Optimization of flight-to-gate assignment based on the passenger transfer demand

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Abstract. Flight-to-gate assignment problem is one of the focused issues in the field of air transportation management and optimization. This paper focuses on improving the used airport gate utilization and minimizing passenger transfer tension via making a reasonable flight-to-gate strategy. A two-stage mathematical model has been formulated. In the first stage, we are aiming to minimize the transfer tension of passengers. Based on the flight-to-gate assignment result from the first stage, the second stage aims to increase the utilization rate of airport gates. Finally, a flight-to-gate assignment plan is designed to certify the validity of our model.

1. Introduction
Flight-to-gate assignment is an important branch of the airport scheduling. The limited number of airport gates cannot satisfy the demands of all landing aircraft. Airport terminal expansion is an efficient measure to ameliorate the pressure of insufficient airport gate. For example, Lhasa Gongga Airport launched the T3 terminal construction plan in 2017. Chongqing Jiangbei Airport is also expected to construct a new terminal in 2020. However, under the condition of airport terminal expansion, it will aggravate the tension of transfer passenger once the flight-to-gate assignment is unreasonable. Additionally, considering the cost of equipment maintenance, it should control the number of used airport gates. Therefore, we focus on making a reasonable flight-to-gate plan which aims to improve the utilization rate of airport gates and to minimize the transfer tension of passengers.

2. Literature review
The issue of flight-airport-gate assignment problem has been explored by many scholars in recent years. [1] summarized existing research contributions that solved gate assignment problem, and divided those literatures into three categories based on their objective functions, which took passenger, airport and robustness as orientation respectively. Besides, they summarized solving approaches used by different literatures. This paper will also carry out discussions from the three aforesaid perspectives. [2] took minimization of total walking distance of passengers as the objective, and developed the greedy assignment method based on passenger number and time of flight’s arrival at gate. To accurately evaluate satisfaction of transfer passengers, [3] has built a mixed integer programming model, and proposed variable reduction neighborhood search (VRNS) heuristic algorithm, which could effectively solve massive problems in a short time. [4] considered issues of reassignment of
flight gates and passengers’ transfer connections, which guaranteed the probability of successful transfer of passengers to the greatest extent.

Certain flights could only stop at temporary gate positions due to the limited fixed gates of an airport, which undoubtedly increased both operating cost of airport and waiting time of passengers. Therefore, for airport management, airport should guarantee both income and provide higher service efficiency through accept as many flights as possible. [5] has proposed BCO-based meta-heuristics based on given flight schedule to find the optimal flight gate assignment. [6] considered the overall performance of flight gate assignment issue, and proposed a new robust optimization strategy. [7] has built stochastic programming model of robust measures, and acquired reasonable flight gate assignment plan through TS algorithm. [8] designed an effective adaptive large neighborhood search (ALNS) algorithm, proposed multi-local search operators, and verified high efficiency and effectiveness of the proposed approach on TS algorithm through examples. [9] mainly considered flight gate assignment problem under the condition of flight delay, and built multi-commodity flow network model. In addition, they also proposed two heuristic algorithms for solution.

Up to now, many scholars have focused on minimizing the airport operating costs, improving the airport gate utilization, as well as minimizing passenger transfer distance and their transfer waiting time to solve the flight-to-gate assignment problem. In this paper, the minimization of passenger transfer tension as well as the improvement of airport gate utilization has been considered under the condition of airport terminal extension.

3. Problem description
In terms of airplanes and flights, normally, one airplane is marked at two flight numbers to carry out a closed loop flight mission. Different airplanes possess different or same size, such as wide-body or narrow-body, and the flight can be divided into the international and domestic attributes. The flight-to-gate assignment is influenced by the airplane size and flight attribute. For example, some airport gate are only allowed to be assigned the airplane with wide-body, some airport gates are only allowed to be assigned the international flight, some airport gates are only allowed to be assigned the domestic flight while some airport gates are both allowed to serve domestic and international flight, etc.

