Airport Gate Scheduling for Passengers, Aircraft, and Operations

Sang Hyun Kim, Eric Féron, John-Paul Clarke, Aude Marzuoli, Daniel Delahaye

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Sang Hyun Kim[1]
Korea Transport Institute, Sejong, 30147, Korea

Eric Feron[2] and John-Paul Clarke[3]
Georgia Institute of Technology, Atlanta, GA, 30332

Aude Marzuoli[4]
Verizon Labs, Palo Alto, CA

and
Daniel Delahaye[5]
École Nationale de l'Aviation Civile, Toulouse, France

Passengers' experience is becoming a key metric to evaluate the air transportation system's performance. Efficient and robust tools to handle airport operations are needed along with a better understanding of passengers' interests and concerns. This paper is concerned with airport gate scheduling for improved passenger experience while ensuring robust air-side operations. Three metrics accounting for passengers, aircraft, and operations are presented. Trade-offs between these metrics are analyzed, and a balancing objective function is proposed. Numerical simulations show that the balanced objective can improve the efficiency of traffic flow in passenger terminals and on ramps, as well as the robustness of gate operations.

Nomenclature

$act_a(i)$ = actual arrival time of flight i

$act_d(i)$ = actual departure time of flight i

d_{jl} = distance between gate j and gate l

d^b_j = distance from gate j to baggage claim

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[1] Associate Research Fellow, Department of Aviation Research, 370 Sicheong-daero
[2] Professor, School of Aerospace Engineering, 270 Ferst Drive, Associate Fellow AIAA
[3] Professor, School of Aerospace Engineering, 270 Ferst Drive, Associate Fellow AIAA
[4] Research Scientist
[5] Professor, Applied Mathematics and Computer Science Laboratory(MAIAA)

d^s_j = distance from a security checkpoint to gate j

F = set of flights

G = set of gates

M = arbitrarily large number

n_i = general form of n^{in}_i and n^{out}_i

n_{ik} = number of transfer passengers between flight i and flight k

n^d_i = number of destination passengers of flight i

n^{in}_i = number of arrival passengers of flight i

n^o_i = number of origin passengers of flight i

n^{out}_i = number of departure passengers of flight i

t^{buff} = buffer time

t^{dly} = taxi delay

t^{in}_i = scheduled arrival time of flight i

t^{out}_i = scheduled departure time of flight i

u^{in}_{ij} = unimpeded arrival taxi time of flight i to gate j

u^{out}_{ij} = unimpeded departure taxi time of flight i from gate j

v^m = average passenger moving speed

$w_{transit}$ = weighting factor for Metric 1

w_{taxi} = weighting factor for Metric 2

w_{robust} = weighting factor for Metric 3

x_{ij} = decision variable (=1 if flight i is assigned to gate j, =0 otherwise)

I.Introduction

FLIGHT delays do not accurately reflect the delays imposed upon passengers' full itineraries. The growing interest in measuring the Air Transportation System's performance calls for new metrics, reflecting passengers' experience [1]. Because of the hub-and-spoke structure of the network of U.S. airports, major airports, such as Hartsfield-Jackson Atlanta International Airport, have a significant impact on the performance of the overall system. In particular, connecting passengers in such hubs may represent the largest share of traffic and are most vulnerable to delays that can severely perturb their journeys. In a worst-case scenario, a single delay can "snowball" through the entire network [2]. In 2015, according to Airlines for America, the cost of aircraft block time for U.S. passenger airlines is $65.43 per minute [3].

