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16. Abstract

Serving one of the largest metropolitan areas in the United States, the George Bush Intercontinental Airport (IAH) is among the 10 airports with the longest average taxi-out and taxi-in times. The first part of this report assesses the congestion at IAH by analyzing taxi times and flight data during different hours of the day. The capacity of IAH is investigated by examining the number of departing flights on the ground. It reveals that IAH is operating close to the capacity most of the time. Since increasing airport capacity can mitigate the congestion, the second part of this report develops a surface operation model based on the analyzed results to achieve this aim. A mixed integer programming formulation is proposed to optimize the total taxi times by finding the optimal taxi routes and the related schedules. Afterwards, the model is applied to a sample from real data.

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Taxiway Aircraft Traffic Analysis at George Bush Intercontinental Airport

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ABSTRACT

Serving one of the largest metropolitan areas in the United States, the George Bush Intercontinental Airport (IAH) is among the 10 airports with the longest average taxi-out and taxi-in times (*1*). The first part of this report assesses the congestion at IAH by analyzing taxi times and flight data during different hours of the day. The capacity of IAH is investigated by examining the number of departing flights on the ground. It reveals that IAH is operating close to the capacity most of the time. Since increasing airport capacity can mitigate the congestion, the second part of this report develops a surface operation model based on the analyzed results to achieve this aim. A mixed integer programming formulation is proposed to optimize the total taxi times by finding the optimal taxi routes and the related schedules. Afterwards, the model is applied to a sample from real data.

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EXECUTIVE SUMMARY

This project analyzes the taxi-in and taxi-out times of flights at the George Bush Intercontinental Airport (IAH) and proposes a method to optimize the taxi schedules. With the increase of air traffic demand during the past few years, IAH is among the 10 airports with the longest average taxi-out and taxi-in times, indicating that it is operating close to its capacity or under congestion most of the time. The taxi-out time of a departing aircraft refers to the amount time that elapses from its gate pushback to the takeoff on the runway, while the taxi-in time of an arriving flight refers to the time measuring between its arriving on the runway and touching the gate. Taxi time delays are most often due to the congestion when the demand of departing and arriving airplanes exceeds the capacity. As a result, it is a fundamental parameter indicating the congestion on the airport ground and efficiency of surface operations.

It is shown that the longest taxi time occurred during the summer. Therefore, this study used the flight data at IAH from June 1 to June 15, 2010. The first part of this report evaluates the congestion at IAH. By analyzing the number of flights on the airport ground during different hours of the day, the busiest hours during which congestion occur are identified. Taxi times are compared among different runways, and the capacity of IAH is investigated by examining the number of departing flights on the ground against the takeoff rate. It reveals that IAH is operating close to the capacity most of the time.

Since increasing airport capacity can mitigate the congestion, the second part of this report develops a surface operation model based on the analyzed results to achieve this aim. A Mixed Integer Programming (MIP) formulation is proposed to improve the taxi time by finding the optimal taxi routes and the related schedules. Since exactly solving the MIP problem with a large flight demand requires an extreme amount of computational time, a heuristic method is adopted to find the solution.

CHAPTER 1:
INTRODUCTION

With the increase of air traffic demand during the past few years, many airports are faced with severe congestion problems. Most major airports are operating close to their capacities. According to data collected by the Bureau of Transportation Statistics for the year 2007, both outbound and inbound taxi times increased noticeably in 2007 and surpassed the previous peak reached in 2000 (*1*).

Serving one of the largest metropolitan areas in the United States, the George Bush Intercontinental Airport (IAH) is among the 10 airports with the longest average taxi-out and taxi-in times (*1*). Given the expected annual growth rate of air traffic demand, it would be very difficult for IAH to handle all the aircraft efficiently. It indicates that IAH needs to take measures to improve its overall capacity. Generally there are two ways to enlarge the airport capacity. The first way is to construct new facilities such runways and taxiways. However, due to the limit of budget and available land space, some airports may prefer an alternative way to improve the capacity. It is recognized that the increase in airport capacity can be achieved through new concept of surface operations (*2*). The airport surface includes the gates with the ramp areas, the taxiways and the runway system. The operations refer to the airplane schedules and interactions between these airport surface components. Hence, the objectives of this paper are: 1) to analyze the departure and arrival data from IAH, and 2) to develop a model to optimize the surface operations based on the analyzed results.

It is shown that the longest taxi-out times occurred during the summer (*1*). Therefore, this study used the departure and arrival data at IAH from June 1 to June 15, 2010. The data are obtained and combined from two sources: the IAH airport and the Research and Innovative Technology Administration (RITA) (*3*). The information from the data includes:

- Scheduled and actual pushback time (gate-out) of each departing flight.
- Scheduled and actual arrival time (gate-in) of each arriving flight.
- Wheel-on time of each arrival and wheel-off of each departure.
- Flight code of each flight.

- Runway usage of each flight.
- General information of gate usage.

This report is organized as follows. First, the general information of IAH is introduced. Then runway operations and taxi times are studied during different hours of the day. The capacity of departures and the congestion are investigated by examining the number of departing flights on the ground. Afterward, based on the analyzed results, a mixed integer programming formulation is proposed for optimizing surface operations. The model can optimize the total taxi times by finding the optimal taxi routes and the related schedules. In addition, the model is applied to some real scheduled flights data.

RESEARCH OBJECTIVES

The objective of this research is to understand the reason of congestion at IAH and develop a model to optimize the surface operations. The data of arrivals and departures are analyzed according to each runway and different hours per day. The focus of data analysis is to determine the capacity of each runway and identify the busy hours. Another focus of this research is to develop a model to optimize the surface operations based on the analyzed results. The model can give a surface moving schedule for each airplane so that the aircraft can experience the minimum delay on the airport ground.

CHAPTER 2:
ANALYSIS OF ARRIVALS AND DEPARTURES

OVERVIEW OF IAH AIRPORT OPERATIONS

Currently, the IAH airport configuration featured two sets of parallel runways and one single runway: 08L/26R, 08R/26L, 15L/33R, 15R/33L, and 09/27, as shown in Figure 1. By the time this study was completed, all the runways were used in a mixed arrival/departure mode to accommodate the increase in air traffic associated with the airport, different from the prior operation strategy that only allowed Runways 15L/R to serve the departing aircraft (*4*). This runway usage strategy can be seen from Table 1, which summarizes the arrival and departure information from June 1 to June 15, 2010.