Figure 1 shows one layout of airport terminal. Apart from the airport gate, there is temporary stop point called parking apron for stopping the flights unassigned to airport gates. Based on the airport terminal Q, another terminal called S has been built to ease the pressure of limited airport gates. Two terminals are connected by tram, which is used for passengers’ transferring between two terminals. Both terminal Q and S possess the function of flight international departure, arrival, and stop, etc. However, only terminal Q has the function of disposing entry and exit function for passengers. That is, any international airplane has to enter terminal Q to dispose entry and exit procedure. For example, one international passenger whose departure flight is at terminal S has to take the tram to arrive at terminal Q to complete exit procedure. Obviously, an unreasonable flight-to-gate assignment will lead to the increase of transfer tension of passengers. Therefore, in this paper, we focus on the problem of flight-to-gate assignment and aim to make a reasonable flight-to-gate assignment plan, by which to improve the sufficient utilization of used airport gates and to decrease the transfer tension of passengers.

![Figure 1. The airport terminal layout](image-url)
4. Model

4.1. Notation definition

Table 1. Notation Definition

| Set and index | Description |
|---------------|-------------|
| U             | Set of airplanes, which is indexed by \( u \) and \( v \), \( U = \{ 1, 2, 3, ..., |U| \} \). |
| M             | Set of airport gates, which is indexed by \( m \) and \( n \), \( M = \{ 1, 2, 3, ..., |M| \} \). |
| T             | Set of the discretized a working day (minute), which is indexed by \( t \), \( T = \{ 1, 2, 3, ..., |T| \} \). |
| Q             | Set of transfer passengers, which is indexed by \( q \), \( Q = \{ 1, 2, 3, ..., |Q| \} \). |

| Parameter | Description |
|-----------|-------------|
| \( F_u^a \) | 0-1 parameter, if the arrival flight is international attribute, \( F_u^a = 1 \); otherwise, \( F_u^a = 0 \). |
| \( F_u^d \) | 0-1 parameter, if the departure flight is international attribute, \( F_u^d = 1 \); otherwise, \( F_u^d = 0 \). |
| \( G_m^a \) | 0-1 parameter, if gate \( m \) is available for stopping a arrival international flight, \( G_m^a = 1 \); otherwise, \( G_m^a = 0 \). |
| \( G_m^d \) | 0-1 parameter, if gate \( m \) is available for stopping a departure international flight, \( G_m^d = 1 \); otherwise, \( G_m^d = 0 \). |
| \( E_m^a \) | 0-1 parameter, gate \( m \) is available for stopping a arrival domestic flight, \( E_m^a = 1 \); otherwise, \( E_m^a = 0 \). |
| \( E_m^d \) | 0-1 parameter, gate \( m \) is available for stopping a departure domestic flight, \( E_m^d = 1 \); otherwise, \( E_m^d = 0 \). |
| \( B_u \)    | 0-1 parameter, if the airplane is wide-body, \( B_u = 1 \); otherwise, \( B_u = 0 \). |
| \( W_m \)    | 0-1 parameter, if the gate is available for stopping a airplane with wide-body, \( W_m = 1 \); otherwise, \( W_m = 0 \). |
| \( t_u^d \)  | Flight departure time from the airport gate. |
| \( t_u^a \)  | Flight arrival time from the airport gate. |
| \( \beta \)  | The safety time interval which allows two different airplanes to be assigned at one airport gate. |
| \( k_{u,v} \) | 0-1 parameter. If \( t_u^d < t_v^a + \beta \) and \( t_u^a > t_v^d - \beta \), two airplanes can not be assigned to the same gate, i.e. \( k_{u,v} = 1 \); otherwise, \( k_{u,v} = 0 \). |
| \( q_{u,v} \) | Number of transfer passengers between flight \( u \) and \( v \). |
| \( \delta_{u,v}^{m,n} \) | Minimum procedure time of transfer passenger between gate \( m \) and \( n \), and his/her arrival flight is \( u \) and departure flight is \( v \). |
| \( l_{u,v}^{m,n} \) | 0-1 parameter, if \( t_v^d - t_u^a \geq \delta_{u,v}^{m,n} \), the transfer of passenger is successful, \( l_{u,v}^{m,n} = 1 \); otherwise, \( l_{u,v}^{m,n} = 0 \). |
| \( \omega_{u,v}^{m,n} \) | The transfer time of passenger on tram. |