Airport Collaborative Decision Making (A-CDM) aims at reducing delays and improving system predictability, while optimizing the utilization of resources and reducing environmental impact. The mechanisms involve the provision of accurate data (estimates of arrival and departure times) to stakeholders, the sharing of information, the airline's decision to cancel or delay flights, and the rescheduling of flights with priority constraints. This effort is currently one of the five priority measures in the Flight Efficiency Plan published by IATA, CANSO and Eurocontrol [4]. In the U.S., the CDM-based ground delay program planning and control appeared in 1998; the stakeholders are the U.S. government, airlines, the Federal Aviation Administration including Air Traffic Control and Air Traffic Flow Management, and airports. Several improvements have been reported resulting from the CDM initiative, such as the Collaborative Departure Queue Management strategy at Memphis International Airport (MEM) [5], the Surface Congestion Management scheme at New York's John F. Kennedy International Airport (JFK) [6], and the pushback rate control demonstrated at Boston Logan International Airport (BOS) [7]. In Europe, CDM has been implemented at Munich Airport [8], Brussels Airport, Frankfurt Airport, London Heathrow Airport, and Paris Charles De Gaulle Airport [9]. However, there is still a growing need for more efficient and more robust tools to improve operations at congested airports. In particular, we believe that this effort should be combined with a necessary shift towards a better understanding of passengers' interests and concerns.

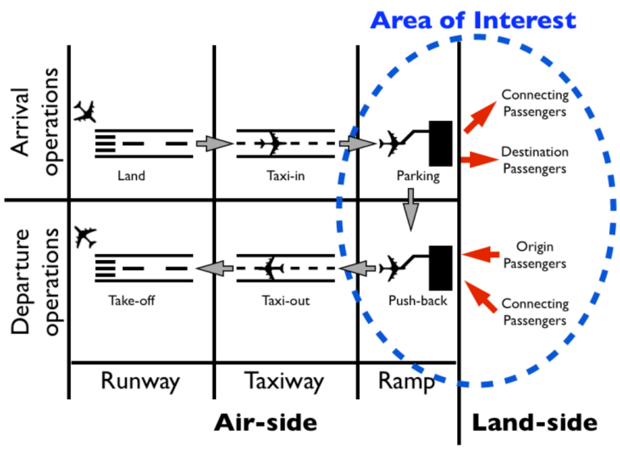

Fig. 1 A synopsis of airport operations

Airport operations range from the landing to the take-off of an aircraft as shown in Fig. 1. When an aircraft lands, it taxies into a ramp area and parks at a gate. While the aircraft is docking at the gate, passengers disembark and board the plane. When the aircraft is ready to depart, it pushes back and taxies out to a runway. Then, the aircraft takes off. Among these operations, this study focuses on the optimization of ramp operations and the accommodation of passengers.

Most air travelers have experienced walking long distances in a passenger terminal to catch a flight or waiting on board their aircraft while it is waiting for a gate or is delayed by the movement of another aircraft. Many such situations can be resolved or reduced by proper gate scheduling or assignment.

The first metric of this study is the transit time of passengers in a passenger terminal. The transit time of passengers consists of the time from the security checkpoint to a gate, from a gate to baggage claim, and from one gate to another gate. This is the most common objective of traditional studies focusing on gate assignment [10, 11].

The second metric of this study is the taxi time on ramps [12]. The taxi time depends on the length of the taxi route. However, interfering taxi routes cause taxi delay. If two aircraft taxi in opposite directions on the same taxi lane, one aircraft moves to different taxi lane and it results in taxi delays. Because the taxi route of an aircraft is determined by the locations of its assigned runway and gate, gate assignment is critical to reduce taxi time and taxi delays on ramps.

The last metric of importance to this study is disturbances in gate operations, or equivalently, the robustness of gate assignment [13, 14]. "Robust" means that the gate assignment is resistant to uncertain delays. Indeed, severe delays perturb gate operations by forcing arriving aircraft to wait for gates, or ramp controllers to reassign gates. The disturbances can be reduced if the gate assignment is robust against uncertain delays. In addition, a robust gate assignment allows air traffic controllers to utilize gate-holding departure control more efficiently [15]. Indeed, the gate-holding departure control, currently in use at many European airports [9] and under evaluation at MEM [5], JFK [6], and BOS [7], delays push-backs in order to reduce taxi times and emissions when the airport surface is congested. As a result, aircraft occupy gates longer than scheduled, which can negatively impact gate operations. If the gate assignment is robust, aircraft are able to stay longer at gates without disturbing gate operations and gate-holding departure control performs better.

All three metrics cannot be optimized at the same time. Hence, this study presents trade-offs between metrics using flight schedules of a major U.S. hub airport.