This table shows the total number of arrivals and departures for each runway, as well as the average value per day. It is clear that Runways 27 and 26L/R handle most of arriving aircraft, and Runways 15L/R deal with most of departing aircraft, indicating that west flow operations occur most often at IAH airport. Rarely using Runway 09 for arrivals reveals that aircraft arriving on it would affect the aircraft departing from Runways 15L/33R and 15R/33L due to the need for a two-mile clearance to protect airspace. Due to the longer distance between Runway 26R/08L and each terminal (see Figure 1), Runways 26L/08R and 27/09 are used more often than 26R/08L. In addition, the total number of arrivals 11,150 is not equal to the total number of departures 11160 (not shown in Table 1) because some flight information is not reported.

Table 1: Summary of arrivals and departures for each runway.

Runway	Total Number of Arrivals	Arrivals/Day (Average)	Total Number of Departures	Departures/Day (Average)
15R	100	6.67	3467	231.13
33L	0	0.00	101	6.73
15L	41	2.73	6618	441.20
33R	4	0.27	174	11.60
09	102	6.80	452	30.13
27	4436	295.73	40	2.67
08R	1149	76.60	5	0.33
26L	3966	264.40	207	13.80
08L	609	40.60	1	0.07
26R	732	48.80	85	5.67
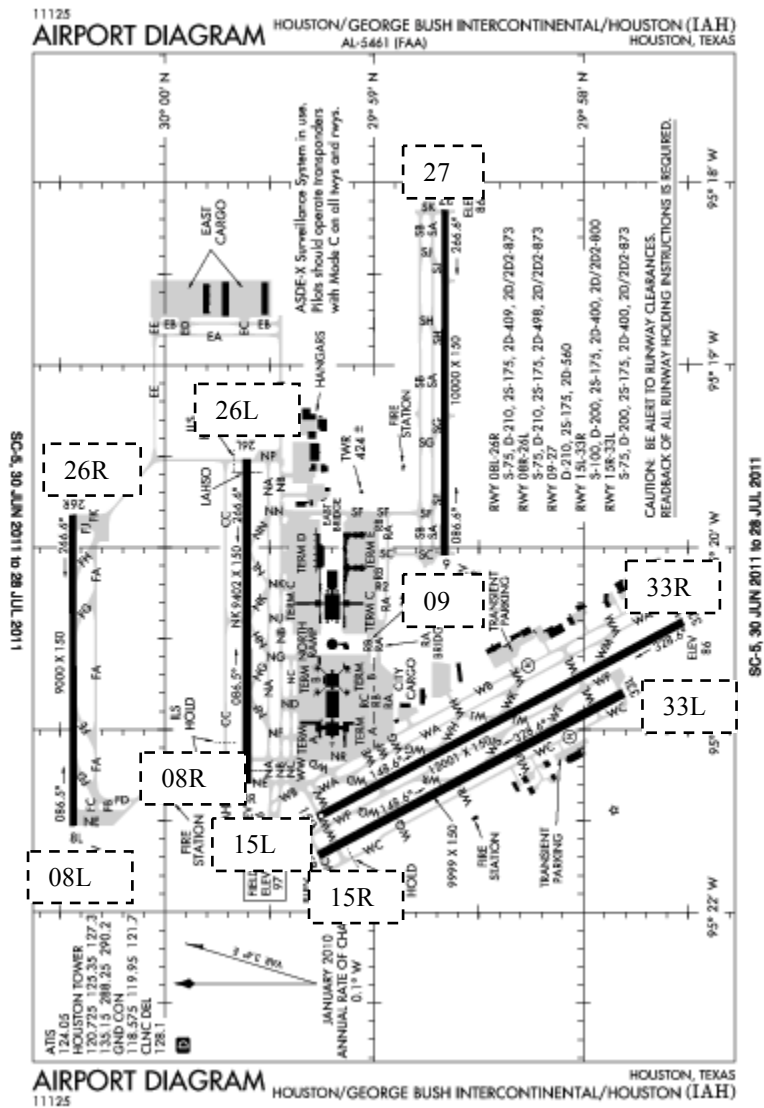
Figure 1: IAH airfield layout and runway system.

ANALYSIS OF ARRIVALS

Airport surface operations consist of those at four regions: the runways, the taxiway system, the ramp areas, and the gates. Operations at each region are critical to each arriving or departing aircraft, and could be a reason to the delay. For the arrival process, an arriving aircraft leaves the runway as soon as possible after touchdown and enters the taxiway system. Then it taxis to the terminal area and may wait on the ramp for a prepared gate. The taxi-in time of arriving aircraft measures the time between landing (wheel-on) and gate arrival (gate-in). For a runway in the mixed usage, arriving aircraft might interact with departing aircraft in some way. Although Idris

et al. (*5*) found a very low correlation between taxi-out delay and arrivals, a re-examination study by Clewlow et al. (*6*) indicated that the number of arriving aircraft did, as one might expect, affect taxi-out times. Hence, this section will first examine the number of arrivals in each hour, as well as the related taxi-in time.

The number of arrivals and departures can vary significantly during different periods of a day. The number of runway operations during one hour may affect the number of departures or arrivals during the next hour. In order to show the statistics of runway operations during different hours of the day, either the mean value or total number of arrivals can be used. However, the problem may occur in these two cases. Because there could be no records of arrivals for a particular hour in some days, a mean value averaging the total number of arrivals over the whole period may underestimate the real value. Likewise, only using the total number of operations cannot tell how busy the runway is during the whole period. To account these factors, Table 2 uses the mean value equal to the total number of arrivals divided by the number of days during which there is at least one arriving aircraft. The table shows the percentage of these days during the whole period as well. For example, 50% of day in use in Table 2 means that only 50% of the whole period (i.e., 15 days in this study) for that particular hour had the runway operations.

Table 2 shows the average number of arrivals on most frequently used runways. It is clear that the busiest period for arrival operations is from 13:00 to 14:00 during most of days. There are also two local arrival peaks from 16:00 to 17:00 and from 19:00 to 20:00. The airport operates with all runways during these periods. Runways 27 and 26L are used most often and their busy periods start from 10:00 to 17:00. Although the records show Runway 08R can handle 30 arrivals during one hour, a detailed examination of the data indicates that the taxi-in times increase during these hours. It indicates that the optimal number of arrivals for this runway may be smaller, since it should not cause increase in taxi times. The available data and the information in Table 2 suggest the optimal maximum number of arrivals for Runways 08R/L and 27 is 25 aircraft per hour.