| Variable | Description |
|----------|-------------|
| \( x_{u,v} \) | 0-1 variable, if airplane \( u \) is assigned to gate \( v \), \( x_{u,v} = 1 \); otherwise, \( x_{u,v} = 0 \). |
| \( z_u \) | 0-1 variable, if airplane \( u \) is assigned to parking apron, \( z_u = 1 \); otherwise, \( z_u = 0 \). |
| \( \theta_{u,v}^{(r,a)} \) | 0-1 auxiliary variable, if \( x_{v,m} = 1 \) and \( x_{v,n} = 1 \), the value of \( \theta_{u,v}^{(r,a)} \) is 1; otherwise, \( \theta_{u,v}^{(r,a)} = 0 \). |
| \( y_m \) | 0-1 variable, if airplane is assigned to gate \( m \), \( y_m = 1 \); otherwise, \( y_m = 0 \). |
4.2. Two-stage mathematical model

Stage 1: minimization of transfer tension of passengers

\[
\min \quad \tilde{f}_1 = \sum_{u \in U} \sum_{v \in U} \sum_{m \in M} \sum_{n \in M} \left[ q_{u,v} \cdot x_{m,n} \cdot x_{v,n} \cdot t_{u,v} \cdot I_{u,v}^{m,n} \right] / (t_v^d - t_u^a) \\
+ \sum_{u \in U} \sum_{v \in U} \sum_{m \in M} \sum_{n \in M} \left[ q_{u,v} \cdot x_{m,n} \cdot x_{v,n} \cdot \mu \cdot (1 - I_{u,v}^{m,n}) \right] / (t_v^d - t_u^a)
\]

(1)

Make the transfer time of passengers as the index of their transfer tension. The objective function of stage 1 aims to minimize the transfer tension of passengers, among which, the first term of Eq.(1) describes the total procedure time of passengers who have succeeded transferring. Parameter \( I_{u,v}^{m,n} \) presents whether the transfer of passenger between flight \( u \) and \( v \) is successful, i.e., if \( t_v^d - t_v^a > \delta_{u,v}^{m,n} \), the transfer of passenger is successful, \( \delta_{u,v}^{m,n} = 1 \). Considering that the airline will undertake more loss if the transfer of passenger is not successful, the flight-to-gate assignment should make sure the success of passenger transfer as far as possible. Therefore, the second term of Eq.(1) is introduced as a penalty term. Parameter \( \mu \) describes the penalty time due to transfer failure, and its value is far bigger than the longest transfer time of passengers.

\[
\theta^{(v,n)}_{(u,m)} \geq x_{m,n} + x_{v,n} - 1 \quad \forall u,v \in U, \forall m,n \in M
\]

(2)

\[
\theta^{(u,m)} \leq x_{u,m} \quad \forall u,v \in U, \forall m,n \in M
\]

(3)

\[
\theta^{(v,n)} \leq x_{v,n} \quad \forall u,v \in U, \forall m,n \in M
\]

(4)

For linearization of the formulated model, we introduce the auxiliary binary variable \( \theta^{(v,n)}_{(u,m)} \), i.e., if \( x_{u,m} = 1 \) and \( x_{v,n} = 1 \), the value of \( \theta^{(v,n)}_{(u,m)} \) is 1; otherwise, \( \theta^{(v,n)}_{(u,m)} = 0 \). Constraints (2)-(4) present the relationship among \( \theta^{(v,n)}_{(u,m)} \), \( x_{u,m} \), and \( x_{v,n} \). Correspondingly, objective function can be transferred into as following:

\[
\min \quad \tilde{f}_1 = \sum_{u \in U} \sum_{v \in U} \sum_{m \in M} \sum_{n \in M} \left[ q_{u,v} \cdot \theta^{(v,n)}_{(u,m)} \cdot t_{p} \cdot I_{u,v}^{m,n} \right] / (t_v^d - t_u^a) \\
+ \sum_{u \in U} \sum_{v \in U} \sum_{m \in M} \sum_{n \in M} \left[ q_{u,v} \cdot \theta^{(v,n)}_{(u,m)} \cdot \mu \cdot (1 - I_{u,v}^{m,n}) \right] / (t_v^d - t_u^a)
\]