II.Gate Assignment Problem

A. Data Source

Prior studies on gate assignment rely on fictitious passenger data (e.g., number of transfer passengers), because such data are not published. Thanks to a major U.S. carrier, this study is able to assign airport gates and analyze gate assignments with the actual number of transfer passengers at a U.S. major hub airport. The carrier provided flight schedules and transfer passenger data from May 1st, 2011 at the hub airport. Passengers who check in at the airport (origin passengers) and those whose final destination is the airport (destination passengers) move from the passenger terminal to a gate or vice versa. Passengers who have connecting flights at the airport (transfer passengers) move from a gate to another gate. Because the only available data are the number of transfer passengers of the carrier, all the flights are assumed to be full with passengers, and passengers other than those transferring within the carrier's flights are considered to be origin and destination (O&D) passengers.

B. Metric 1: Passenger Transit Time

The first metric is the transit time of passengers. Passengers in an airport are categorized into three groups. Origin passengers begin their itinerary from the airport. Destination passengers finish their itinerary at the airport. Transfer passengers connect from one flight to another at the airport.

The transit time of O&D passengers depends on the distance from a point of the airport (e.g., security checkpoint, baggage claim) to a gate. Assume that flight i is assigned to gate j. Then the total transit time of origin passengers of flight i is $n^o_i\ d^s_j/\ v^m$. v^m varies with the configuration of the passenger terminal: v^m is higher where passengers can move faster by taking a moving sidewalk, underground people mover, etc. Similarly, the total transit time of destination passengers of flight i is $n^d_i\ d^b_j/\ v^m$. Therefore, the transit time of O&D passengers is determined by the location of a single gate because the locations of the security checkpoint and baggage claim are fixed.

The transit time of transfer passengers depends on the distance between two gates. Assume that flight k is assigned to gate l. Then, the total transit time of passengers who transfer between flight i and flight k is $n_{ik}\ d_{jl}/\ v^m$.

Consequently, the transit times of O&D passengers are expressed by linear terms of the decision variable and the transit times of transfer passengers are expressed by quadratic terms in Eq. (1). A mathematical expression for the first metric is therefore

$$Metric_{transit} = \sum_{i \in F} \sum_{j \in G} (n_i^o \frac{d_j^s}{v^m} + n_i^d \frac{d_j^b}{v^m}) x_{ij} + \sum_{i \in F} \sum_{j \in G} \sum_{k \in F, k > i} \sum_{l \in G} n_{ik} \frac{d_{jl}}{v^m} x_{ij} x_{kl} \tag{1}$$

C. Metric 2: Aircraft Taxi Time

The second metric is the sum of unimpeded taxi time and taxi delay. The unimpeded taxi time for an arrival is the time taken for an aircraft to taxi from a spot to a gate when congestion or other taxi impediments are not present. The taxi time from a spot to a gate is calculated by dividing the distance from a spot to a gate by the taxi speed. The unimpeded taxi time for a departure is the time needed by an aircraft to taxi from a gate to a spot when congestion or other taxi impediments are not present. This unimpeded taxi time includes the time needed for the aircraft to push back. This study accounts for taxi delays that happen when either of the following cases occurs. 1) A taxiing aircraft prevents another aircraft from pushing back. 2) Two aircraft taxi in opposite directions on the same taxi lane. The first case is called a push-back blocking and the push-back is delayed until the taxiing aircraft passes through the push-back route. The second case is called a taxi blocking and one of the aircraft must shift its taxi lane to another taxi lane; there are two parallel taxi lanes in the ramp area at the airport of interest as shown in Fig. 2. Therefore, taxi delays depend on the taxi routes of two aircraft. Authors collected the taxi delay characteristics. Detailed information is available in [12].