Figure 2 shows the average taxi-in times during each hour of the day. There is no significant difference in taxi-in times between Runway 27 and 26L/08R, both of them bellow 10 minutes per aircraft. The Runway 08R taxi times have two peaks around 11:00 and around 17:00. For

Runway 26R/08L, the average taxi-in times are larger than 10 minutes. It may not be surprising since it is farther from the terminal than other runways. One may ask why there is a peak of taxi-in time larger than 15 min for Runway 08L around 9:00. A detailed examination of the data shows that there were abnormal operations on June 9: no runway except 08L served arrivals from 9:00 to 10:00 and thus it caused increase in the taxi-in times. It seems that Runway 26L/08R was closed due to some unknown reasons.

Table 2: Runway operations for arrivals during each hour of day.

Runway	27		08R		26L		08L		26R	
Hour	Mean	% of Day in Use	Mean	% of Days in Use	Mean	% of Days in Use	Mean	% of Days in Use	Mean	% of Days in Use
0:00	2.38	53%	1.83	40%	2.67	20%	0.00	–	0.00	–
1:00	1.29	47%	1.33	20%	1.00	7%	0.00	–	0.00	–
2:00	1.00	13%	0.00	–	1.00	7%	0.00	–	0.00	–
3:00	1.50	27%	1.00	13%	1.33	20%	1.00	7%	0.00	–
4:00	2.00	80%	1.00	7%	1.50	13%	0.00	–	0.00	–
5:00	4.07	100%	7.42	80%	1.50	13%	0.00	–	0.00	–
6:00	7.87	100%	8.58	80%	4.91	73%	1.00	7%	0.00	–
7:00	19.53	100%	0.00	–	21.40	100%	0.00	–	8.73	100%
8:00	16.93	100%	0.00	–	17.40	100%	1.00	7%	3.50	53%
9:00	24.83	80%	4.00	7%	17.21	93%	6.50	13%	2.83	40%
10:00	25.45	73%	16.00	13%	21.69	87%	12.67	20%	5.33	40%
11:00	22.15	87%	27.00	7%	20.00	87%	11.67	20%	2.25	53%
12:00	20.07	93%	30.00	7%	18.50	93%	10.33	20%	2.00	40%
13:00	26.07	93%	27.00	13%	24.92	87%	27.00	13%	6.42	80%
14:00	26.46	87%	31.00	13%	26.92	87%	28.00	13%	5.17	80%
15:00	15.73	100%	7.75	27%	14.80	100%	4.75	27%	2.57	47%
16:00	21.93	93%	21.20	33%	23.23	87%	21.00	27%	7.11	60%
17:00	24.20	67%	24.86	47%	22.40	67%	20.67	40%	8.00	60%
18:00	16.83	80%	17.86	47%	15.58	80%	9.83	40%	2.57	47%
19:00	27.50	80%	20.40	33%	23.46	87%	17.00	20%	11.91	73%
20:00	11.85	87%	22.00	27%	18.42	80%	7.80	33%	3.91	73%
21:00	13.08	80%	10.50	27%	4.60	67%	1.50	13%	1.13	53%
22:00	5.71	93%	4.83	40%	5.89	60%	0.00	–	0.00	–
23:00	6.62	87%	4.13	53%	3.78	60%	0.00	–	0.00	–
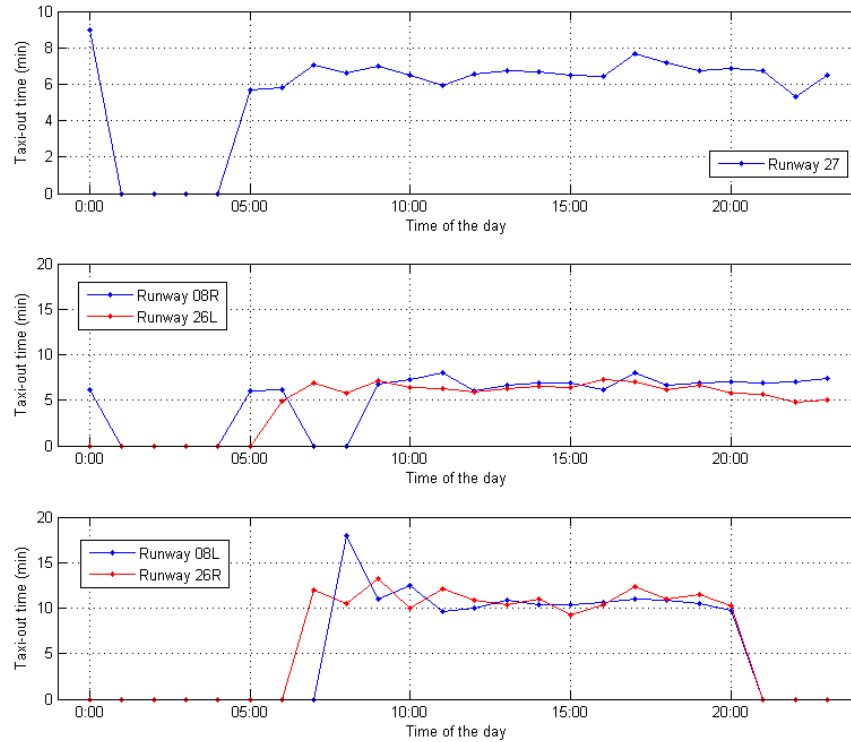
Figure 2: Taxi-in time during different hours of day.

CONGESTION DETERMINATION

Most major airports face congestion that occurs when departure demand exceeds the capacity
(*7*). Although sometimes such phenomenon is due to the reduced capacity during bad weather or
construction of runways, inefficient taxi operations for departing aircraft can contribute to the
most time of congestion, especially at some airports where the conservative taxi strategy is
adopted. However, without detail data such as taxi routes, the analysis can be done only through
macroscopic observations. Since a better understanding of taxi process for departures can help to
analyze the congestion, we first describe the departure process and discuss the factors affecting
the taxi-out time from macroscopic perspective.