Constraints (5)-(14) are formulated as following. Constraints (5) means each airplane can be only assigned to one airport gate (including the temporary position of parking apron). Constraints (6) – (9) make sure the attribute match between flight and airport gate, i.e., some airport gates are only allowed to be assigned the international flight, some airport gates are only allowed to be assigned the domestic flight and some airport gates are both allowed to serve domestic and international flight. Considering the size match of between airplane and airport gate, constraints (10) and (11) are formulated. That is, some airport gates are only allowed to be assigned the airplane with wide-body, while some airport gates are only allowed to serve the airplane with narrow-body. Constraints (12) and (13) present two airplanes which are not allowed to be assigned in the same airport gate if their safety time interval is not satisfied. The time interval of two airplanes refer to the time difference of the departure time of earlier arrival airplane and the arrival time of later arrival airplane. Constraints (14) show \( x_{u,m} \), \( z_u \) and \( \theta^{(v,n)}_{(u,m)} \) are 0-1 variables.

\[
z_u + \sum_{m \in M} x_{u,m} = 1 \quad \forall u \in U
\]

(5)

\[
F_u^a \cdot x_{u,m} \leq G_u^a \quad \forall u \in U, \forall m \in M
\]

(6)

\[
(1 - F_u^a) \cdot x_{u,m} \leq E_u^a \quad \forall u \in U, \forall m \in M
\]

(7)

\[
F_u^d \cdot x_{u,m} \leq G_u^d \quad \forall u \in U, \forall m \in M
\]

(8)

\[
(1 - F_u^d) \cdot x_{u,m} \leq E_u^d \quad \forall u \in U, \forall m \in M
\]

(9)

4
\[ B_u \cdot x_{u,m} \leq W_m \quad \forall u \in U, \forall m \in M \]  
(10)

\[ (1 - B_u) \cdot x_{u,m} \leq 1 - W_m \quad \forall u \in U, \forall m \in M \]  
(11)

\[ x_{u,m} + x_{v,m} \leq 1 + M \cdot (1 - k_{u,v}) \quad \forall u \in U, \forall m \in M \]  
(12)

\[ x_{u,m} + x_{v,m} \leq 2 + M \cdot k_{u,v} \quad \forall u \in U, \forall m \in M \]  
(13)

\[ z_u, x_{u,m}, x_{v,m} \in \{0, 1\} \quad \forall u \in U, \forall m \in M \]  
(14)

Stage 2: minimization of the number of used airport gates

\[
\min \quad f_2 = \sum_{m \in M} y_m
\]
(15)

\[
\sum_{m \in M} x_{u,m} = 1 \quad \forall u \in U
\]
(16)

\[
y_m \leq \sum_{u \in U} x_{u,m} \quad \forall m \in M
\]
(17)

\[
y_m \geq x_{u,m} \quad \forall u \in U, \forall m \in M
\]
(18)

\[
y_m, x_{u,m}, x_{v,m} \in \{0, 1\} \quad \forall u, v \in U, \forall m \in M
\]
(19)

Based on the stage 1, we can gain the assigned flights in terminal Q and S. The assigned results are set to be the input of stage 2. That is, for keeping the overall transfer time of passengers being not changed, make the assigned flights in terminal Q and S are same as that in stage 1, by which further realize the reassignment of airport gates for the assigned flights in terminal Q and S, respectively. The mathematical model of stage 2 aims to minimize the number of used airport gates in terminal Q and S, respectively, which can contribute to the improvement of each used airport gate utilization. Constraints (16) means each airplane can only be assigned to a airport gate during reassignment. Constraints (17) and (18) present the relationship between variable \( y_m \) and \( x_{u,m} \). Constraints (19) show that \( y_m \) and \( x_{u,m} \) are 0-1 variables.