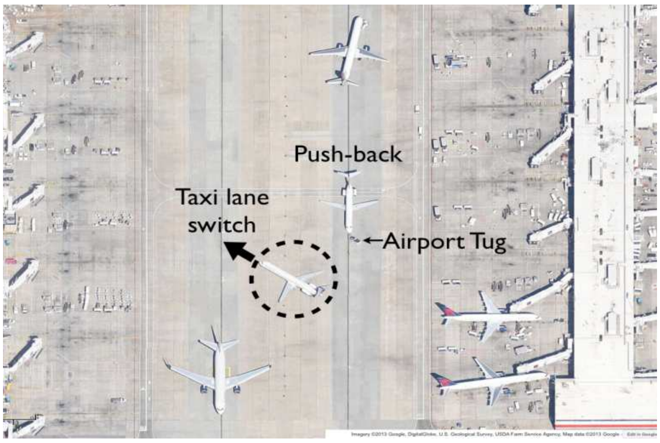

Fig. 2. Satellite picture of the airport of interest from Google Maps [16]. There are two parallel taxi lanes, and one aircraft (circled) is taxiing from a taxi lane to another in order to avoid the pushing-back aircraft.

Assume that flight i is assigned to gate j. Then, the unimpeded taxi time of flight i, which is weighted by the number of passengers on board, is $n^{in}_i u^{in}_{ij} + n^{out}_i u^{out}_{ij}$. Note that n^{in}_i includes both destination passengers and transfer passengers, and u^{in}_{ij} depends on the distance between gate j and the arrival spot of flight i. Thus, the weighted unimpeded taxi time is a linear function of x_{ij} in Eq. (2).

Taxi delay involves a pair of aircraft, and it is weighted by the sum of the number of passengers on board both aircraft. For instance, if the taxi delay occurs between two arrivals, the total number of passengers is $n^{in}_i + n^{in}_k$. So, the taxi delays, which are quadratic terms of Eq. (2), are weighted by a general form of the total number of passengers on board flight i and k, $n_i + n_k$.

The formulation of the second metric is given below.

$$Metric_{taxi} = \sum_{i\in F}\sum_{j\in G}(n^{in}_i u^{in}_{ij} + n^{out}_i u^{out}_{ij})x_{ij} + \sum_{i\in F}\sum_{j\in G}\sum_{k\in F, k>i}\sum_{l\in G}(n_i + n_k)t^{dly}x_{ij}x_{kl} \quad (2)$$

D. Metric 3: Robustness of Gate Assignments

The third metric is the robustness of gate assignments. Equivalently, the metric is the duration of gate conflicts. If a gate is still occupied by an aircraft when another aircraft requests the gate, the latter should wait until the assigned gate or another gate is available, which corresponds to a gate conflict. Fig. 3 illustrates a gate conflict, where the gate separation is the time gap between t^{out}_i and t^{in}_k. In Fig. 3, flight i is scheduled to leave the gate before flight k arrives, but the departure time of flight i is delayed, and flight k arrives earlier than scheduled. So, when flight k arrives, the gate is not released yet and flight k has to wait for a gate.

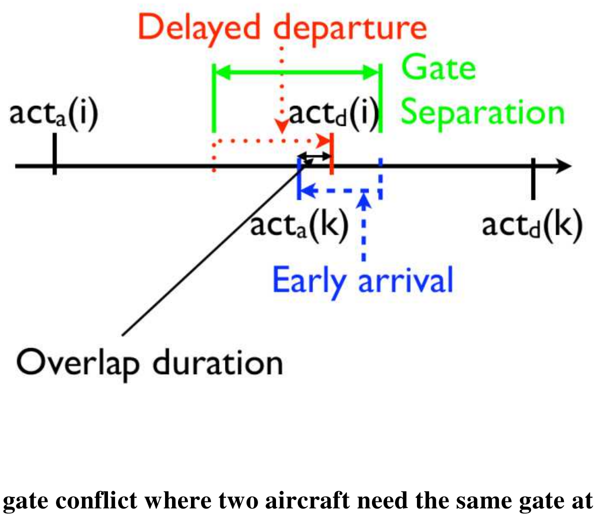

Fig. 3. Typical gate conflict where two aircraft need the same gate at the same time.

Because the actual arrival and departure times are unknown when gates are assigned, the duration of a gate conflict is estimated based on the probability distributions of arrival delay and departure delay. The expected duration of a gate conflict is calculated by E[$act_d(i)$-$act_a(k)$ | $act_d(i)$>$act_a(k)$] when $t^{in}_k > t^{out}_i$. Details of the calculation are given in [14].