In contrast to arrival process, departing aircraft would experience delay at each surface operation
region. At the gate, they should wait for pushback because of long pushback queue. They should
wait with others at the ramp to enter the taxiway system and when they taxi to the runway, they
may wait in the departure queues at the runways to take off. When there is a large departure

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demand, the queue can form in any above region. Individual departing aircraft would experience a long taxi-out time, resulting in a large number of aircraft kept on the airport surface. It indicates there is a saturation departure rate or a capacity at the airport. We will see later that although this concept is intuitively clear, it is hard to determine the capacity in practice.

In order to determine the saturation departure rate at IAH, the approach used by Simaiakis et al (*7, 8*) is adopted in this study. It considers the throughput of the departure runway with respect to the number of aircraft, denoted by N, on the ground after pushback from their gates. As the number N increases, the mean of departure rate increases until some maximum value. There is no additional increase in the mean of throughput on average if N still increases. Such maximum value can be seen as the capacity and the minimum number of N at the capacity is defined as the saturation point (*7*). Conceptually, if the number of departing aircraft on the ground exceeds the saturation point, the airport experiences the congestion. The weakness of such approach needs to be pointed out. At one particular N, the takeoff throughput may vary significantly comparing to the mean value. Even when N exceeds the threshold, the variance of throughput could be still large. It implies that there are many other factors to affect the departure throughput and it may require some more precise method to obtain the capacity. However, due to the limited available data, this approach is easily implemented and can be accepted as a tool to estimate the capacity in practice.

For the data used in this study, the average hourly departure throughput saturates at 50 when there are 43 departing aircraft on the ground. Here, the capacity refers to the total maximum hourly through of Runways 33L/15R and 33R/15L. Hence, the saturation point is 43 and the capacity is 50 aircraft per hour. It should be emphasized that this departure capacity is for the day only. Due to lack of data, the capacity during the night cannot be obtained.

Now, the congestion at IAH can be analyzed. In Figure 3, the solid bars show the mean values of the number of departing aircraft on the ground with respect to each hour of the day. The error bars denote the standard deviation. This figure reveals that the number of departures is significant larger than the saturation point of 43 aircraft for 2 hours of the day, i.e., from 15:00 to 16:00 and from 19:00 to 20:00. However, except these 2 hours, there is no significant difference between the maximum number of departing aircrafts and the capacity. It is reasonable to argue

that if the efficiency of taxi operations at IAH could be improved, the congestion might mitigate during above 2 hours.   Moreover, the examination of the standard deviation suggests that airport may experience congestion occasionally from 10:00 to 12:00 and from 14:00 to 15:00. A more detailed investigation shows that such occasional congestion periods exist shortly. The above analysis might also suggest that the airport would benefit if the controllers could adopt some more efficient strategy.
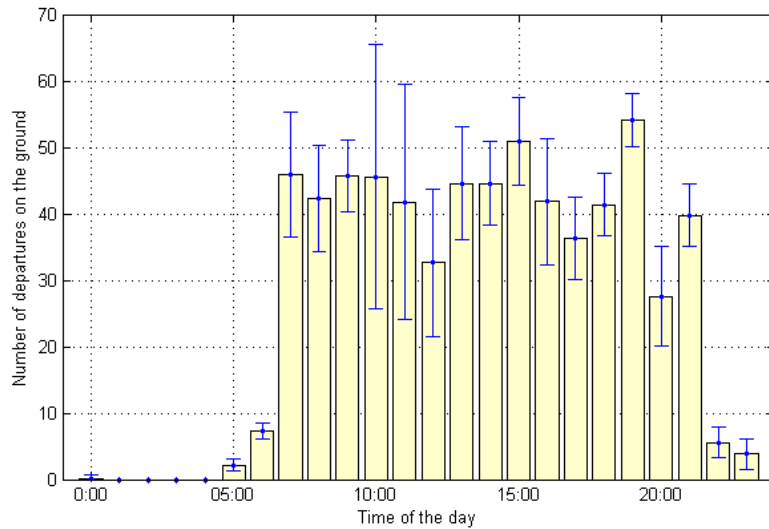
Figure 3: Number of departing aircraft on the ground during each hour.

ANALYSIS OF DEPARTURES

The number of departures and taxi-out times are analyzed in detailed in this section. Due to the west flow operations occurring most of the time at IAH, Runways 15L/33R and 15R/33L are used most often for departing aircraft. Table 3**Error! Reference source not found.** shows the average number of departures on these runways. The meaning of "percentage of day in use" is the same to that in Table 2. This table illustrates that the peak hours of Runway 15R, during which the number of departing aircraft per hour exceeds 20, are three periods of the day, i.e., from 9:00 to 10:00, from 13:00 to 14:00 and from 18:00 to 20:00. However, it seems that Runway 15L keeps operating in a high throughput rate for most hours of the day. Combining the information from Figure 3, a crude estimate of the capacity of Runway 15L is 30 aircraft per hour. Comparing the operations on Runways 15R and 15L, Runway 15L handles more aircraft,

and Runway 15R cannot operate in a high throughput rate for most of time. One possible reason is that, being closely spaced, these two runways are interdependent. In other words, departures from Runway 15R may depend upon the departures from 15L. Runway 15L can still handle a large amount of departures per hour from 21:00 to 22:00, implying that the light condition does not influence the capacity of this runway.

Furthermore, the standard deviation of the number of departures does not show in this table, as the values generally range from 5.00 to 8.00 during most of periods. The only exception occurs from 11:00 to12:00 during which the standard deviation for both runways reaches as high as 10.00. It indicates that the departure demand fluctuates around noon. In addition, the data show that Runways 33R and 33L are occasionally used for departures. Since all terminals for passengers are close to the thresholds of Runways 15L and 15R as seen in Figure 1, the departures used Runways 33R and 33L could be some cargo or other type of aircraft, whose information is missing in the current data.

Taxi-out times of departures on Runways 15R and 15L are also shown through their mean values and standard deviations (used as "std" in short) in Table 3**Error! Reference source not found.**. Generally speaking, the taxi-out time increases as the number of departures increases. In addition, during the peak hours, the taxi-out time from gates to Runway 15L is longer than 15 minutes per aircraft, and the taxi-out time to Runway 15R is longer than 20 minutes per aircraft. There is a 5-minute difference between them. It is also clear that the standard deviation is relatively large during the busy hours. This fact implies that the congestion of airport not only leads to the increase of taxi-out times but also brings about the uncertainty of handling departing aircraft. Moreover, the taxi-out time from the gate to Runway 15R is about 3 minutes longer than that to Runway 15L on average. On one hand, this is simply because the aircraft require more time to reach the Runway 15R threshold. On the other hand, considering a 5-minute difference during the peak hours, one can reasonably infer that the queues at Runway 15L probably influence the aircraft taxiing to Runway 15R.