5. Numerical experiment

Adopt the flight and passenger booking data of one certain airport in Shanghai to test performance of the two stage model. Solve the model by CPLEX solver (MATLAB 2018a). Figure 2 shows the occupation time of each used airport gate by gantt chart, which intuitively presents the utilization of each used airport gate.

![Figure 2. Gantt chart of flight-to-gate assignment plan](image)

Detailed test results are as following:

There are 69 airport gates in terminal Q and S, i.e., the number of airport gate in terminal Q and S are 28 and 41, respectively. Totally 165 flights arrived at the terminal on January, 18, 2018. In the flight-to-gate assignment plan, 134 airplanes (268 flights) were assigned to different 47 airport gates.
and 31 airplanes were assigned to temporary parking apron. The total use rate of airport gates at terminal Q and S is 68.12%. Detailedly, in the solution of stage 1, 134 airplanes totally used 52 airport gates. Based on the reassignment of flight-to-gate of stage 2, the 134 airplanes were reassigned to 47 airport gates. The use rate of airport gates is reduced by 7.24%. Analyzing the used 47 airporite gates, they are consisted with 28 airport gates in terminal Q and 19 airport gates in terminal S. In other words, the use rate of airport gates in terminal Q and S are 100% and 46.34%, respectively.

In terms of transfer passengers, there are totally 2,510 passengers arrived at the airport for transfer, and 2,037 of them were assigned to 34 airport gates. Other passengers are not our research target who need to take the shuttle bus for transfer to arrival at their flights assigned in temporary parking apron. The overall transfer tension of passengers assigned to the airport gates was 469.4975.

Two terminals possess 24 airport gates which are allowed to assign the airplane with wide-body, and 45 airport gates which is allowed to assign the airplane with narrow-body. For the match size of airplanes and airport gates, there are 35 airplanes with wide-body in the 134 airplanes, and they use the corresponding airport gate number is 16. The number of airplanes with narrow-body was 99, and it uses 31 corresponding airport gates. Therefore, the use rate of airport gates which are allowed to assign airplane with wide-body and narrow-body are respectively 66.67% and 68.89%.

Making the proportion between the total occupied time of one airport gate by flights and one day time (min) as the index to measure the utilization rate of one airport gate. Figure 3 and 4 show the number of 268 flights assigned at each used airport gate at terminal Q and S and the utilization of each used airport gate, respectively. There are 72.39% of flights were assigned to 28 airport gates at terminal Q, and 27.61% of flights were assigned to 19 airport gates of terminal S. The average utilization of used airport gates at terminal Q and S are respectively 35.85%, and 27.50%. Obviously, the flight-to-gate assignment result at terminal Q is better than that at terminal S. The reason is that each airport gate at terminal S does not simultaneously possess the function of serving international and domestic flight. However, some airport gates at terminal Q is allowed to assign both international and domestic flight.
6. Conclusion
Flight-to-gate assignment is one important branch of researches on air transportation management. Airport terminal expansion is an efficient measure to ease the insufficient airport gate. However, under the condition of terminal expansion, it will aggravate the passenger transfer tension if the flight-to-gate assignment is unreasonable. The development of flight-to-gate assignment plan can provide an efficient theory guide for the flight schedule. Therefore, we focus on making a reasonable flight-to-gate plan to improve the utilization rate of airport gates and to minimize passenger transfer tension. The two-stage mathematical model is formulated. The first stage makes sure the minimization of passenger transfer tension and the second stage aims to improve the utilization of used airport gates. The numerical experiment further certifies the validity of the two-stage model.

In the future an interesting work, it maybe interesting to consider the influence of bad weather. Furthermore, we can combine the flight-to-gate assignment problem with air crew scheduling, by which it will develop a flexible flight-to-gate plan. Besides, it is useful to involve the ground traffic control issues in the flight-to-gate plan.

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