The expected duration of a gate conflict is known to depend on gate separation [14]. Using the delay data of the U.S. carrier at the hub airport, which focused our attention, collected in May 2011, the expected duration of gate conflict as a function of gate separation is shown in Fig. 4. It is matched with the exponential fit $a*b^{\mathrm{sep}(i,k)}$, where a = 12.4, b = 0.96, and sep(i,k) denotes the gate separation between flights i and k.

The formulation of the third metric is given in Eq. (3) below. Note that the expected duration of a gate conflict is weighted by the number of arrival passengers because only arrivals are delayed due to a gate conflict.

$$Metric_{robust} = \sum_{i \in F} \sum_{k \in F, k>i} n^{in} \times 12.4 \times 0.96^{\mathrm{sep}(i,k)} \sum_{j \in G} x_{ij} x_{kj} \quad (3)$$

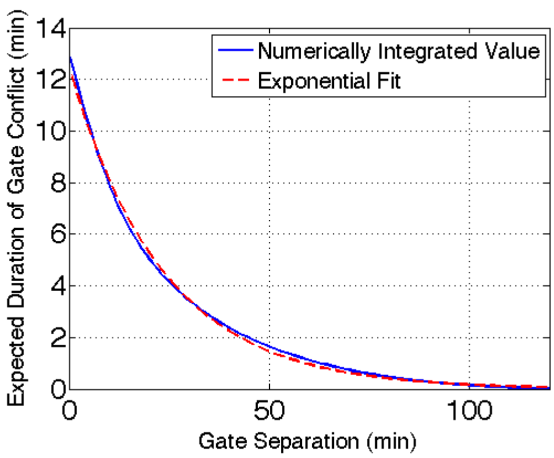

Fig. 4. Expected duration of gate conflict as a function of planned separation between consecutive occupancies, together with the exponential fit 12.4*0.96$^{\mathrm{sep}(i,k)}$.

E. Trade-offs of Multiple Metrics

It is known that the metrics presented above cannot be all simultaneously optimized; thus, optimal trade-offs must be achieved instead [12]. In order to analyze the trade-offs among the three metrics, a composite objective function is given below.

$$Obj = w_{transit} Metric_{transit} + w_{taxi} Metric_{taxi} + w_{robust} Metric_{robust}, \quad (4)$$

,where

$$w_{transit} + w_{taxi} + w_{robust} = 1, \quad (5)$$

and

$$w_{transit}, w_{taxi}, w_{robust} \geq 0. \quad (6)$$

The optimization problem for the analysis of trade-offs among the three metrics is given below.

Minimize *Obj* (7)

subject to the constraints

$$\sum_{j \in G} x_{ij} = 1, \forall i \in F \quad (8)$$

$$(t_i^{out} - t_k^{in} + t^{buff})(t_k^{out} - t_i^{in} + t^{buff}) \leq M(2 - x_{ij} - x_{kj}), i \neq k, \forall i, k \in F, \forall j \in G \quad (9)$$

$$x_{ij} \in \{0,1\}, \forall i \in F, \forall j \in G. \quad (10)$$

Two constraints are given in Eqs. (8)-(9). Eq. (8) makes sure that every flight is assigned to a single gate. Eq. (9) constrains two successive gate occupancies, so that they are separated by more than a certain amount of time, which is called buffer time. Eq. (9) is binding only if flights i and k are assigned to gate j ($x_{ij}=x_{kj}=1$), because M is an arbitrarily large number.

The objective function, Eq. (4), is a linear combination of the metrics Eq. (1), Eq. (2), and Eq. (3). For instance, when $w_{transit}$ is 1, the resulting optimization problem minimizes passenger transit time only. In the trade-off study that follows, the weighting factors are explored in increments of 0.1, so the number of possible combinations of the weighting factors is 66. All the possible combinations are evaluated for the analysis of trade-offs of multiple metrics.

