters and denotations

(Flight)

I Flight set which is indexed by i and j

A Arrival flight set

D Departure flight set, $I = A \cup D$

F Flight delay copies which is indexed by f

δ_i The set of flight delay copies corresponding to flight i

a_{ij} The relationship between arrival flight i and departure flight j ; $=1$ indicates i and j are flown by the same aircraft successively

(Time point)

T The set of all time points which is indexed by t

h_t The set of flight delay copies that cover time point t

t

s_f Starting time of flight delay copy f

r_i Duration of flight i occupying the gate

(Gate)

G The set of available gates which is indexed by g and k

Ω Shadow set which is indexed by $\omega = (g, k, i, j)$

d_g The distance from gate g to the transfer service counter
(Passenger)

n_i The number of transfer passengers on flight i , $i \in I$

m_{ij} The number of transfer passengers from flight $i \in A$ to flight $j \in D$, $\sum_{j \in D} m_{ij} = n_i$, $\sum_{i \in A} m_{ij} = n_j$

M Sufficiently large number

2) Decision variables

x_{fg} Binary decision variables which indicate the assignment of flight f to gate g

z_{ij} Auxiliary decision variables which is used to count the number of transfer passengers who miss their connection

3) Model

Objectives:

$$\text{Min} \quad \sum_{i \in I} n_i \sum_{g \in G} d_g \sum_{f \in \delta_i} x_{fg} \quad (1)$$

$$\text{Min} \quad \sum_{i \in A, j \in D} m_{ij} z_{ij} \quad (2)$$

Subject to:

$$\sum_{f \in \delta_i} \sum_{g \in G} x_{fg} = 1, \forall i \in I \quad (3)$$

$$\sum_{f \in h_t} x_{fg} \leq 1, \forall g \in G, t \in T \quad (4)$$

$$\sum_{f \in \delta_i} \sum_{g \in G} x_{fg} (s_f + r_i) \leq \sum_{f \in \delta_j} \sum_{g \in G} x_{fg} s_f + (1 - a_{ij})M, \forall i \in A, j \in D \quad (5)$$

$$\sum_{f \in \delta_i \cap h_t} x_{fg} + \sum_{f \in \delta_j \cap h_t} x_{fg} \leq 1, \forall \omega = (g, k, i, j) \in \Omega, t \in T \quad (6)$$

$$M * z_{ij} \geq \sum_{f \in \delta_i} \sum_{g \in G} x_{fg} (s_f + r_i) - \sum_{f \in \delta_j} \sum_{g \in G} x_{fg} s_f, \forall i \in A, j \in D \quad (7)$$

$$x_{fg} \in \{0, 1\}, f \in F, g \in G \quad (8)$$

The objective function (1) is designed to minimize the total walking distance for all transfer passengers. The objective function (2) is designed to minimize the number of passengers who will miss their connections. Constraint (3) indicates each flight is assigned to exactly one gate, with the specific delay copy indicate the flight's starting time. Constraint (4) ensures no time overlapping occurs at any gate. Constraint (5) guarantees the starting time of the departure flight must be later than the ending time of its arrival flight flown by the same aircraft. Constraint (6) is the gate adjacency constraint, denoting that two conflict flights cannot be concurrently assigned to some specific adjacent gate pair. Constraint (7) is used to decide the value of decision variable $z_{<i,j>}$, which indicates whether the passengers from flight i to flight j are disrupted. Constraints (8) and (9) indicate x is binary variable and z is a positive integer variable.

This model can be solved using mathematical optimization solver like CPLEX when the problem size is small (fewer than 100 flights). However, when problem size grows larger, loading data and building the preliminary model are already intractable. This is due to there are too many decision variables introduced by considering passenger connections. Moreover, the existence of big M makes the model intractable. Therefore, we propose another model which is also a foundation of our heuristics to solve larger problems.

B. The Multi-Commodity Network Model (Model 2)

1) The network design

Flight arc: the flight arc whose head node indicate its starting time and tail node indicates its ending time. This set includes original flight arcs and candidate delay copies.

Node: This set includes the nodes that occur in all flight arcs, except that the node is counted only once if multiple nodes have the same time. It also includes the starting node and the ending node which indicate the gate's earliest available time and the ending time of re-assignment respectively.

Ground arc: the ground arcs are built for each two successive nodes chronologically. The network is illustrated in Fig. 1. The nodes $n1$ and $n8$ represent starting time and ending time of the gate respectively.

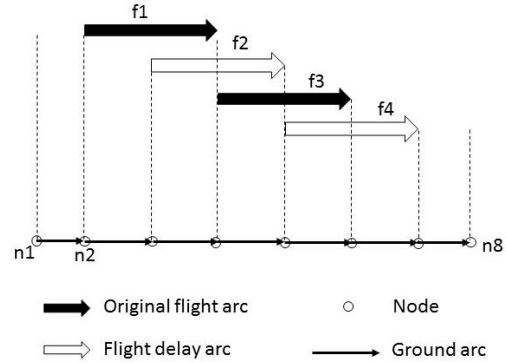


Figure 1. Flight arc, ground arc and node in the network.