Table 3: Runway operations for departures and taxi-out times during each hour of day.

Runway	15R				15L			
	Number of Departures		Taxi-out time		Number of Departures		Taxi-out time	
Hour	Mean	% of Day in Use	Mean	Std	Mean	% of Day in Use	Mean	Std
0:00	1.00	7%	0.00	0.00	2.30	67%	0.00	0.00
1:00	0.00	0%	0.00	0.00	3.00	7%	0.00	0.00
2:00	0.00	0%	0.00	0.00	2.00	7%	0.00	0.00
3:00	0.00	0%	0.00	0.00	1.00	7%	0.00	0.00
4:00	1.00	13%	0.00	0.00	1.00	7%	0.00	0.00
5:00	1.00	7%	0.00	0.00	2.40	100%	10.33	2.75
6:00	2.14	47%	12.50	3.99	11.00	100%	12.82	3.34
7:00	13.07	93%	17.27	3.05	24.00	100%	14.11	1.03
8:00	13.80	100%	23.56	10.80	22.67	100%	15.92	6.95
9:00	21.73	100%	22.00	10.00	34.40	100%	16.61	4.43
10:00	17.50	93%	17.38	5.74	28.07	100%	16.93	6.15
11:00	17.43	93%	16.26	2.81	29.93	100%	17.31	5.14
12:00	10.42	80%	15.67	2.26	24.00	93%	13.52	1.07
13:00	20.00	93%	17.45	4.24	32.00	93%	15.29	2.88
14:00	14.40	100%	15.78	1.85	29.80	100%	13.54	2.03
15:00	17.57	93%	17.47	4.86	28.40	100%	14.73	4.45
16:00	18.87	100%	21.41	8.42	27.93	100%	19.23	7.93
17:00	10.00	73%	21.34	11.52	25.00	93%	13.85	4.23
18:00	23.07	93%	18.50	2.95	30.79	93%	14.45	2.39
19:00	22.93	100%	17.87	2.78	33.93	100%	15.78	2.04
20:00	6.93	93%	15.62	4.50	20.60	100%	11.44	1.21
21:00	12.47	100%	20.09	8.78	29.73	100%	14.08	2.63
22:00	3.50	53%	24.42	13.05	7.60	100%	11.14	2.34
23:00	1.00	27%	8.67	1.25	5.08	87%	10.82	3.17

Taxi-out times are known to vary from day to day, depending on the congestion situation at the airport. This effect may influence the accuracy of estimating the mean value and reflect in a large standard deviation. For example, Figure 4 illustrates the mean values of taxi-out time to Runways 15R and 15L between June 1 and June 5, 2010. These five days are chosen because the IAH airport is much busier than other days in the available data of this study. The taxi-out times in these five days are generally longer than the overall average, especially during the periods

around 10:00, 17:00, and 21:00. In Table 3**Error! Reference source not found.**, the difference of taxi-out times between Runways 15R and 15L is not significant for most of hours. However, this is not true in Figure 4, where the difference is significant during most of the time. The figure suggests that the taxi-out times from gates to Runway 15R could become excessive when the airport encounters congestion. This case suggests that one should take care when dealing with the data over a long period, and more insightful investigation is needed in the future study.
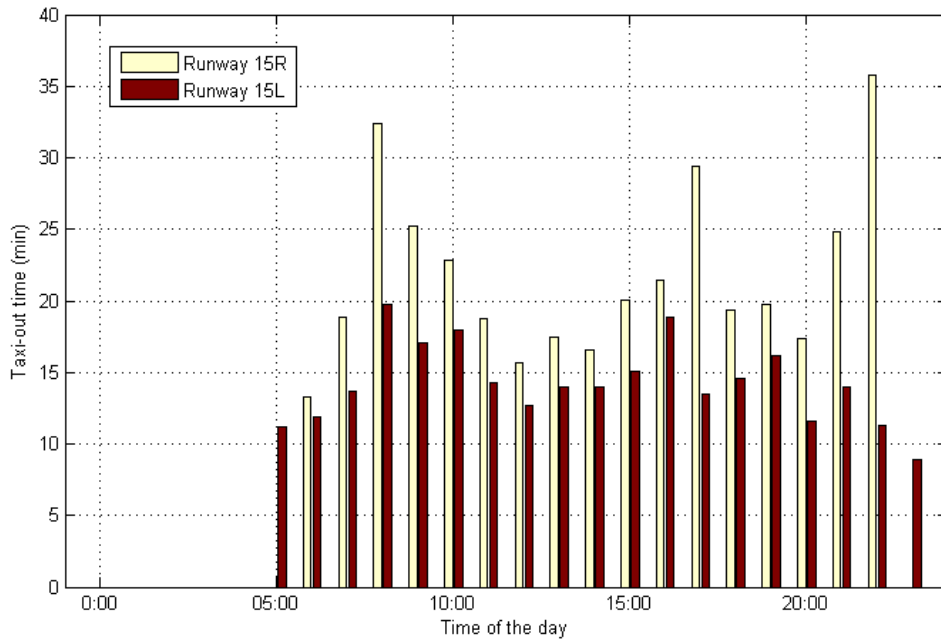
Figure 4: Taxi-out times from gates to Runways 15R/L between June 1 and June 5, 2010.

CHAPTER 3:
MODEL OF SURFACE OPERATIONS

The above analysis shows that the taxi times become longer during the busy hours of IAH airports. Although this phenomenon is normal at most major airports, sometimes it might be due to the inefficient taxi operation strategy. Hence, this study proposed a model to optimize the surface operations.