F. Optimization Method

The Tabu Search (TS) is a meta-heuristic algorithm known to efficiently deal with combinatorial optimization problems such as the gate assignment problem [17, 18]. Although it is difficult for any optimization methods to find optimal solutions at all, our previous experience indicates that the TS can outperform the Branch and Bound and Genetic Algorithm in terms of solution time and solution accuracy for the gate assignment problem [12]. The results presented in this paper, therefore, rely on our use of TS for the optimization problem. The TS is a local search, so the algorithm can converge to a local optimum, which is not the global optimum. In order to help the TS escape from a local optimum, a tabu memory prevents the TS from utilizing recently used search moves for certain iterations. However, if a restricted search move improves the objective value, the search move can be used regardless of the tabu memory, known as the aspiration criterion. Two types of neighborhood search moves of the TS have been used for the solution to the problem. They are shown in Fig. 5 and Fig. 6. The *insert* move changes a flight's gate assignment from one to another, and the *interval exchange* move swaps the gate assignments of two groups of flights. Note that each gate has a list of equipment types that the gate can serve, and flights whose equipments are incompatible with the gate cannot be assigned to the gate.

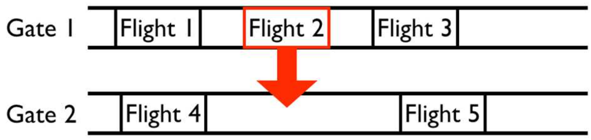

Fig. 5. Insert move: Change a flight's assignment from one gate to another that is also able to serve the equipment type of the flight.

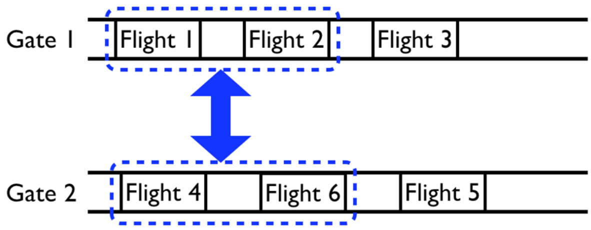

Fig. 6. Interval exchange move: Swap two groups of assignments if the correponding two gates are able to serve the equipment types of the groups.

The TS iterates until the number of iterations reaches the maximum iteration or there is no improvement of the objective value after some iterations past the last best score. The insert move is evaluated at every iteration in order to intensify a local search around a narrow neighborhood of the current solution. The interval exchange move is evaluated periodically in order to diversify the search: the interval exchange move brings a relatively large change in the current solution. More details of the implementation of the TS on the gate assignment problem are given in [12].

III.Results

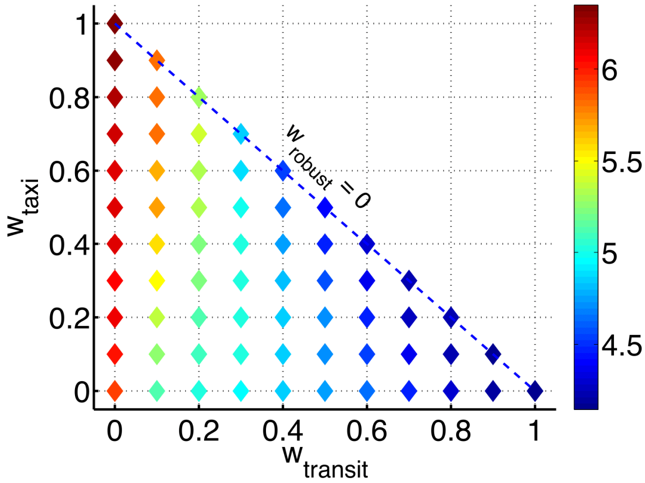

Fig. 7. Average transit time in minutes per passenger for 66 values of ($w_{transit}$, w_{taxi}, w_{robust}): transit times are color-coded from blue (~4 min) to red (~6.5 min).

Fig. 7 illustrates the average transit time experienced by each passenger, which is given in Eq. (11).

Average transit time = $Metric_{transit}$ / number of passengers. (11)

The number of passengers is the sum of the number of O&D passengers and the number of transfer passengers. Each data point of Fig. 7 represents a value of three weighting factors ($w_{transit}$, w_{taxi}, w_{robust}). The value of the horizontal axis is $w_{transit}$ and the value of the vertical axis is w_{taxi}. w_{robust} is obtained from Eq. (5) because the sum of three weighting factors is equal to 1. For instance, the bottom-left vertex corresponds to the value ($w_{transit}$, w_{taxi}, w_{robust}) = (0, 0, 1). The passenger transit time for each value of the weighting factors is color-coded: the blue-end indicates the shortest transit time and the red-end indicates the longest transit time. As expected, the average transit time experienced by each passenger tends to become shorter as $w_{transit}$ gets larger.