2) Parameters and denotation

(Flight and delay copy arcs)

I Flight set which is indexed by i and j

F Flight arcs which is indexed by f

δ_i The set of flight arcs corresponding to flight i

$c_{<f,g>}$ Arc cost

(Nodes)

N The set of time nodes (including the initial node and final node) which is indexed as t

(Ground Arcs)

R The set of ground arcs (including the cycle arc) which is indexed as r

(Head Node and Tail Node)

F_{tail}^t The set of flight arcs with node t as the tail node

F_{head}^t The set of flight arcs with node t as the head node

R'_{tail} The set of ground arcs with node t as the tail node

R'_{head} The set of ground arcs with node t as the head node
(Gate)

G The set of available gates which is indexed by g and k

Ω Shadow set which is indexed by $\omega = (g, k, fi, fj)$
(Passenger)

w_{ij} Award the success of connecting transfer passengers from flight arc i to flight arc j , if starting time of flight arc j is later than flight arc i , then $w_{ij} = m_{ij}$, otherwise $w_{ij} = 0$

(Conflict Set)

Φ_a Flight arcs whose time are overlapped and belong to the same aircraft

Φ_h Hard constraint set that ensures some passenger connections must be served

1) Decision variables:

$x_{<f,g>}$ Binary decision variables, =1 indicates the assignment of flight arc f is assigned to gate g

$y_{<r,g>}$ Binary decision variables, =1 indicates the assignment of ground arc r is assigned to gate g

$z_{<fi,fj>}$ Binary decision variable, =1 indicates arrival flight arc fi and departure flight arc fj are both adopted in the assignment

2) Model

Objectives:

$$\text{Min} \quad \sum_{f \in F} \sum_{g \in G} x_{<f,g>} * c_{<f,g>} \quad (10)$$

$$\text{Min} \quad - \sum_{i \in A} \sum_{j \in D} \sum_{f \in \delta_i} \sum_{fj \in \delta_j} z_{<fi,fj>} * w_{<fi,fj>} \quad (11)$$

Subject to:

$$\sum_{f \in \delta_i} \sum_{g \in G} x_{<f,g>} = 1, \forall i \in I \quad (12)$$

$$\sum_{f \in F} x_{<f,g>} + \sum_{r \in R} y_{<r,g>} \leq 1, \forall g \in G \quad (13)$$

$$\sum_{f \in F'_{tail}} x_{<f,g>} + \sum_{r \in R'_{tail}} y_{<r,g>} = \sum_{f \in F'_{head}} x_{<f,g>} + \sum_{r \in R'_{head}} y_{<r,g>}, \forall t \in N, g \in G \quad (14)$$

$$z_{<i,j>} \leq 0, \forall <i,j> \in \Phi_a \quad (15)$$

$$z_{<i,j>} \geq \sum_{g \in G} x_{<i,g>} + \sum_{g \in G} x_{<j,g>} - 1 \quad (16)$$

$$z_{<i,j>} \leq \sum_{g \in G} x_{<i,g>} \quad (17)$$

$$z_{<i,j>} \leq \sum_{g \in G} x_{<j,g>} \quad (18)$$

$$x_{<fi,g>} + x_{<fj,g>} \leq 1, \forall \omega = (g, k, fi, fj) \in \Omega \quad (19)$$

$$x_{<f,g>} \in \{0,1\}, \forall f \in F, g \in G \quad (20)$$

$$z_{<i,j>} \in \{0,1\}, \forall i \in A, j \in D \quad (21)$$

The objective function (10) is designed to minimize the total walking distance for all transfer passengers. Unlike the penalty method adopted in Equation (2), the objective function (11) used award to maximize the number of passengers who will catch their connections. Objectives (2) and (11) are equivalent to each other since the number of total transfer passenger is constant. Constraint (12) indicates exact one flight delay arc is chosen by each flight. Constraint (13) ensures each gate is used at most once for the arc list. Constraint (14) is flow conservation. Constraint (15) guarantees the starting time of the departure flight must be later than the ending time of its arrival flight flown by the same aircraft. Constraint (16)-(18) indicate the relationship between decision variables x and z . Constraint (19) is adjacency constraint. Constraint (20) and (21) indicate x and z are binary variables.