Modeling taxi processes and determining the taxi routes for arriving and departing aircraft are important for optimizing the surface operations and developing related decision support tools (*9*). Optimization tools can assist those controllers to better navigate the aircraft operations. Extensive research has been done in optimizing the airport surface operations. While some apply dynamic programming with shortest path algorithm (*10*), most of authors use Mixed Integer Linear (MIP) programming (*11,12,13*) to incorporate different kinds of control strategies. Some studies model the surface operations through the time-space network models (*12*), and some use network assignment techniques to decide the taxi routes (*14*). Among these models, control strategies and taxi route decisions are critical to the performance, since most constraints such as link directions, time continuity, and order constraints are similar to the constraints in the traditional vehicle routing and scheduling problem. In the study of Smeltink et al. (*11*), each individual aircraft is assigned a fixed taxi route no matter if it is a departure or an arrival. Then the problem becomes a scheduling problem, which requires the aircraft to reach each segment of taxi route at a scheduled time. In Balakrishnan and Jung (*15*), the taxi routes are chosen from a preferred set and two different controlled strategies, namely controlled pushback and taxi reroutes, are assessed. This taxi routes strategy is more flexible than pre-assigned routes and enjoys quite efficient computational time. The authors show that the taxi-out times are reduced and the airport would benefit from these control strategies especially for high-density operations. Although some studies (*9, 16*) recommended that several airport ground systems should be considered together, the problems become too complex and not practical in implementation.

This study proposes an MIP programming and adopts a centralized control strategy to investigate the taxi planning in good weather conditions. The proposed model aims at automatically providing non-conflict taxi routes and scheduling plans for all aircraft on the airport ground, in

order to minimize the overall taxi times. Before we formulate the problem, we state the taxi routes decision and control strategy used in this study.

TAXI ROUTES DECISION AND CONTROL STRATEGY

In practice, taxiing aircraft have the option to take multiple taxi routes. If controllers realize that some taxiways are occupied by another aircraft during a busy period, they may assign the aircraft an alternative route to reduce the congestion. Along this direction, we adopt the method in (*12*) and only fix the origin and destination of each aircraft. With proper objective and constraints in the model, the aircraft must follow the same taxi route to their destination when there is no congestion on the ground. If there is congestion on some links, the solution can search optimal routes for all the aircraft as well as their schedules of using those routes. Nevertheless, due to the increase of variables and constraints, the computation time can be large and some heuristic methods should be adopted.

During the congestion on the ground, the aircraft are sometimes required to hold on some area along their routes to wait for queue clearance. The most commonly used holding points are gates. If one aircraft frequently holds on the middle of the path with engine on, the stop-and-go phenomenon would burn much fuel. From both economical and environmental perspectives, it is desirable to hold the aircraft at the gates if there is a need.

MODEL FORMULATION

The IAH airport surface is modeled as a graph of nodes and links, denoted by $G = \{N, L\}$. N is a set of nodes, which can represent gates, intersections of taxiways, runway crossing points, runway threshold, and runway exits. L is a set of directed links representing taxiways and other links connecting the nodes.

Let $F = \{D, A\}$ be the aircraft set where D is the set of departures and A is the set of arrivals. For each aircraft $i \in F$, the origin (denoted by ORI_i) and the destination (denoted by DES_i) are fixed. A taxi route for aircraft i is thus a sequence of nodes connecting the origin and the destination. For the departure aircraft, the gate is the origin and the runway threshold is the destination. Similarly, for the arrival aircraft, the origin is the landing runway exit and

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destination is the assigned gate. A dummy node N_{air} is introduced in this model and can be understood as the outside of the airport ground network. Each departing aircraft reaches the destination and then enters this dummy node.

We let each aircraft associate with a sequence of planning periods, denoted by $\{E_1, E_2, ..., E_p\}$. Each E_j is a length of time. The fixed number p is chosen to guarantee every aircraft can finish the movement from the origin to the destination. When an aircraft leaves a certain node, a new planning period begins. It is assumed that all aircraft enter the dummy node within E_p planning periods, implying that they complete their paths. If the aircraft enters the dummy node in E_j where $j \neq p$, the left planning periods are set to zero. For each arriving or departing aircraft, the taxi time is between its first planning period and its last planning.

Variables Definition

- $R^j_{(i,n_1,n_2)}$: Route variable; equal to 1 if aircraft i moves from node n_1 to node n_2 at planning period j; equal to 0 otherwise.

- $Z^n_{(i,j)}$: Order variable; equal to 1 if aircraft i arrives at node n earlier than aircraft j; equal to 0 otherwise. The dummy node is not considered for this variable.

- $C^{n_r}_{(i,j)}$: equal to 1 aircraft i_1 takes off earlier than the time when aircraft i_2 (if any) cross the runway; otherwise it is 0. The notion n_r is the threshold of runway.

- t^j_i: representing the starting time of planning period j for aircraft i.

- EPT_i and EAT_i: Planned pushback time for departures and planned arrived time for arrivals, respectively.

Objective Function

The objective is to minimize the total cost and total taxi times by finding the taxi routes and schedules for all aircraft. Such objective is expressed as Equation 1, where f_i is a cost variable associated with each departing and arriving flight. For different flights, f_i can be different according to the urgency of each individual flight.

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$$\min \sum_{i \in F} f_i(t_i^{E_p} - t_i^1) \tag{1}$$

General Constraints

Aircraft can use any link connecting the node in the airport network, and an individual aircraft should move from the origin to the destination. These requirements are expressed as constraints 2. Constraints 3 ensure that each aircraft moves once in each planning period. Aircraft that move to one node in one planning period should move to another from this node. Although the aircraft can stay in the same node, it cannot be allowed to turn back. Constraints 4 represent these requirements. The above constraints are seen in many other models (*16*).

$$R_{(i,n_1,n_2)}^j \leq C_{(n_1,n_2)}, \ R_{(i,DES_i,DES_i)}^p = 1 \text{ and } R_{(i,ORI_i,ORI_i)}^1 = 1, \ \forall i \in F, j \in \{1...p\}, \ n_1, n_2 \in N \tag{2}$$

$$\sum_{m \in N} \sum_{n \in N} R_{(i,m,n)}^j = 1, \ \forall j = \{1...p\} \tag{3}$$

$$\sum_{n \in N} R_{(i,n,m)}^j = \sum_{n \in N} R_{(i,n,m)}^{j+1} \text{ and } R_{(i,n_1,n_2)}^j + R_{(j,n_2,n_1)}^{j+1} \leq 1, \ \forall j \in \{1,...,p-1\} \tag{4}$$