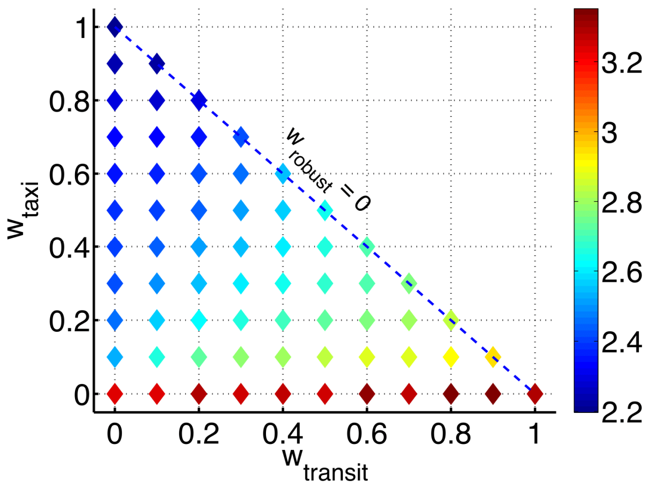

Fig. 8. Average taxi time in minutes per passsenger for 66 values of ($w_{transit}$, w_{taxi}, w_{robust}): taxi times are color-coded from blue (~2.2 min) to red (~3.4 min).

Fig. 8 shows the average taxi time experienced by each passenger, which is given in Eq. (12).

Average taxi time = $Metric_{taxi}$ / number of passengers on board. (12)

Note that the number of passengers on board is not equal to the number of passengers. Transfer passengers take flights twice (an arrival and a departure), so they count twice. Hence, the number of passengers on board is larger than the number of passengers. Each data point represents a value of the weighting factors the same as Fig. 7. Similar to Fig. 7, the average taxi time tends to become shorter as w_{taxi} gets larger.

Table 1 Trade-off between average transit time and average taxi time when w_{robust} = 0

($w_{transit}$, w_{taxi}, w_{robust})	Average Transit Time	Average Taxi Time
(0, 1, 0)	6.3 min	2.2 min
(1, 0, 0)	4.1 min	3.3 min

From Fig. 7 and Fig. 8, the trade-off between average transit time and average taxi time per passenger can be analyzed. First, w_{robust} is set to zero, which corresponds to $w_{transit}$ and w_{taxi} standing on the longest edge of the triangular shape. Then, there are 11 data points on the line from (0, 1, 0) to (1, 0, 0). When $w_{transit}$ is 0 and w_{taxi} is 1, the average transit time is the longest and the average taxi time is the shortest along the line (w_{robust} = 0). On the other hand, when $w_{transit}$ is 1 and w_{taxi} is 0, the average transit time is the shortest and the average taxi time is the longest along the line (w_{robust} = 0). Table 1 shows the details on the trade-off between average transit time and average taxi time per passenger when w_{robust} is equal to zero. Therefore, there is a trade-off between transit time and aircraft taxi time as discussed in [12]. Focusing on one metric alone will harm the others.

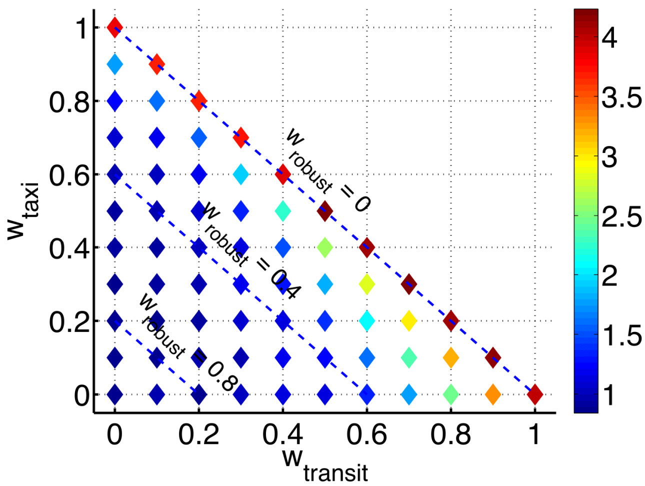

Fig. 9. Average duration of gate conflict in minutes per passenger for 66 values of ($w_{transit}$, w_{taxi}, w_{robust}): gate conflict durations are color-coded from blue (~1 min) to red (~4 min).