IV. THE PROPOSED HEURISTIC

Note that although the network flow model solves the problem brought by the capital M , the number of decision variables are still large. This is due to that when the number of flights grows, the number of z grows in quadratic amount. And the number of constraints (16)-(18) are determined by the number of z . As a result, both the number of decision variables and constraints grows fast. To deal with this problem, we separate the award of transfer connections into two parts: hard set in which the passengers must catch their connections and soft set in which passenger may miss their connections. To be specific, the objective (11) is substituted by objective (22) and adding constraint (23). Constraint (23) is the hard constraint for the passenger connections that are regarded as hard AD pair.

$$\text{Min} - \left(\sum_{<i,j> \in \text{hard_set}} z_{<i,j>} * w_{<i,j>} + \sum_{fj \in \text{soft_set}} z_{<i,j>} * w_{<i,j>} \right) \quad (22)$$

As we force $z_{<i,j>} = 1$ for $<i,j> \in \text{hard_set}$, the objective can be further written as:

$$\text{Min} - \sum_{fj \in \text{soft_set}} z_{<i,j>} * w_{<i,j>} \quad (24)$$

The constraints (16)-(18) are updated accordingly. We can see the number of decision variables and constraints will reduce significantly if we put the majority of $<i,j>$ into hard set. If the hard set is empty, the result obtained from Equations (10), (12)-(21), (23)-(24) is optimal. We can also infer that the optimal result obtained from solving (10)-(22) must contain a set for $<i,j>$ in which the passengers will catch their connection. This set is what we want in searching for our hard set.

In order to find a good hard set, we propose a heuristic as follows:

- Initialize the hard pair set and hard conflict constraint set (Φ_h) as empty set.

- Sort all the arrival-departure flight pair (AD pair) according to the number of transfer passenger between them.
- Move AD pair from the pool to hard pair set until the predefined set size is achieved. The AD pair is chosen randomly each time, favoring those ranking ahead. Specifically, the rank of AD pair to be chosen is Np^D , where N is the number of AD pairs in the pool, p is a random number between 0 and 1, D is a constant number greater or equal to 1. The larger D is, the higher the probability we will choose the pairs ranking ahead. If D equals 1, then the AD pair is randomly chosen from the pool with a uniform distribution. If D is positive infinite, then the first AD pair is always chosen.
- The Φ_h is generated according to the hard pair set.
- Solve the problem (10), (12)-(21), (23)-(24) using CPLEX.

The processes 1) to 5) are iterated until termination condition is achieved.

V. IMPLEMENTATION AND RESULTS

A. Test Data Generation

Starting time of arrival flight of aircraft i (asi) is randomly generated in the interval $[10i, 10i+7]$, and the ending time of arrival flight of aircraft i is generated in the interval $[asi+20, asi+40]$. Starting time of departure flight of aircraft i (dsi) is randomly generated in the interval $[asi-10, asi+10]$, ending time of departure flight of aircraft i is generated in the interval $[dsi+20, dsi+40]$.

The transfer passenger number between arrival flight and departure flight is generated in the interval $[5,20]$. The distance from each gate to the transfer service counter is generated in the interval $[5,30]$.

TABLE I. TYPE COMPARISON OF TWO MODELS

set	mip-result		network-result		deviation	
	value	cpu	value	cpu	value%	cpu%
50f	73879	2.18	75597	1.59	2.33%	27.06%
60f	120148	2.93	124938	2.11	3.99%	27.99%
70f	137429	11.1	142937	1.23	4.01%	88.93%
80f	173754	55.3	179571	16.5	3.35%	70.19%
90f	222167	197	236205	122	6.32%	38.03%
100f	243316	386	254806	43.7	4.72%	88.67%
110f	327203	869	337653	284	3.19%	67.34%
120f	410304	1336	422844	209	3.06%	84.39%
130f	453403	1698	467261	220	3.06%	87.05%
140f	381634	2501	401108	389	5.10%	84.45%
150f	621429	2856	648030	320	4.28%	88.80%

B. Computational Results and Comparison

We solve 11 set of data with flight size from 50 to 150. We use java language coupled with CPLEX 12.1 to build the model and solve the problem. The results are shown in Table I.

From the Table I, we can see that the result from the second model is not as good as the first one, as it is heuristically used to solve the problem. But the computation time of the second method is much faster especially when problem size grows larger, which is very essential for solving problems in real-time.

VI. CONCLUSIONS AND FUTURE STUDY

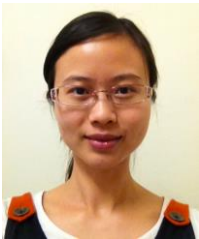
In this paper, we have proposed two models to solve the airport gate reassignment problem which focuses on the transfer passengers' satisfaction level. The first model is a direct integer programming model and the second model is built with a network model. The second model overcome the limitations of the first model in solving large problems in real-time. A set of instances are simulated to compare the performance of these two models.

Future research will focus on improving performance of the proposed heuristic of finding better 'hard set' in the second model. Both mathematical methods and meta-heuristic methods will be explored to improve the capability of the second model.

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