In order to implement the control strategy, the variables DEP_i are introduced to represent the maximum allowed pushback delay for each departure. The pushback time found by the model should be not less than planned pushback time and the pushback delay should not be longer than the maximum allowed delay. For arrivals, the situation is a little difficult. The airport usually only has the planned arrival time for each flight. However, the flight can either arrive earlier or later than planned time according to some uncertainty. Thus, the arrival times might be considered as random variables, resulting in a complex model. To simplify the procedure, we introduce the variables DEA_i to represent the possible time deviation from planned arrival. Although one flight may not arrive at the time found by the model, the flight can still follow the taxi route calculated by the model as long as the time deviation is not too large. In addition, the first planning period is used to fix aircraft to its origin. Hence, the constraints 5 express the above requirements.

$$t_i^1 = t_i^2$$
$$EPT_i \leq t_i^2 \leq EPT_i + DEP, \ \forall i \in D \tag{5}$$
$$EAT_i - DEA \leq t_i^2 \leq EAT_i + DEA, \forall i \in A$$

To make sure that aircraft i_1 and aircraft i_2 to pass the node n in an order, order constraints should be considered. In addition, we set the order variables to zero for the same aircraft. Then, we have the constraints 6.

$$Z_{(i,i)}^n = 0$$
$$Z_{(i_1,i_2)}^n + Z_{(i_2,i_1)}^n \leq (\sum_{m \in N} \sum_{j \in P} R_{(i_1,m,n)}^j + \sum_{m \in N} \sum_{j \in P} R_{(i_2,m,n)}^j) / 2 \tag{6}$$
$$Z_{(i_1,i_2)}^n + Z_{(i_2,i_1)}^n \geq \sum_{m \in N} \sum_{j \in P} R_{(i_1,m,n)}^j + \sum_{m \in N} \sum_{j \in P} R_{(i_2,m,n)}^j - 1$$

Safety Constraints

In this study, we assume that the taxiway is wide enough to allow only one aircraft to move. Furthermore, if one aircraft arrives at one node earlier than another on the same link, it should arrive at the next node earlier as well. Hence, we have the constraints 7. In addition, two aircraft have to avoid the head-to-head collision, i.e., moving toward each other. Then the according constraints can be obtained by using $R_{(i_1,n_2,n_1)}^j$ in constraints 7 instead of $R_{(i_1,n_1,n_2)}^j$.

$$Z_{(i_1,i_2)}^n + Z_{(i_2,i_1)}^n \leq 2 - (\sum_{j \in P} R_{(i_2,n_1,n_2)}^j + \sum_{j \in P} R_{(i_1,n_1,n_2)}^j), \forall i_1 \neq i_2 \in F, n_1 \neq n_2 \in N$$
$$Z_{(i_1,i_2)}^n + Z_{(i_2,i_1)}^n \geq (\sum_{j \in P} R_{(i_2,n_1,n_2)}^j + \sum_{j \in P} R_{(i_1,n_1,n_2)}^j) - 2. \tag{7}$$

Minimum Separation and Runway Crossing Constraints

For safety, taxiing aircraft must maintain a certain distance with each other. No uniform standard exists for the minimum separation since different authors apply different standards in literature (*11,12,13,14*). However, any standard needs the data to support and this issue needs to be investigated in the future. In this study, we use a minimum separation time t_{sep} instead of a minimum separation distance in order to make the constraint simpler. Due to the uncertainty of

taxiing speed in the trajectory, the minimum separation needs to be large enough to ensure the safety. This principle is illustrated in constraints 8, where M is a large constant.

$$t_{i_1}^{j_1+1} + t_{sep} \leq t_{i_2}^{j_2+1} + M(3 - Z_{(i_1,i_2)}^n - \sum_{m \in N}(R_{(i_1,m,n)}^{j_1} + R_{(i_2,m,n)}^{j_2})) \tag{8}$$

Although runway crossing is not allowed currently at IAH airport, it is a popular phenomenon in many major airports. A success runway crossing has to account the factors such as the runway occupancy time and the crossing time. To complete the model, we present related constraints here. We assume that the aircraft i_2 wishes to cross an active runway from the node n_{cb} to n_{ca} and aircraft i_1 at runway threshold n_r uses the runway. Let $Y_{(i_1,i_2)}$ be the total time that is needed to complete one crossing. Constraints 8 illustrate the above requirements for the case that one departing aircraft uses the runway.

$$t_{i_1}^{j_1+1} + Y_{(i_1,i_2)} \leq t_{i_2}^{j_2+1} + M(3 - C_{(i_1,i_2)}^{n_r} - \sum_{m \in N}(R_{(i_1,m,n_r)}^{j_1} + R_{(i_2,m,n_{cb})}^{j_2})), \forall i_1 \in D, j_1, j_2 \in \{1...p\}$$
$$t_{i_1}^{j_1+1} \leq t_{i_2}^{j_2+1} + M(2 + C_{(i_1,i_2)}^{n_r} - \sum_{m \in N}(R_{(i_1,m,n_{ca})}^{j_1} + R_{(i_2,m,n_r)}^{j_2})) \tag{9}$$

For actual operations, arrival aircraft has priority to departure aircraft. Departure aircraft have priority to crossing aircraft.

Solution Method

If one is able to solve the proposed MIP model, he can obtain the optimal solution. Although similar models have been widely used to formulate the airport surface operations problem, the computation time of obtaining the optimal solution would be extremely long when the problem size becomes large. Furthermore, limited by the memory of the computer, only a medium-sized network can be solved by generic MIP solver. Hence, it is reasonable to apply some heuristic methods to obtain a suboptimal solution of the proposed MIP model within a reasonable time. This study adopts the heuristic rolling method, which has been used in solving many scheduling problems (*17,18*). Although it cannot guarantee the optimal solution, the result of such method is always close to the optimal solution (*17*).

The basic idea of rolling horizon is to divide a long planning period into several small non-overlapping sub-periods and to optimize the schedules within each sub-period. Although the original desire of this method is to decide a schedule independently within each sub-period, for the proposed model, the taxi time of some aircraft could cross two sub-periods (Here we assume that any two consecutive sub-periods can cover the taxiing time of one aircraft). In this case, the method should take care of these aircraft in the next sub-period.

In this study, the length of each sub planning period can vary in a way that the number of aircraft scheduled in each period maintains relatively stable. The obtained feasible solution needs to be compared with some bound of the optimal planned taxi times to show how this solution reaches the optimality. Such bound can be achieved by some heuristic methods.