Fig. 9 shows the average gate conflict duration experienced by each passenger, which is given in Eq. (13).

$$\text{Average gate conflict duration} = Metric_{robust} / \text{number of arrival passengers}. \quad (13)$$

Note that the arrival passengers are the passengers who take flights arriving the airport. Similar to the previous analyses on transit time and taxi time, the duration of gate conflict becomes shorter as w_{robust} gets larger.

Then, we compare the optimized gate assignment with the current gate assignment in order to assess how airlines accommodate passenger experience in the three metrics proposed in this paper. The current gate assignment is obtained from the carrier, and the optimized gate assignment is chosen with ($w_{transit}$, w_{taxi}, w_{robust}) = (0.2, 0.2, 0.6). However, the choice of the weighting factors can depend on the policy of airport gate managers and airlines.

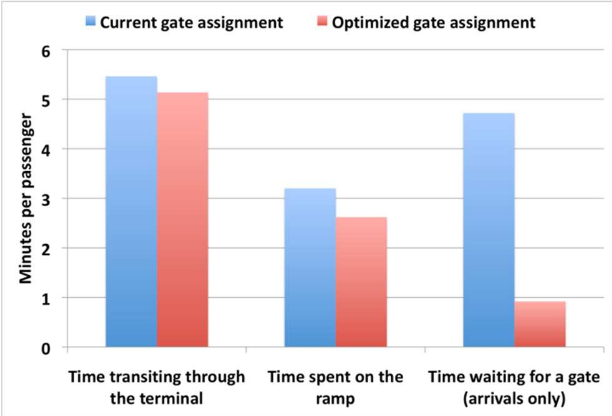

Fig. 10. Comparison of the current gate assignment and the optimized gate assignment: The current gate assignment is obtained from the U.S. carrier and the optimized gate assignment corresponds to ($w_{transit}$, w_{taxi}, w_{robust}) = (0.2, 0.2, 0.6).

Fig. 10 shows the comparison of the current gate assignment and the optimized gate assignment. From the perspective of a passenger, the average taxi time is the time spent on the ramp and the average duration of gate conflict is the time waiting for a gate, which happens only to arrivals. It is shown that the optimized gate assignment can improve all the metrics compared to the current gate assignment. Specifically, average transit time, average taxi time, and average gate conflict duration are reduced by 6%, 18%, and 81% respectively with the optimized gate assignment. In conclusion, the saving from the optimized gate assignment is 4.7 minutes per passenger, which means that passengers save 4.7 minutes on average in the passenger terminal and the ramp area.

IV.Conclusion

This study presents three of the metrics that most affect passenger experience at congested airport. These metrics are transit time of passengers in passenger terminals; aircraft taxi time on ramps; and the duration of gate conflicts. It is known that these metrics compete against each other, so an objective function that balances three metrics is proposed. The objective function can simulate the preferences of the airline, the air navigation service provider, or passengers by combining a value of the weighting factors. Different values of the weighting factors result in significantly different gate allocation strategies. Moreover, the performance obtained by optimizing the balanced objective function appears to outperform the observed, real-life gate assignment in every metric. Therefore, and although further studies are necessary to understand this difference in performance, the gate assignment of the airport offers the potential to improve the efficiency of traffic flow in passenger terminals and on ramps, as well as the robustness of gate operations.

Future work will account for gate-holding strategies generated by Airport CDM [15]. Although this study in this paper includes the robustness of gate assignment, which was shown to help gate-holding strategies perform better [15], a comprehensive analysis of gate-holding strategies and passengers' experience at the airport is still needed.

Acknowledgments

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