RESULTS AND DISCUSSION

In order to test the case that there are more interactions between departures and arrivals, the configuration of Runways 26R/08L, 26L/08R, and all gates at five terminals are coded into the model. This is because both runways are used in a mixed mode at IAH. In addition, since it would be too complex if every gate (larger than 100 in total) is modeled as a node, the gates are grouped into nine nodes in the model. Sampled from the pushback schedule of departures at IAH from 18:00 to 19:00 on June 1, 2010, 46 departures are used in the test, along with 18 arrivals. It is assumed that Runway 26R/08L is used for arrivals and Runway 26L/08R is used for departures. To test the model performance, one crossing point is allowed for Runway 26R/08L.

There are nine planning sub-periods in the rolling horizon method. For each planning period, six arrival aircraft and two departure aircraft are scheduled. The proposed model was solved using generic MIP solver in ILOG CPLEX with a version of 12.1 (*19*). The results are shown in Table 4**Error! Reference source not found.**. In this table, the total taxi time represents the value of objective function. The bound of total taxi time is obtained by estimation heuristically without the rolling horizon method. Since the schedules of some aircraft should be optimized within two planning periods, it increases the solution time in the related planning period. The high computational times in planning periods 4 to 6 are due to this reason. Although the bound of the solution can be computed quickly, there are some large gaps between the bound and the solution of rolling horizon method. From this table, the obtained average taxi time is around 5 minutes,

which is close to the real value in this test runway configuration. However, it is clear that solution time is relatively large for this small-scale test case. It indicates that the advanced solution method should be studied in the future.

Table 4: Results of the proposed model.

NO. of Planning Period	Objective Value/Total Taxi Time (Min)		Ratio (Bound/Solution of Rolling Horizon Method)	Computational Time (Seconds)	
	Bound	Rolling Horizon Method		Rolling Horizon Method	Bound
1	30.4	30.4	100%	26.36	26.36
2	35.1	39.4	88%	174.35	11.9
3	37.3	38.8	96%	24.93	11.06
4	37.0	40.3	91%	422.58	34.54
5	32.1	37.0	85%	208.54	20.65
6	38.2	39.4	97%	328.15	57.95
7	33.2	33.3	100%	80.93	22.43
8	34.3	38.8	87%	46.96	12.95
9	42.2	43.8	96%	57.83	23.53
Total	319.8	341.1	93%	1370.63	221.37
Average Taxi Time (min)			5.32		

CHAPTER 4:
CONCLUSION

This research analyzes the data of arrivals and departures according to each runway and different hours per day. The capacity of each runway and its busy hours are identified. The analysis shows that IAH is operating close to the capacity during most of the time. The taxi-out times at IAH fluctuate during the different hours and are generally long, while the taxi-in times are relatively stable at IAH. Although the departing capacity of IAH is analyzed, its value may be unstable due to the uncertainty. The analysis indicates that the advanced statistical method is required to investigate the airport data.

The proposed model for planning surface operations can be helpful for ground controllers to find more efficient plans for aircraft to save taxi times as well as to reduce the fuel consumption. However, it is hard to handle a large scale problem due to the complexity of this model. The more efficient algorithm to solve the model will be studied in the future.

REFERENCES

1. *Bureau of Transportation Statistics Special Report.* SR-008. Research and Innovative Technology Administration (RITA), May, 2008.

2. *Operational Evolution Plan: Version 8.0.*, Federal Aviation Administration. 2006.

3. Data and Statistics, the Research and Innovative Technology Administration (RITA), Bureau of Transportation Statistics.
   http://www.bts.gov/xml/ontimesummarystatistics/src/index.xml.

4. George Bush Intercontinental Airport, Master Plan and Technical Reports. Houston Airport Systems, City of Houston. 2006.

5. Idris, H., Clarke, J.P., Bhuva, R., and L. King. "Queuing Model for Taxi-Out Estimation." *Air Traffic Control Quarterly*, Vol. 10(1), 2002, pp. 1–22.

6. Clewlow, R., Simaiakis, I., and H. Balakrishnan. "Impact of Arrivals on Departure Taxi Operations at Airports." *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, August, 2010.

7. Simaiakis, I., and H. Balakrishnan. "Impact of Congestion on Taxi Times, Fuel Burn, and Emissions at Major Airports." *Transportation Research Record: Journal of the Transportation Research Board, No. 2184,* 2010, pp. 22–30.

8. Simaiakis, I., Khadilkar, I., Balakrishnan, H., Reynolds, T.G., Hansman, R.J., Reilly, B., and S. Urlass. *Demonstration of reduced airport congestion through pushback rate control*, January 2011, MIT ICAT report, Report No. ICAT-2011-2.

9. Atkin, J., Burke, E., and S. Ravizza. The airport Ground Movement Problem: Past and Current Research and Future Directions. *Proceedings of 4th International Conference of Research in Air Transportation*, 2010.

10. Cheng, V.H.L. Airport Surface Operation Collaborative Automation Concept. *Proceedings of the AIAA Guidance, navigation and control conference and exhibit*, Austin, TX, August 2003.

11. Smeltink, J.W., Soomer, M. J., de Waal, P. R., and R. D. van der Mei. *Optimization of Airport Taxi Planning. Proceedings of the INFORMS Annual Meeting*, Denver, USA, 2004.

12. Marin, A. "Airport Management: Taxi Planning." *Annals of Operations Research*. Vol. 143, no. 1, 2006, pp. 191–202.

13. P. C. Roling and H. G. Visser. Optimal Airport Surface Traffic Planning Using Mixed-Integer Linear Programming. *International Journal of Aerospace Engineering,* Volume 2008. doi:10.1155/2008/732828.

14. Baik, H., Sherali, H., and A. A. Trani. Time-Dependent Network Assignment Strategy for Taxiway Routing at Airports. *Transportation Research Record: Journal of the Transportation Research Board, No.1788.* 2002. pp. 70–75.

15. H. Balakrishnan and Y. Jung. A Framework for Coordinated Surface Operation Planning at Dallas-Fort worth International Airport. *Proceedings of the AIAA Guidance, Navigation and Control Conference, Hilton Head, USA, 2007.*

16. Keith, G., and A. Richards. Optimization of Taxiway Routing and Runway Scheduling. *Proceedings of the AIAA Guidance, Navigation and Control Conference*, Honolulu, Hawaii, USA, 2008.

17. Araujo S. A., Aranales M. N., and A. Clarck. Lot Sizing and Furnace Scheduling in Small Foundries. *Computers and Operations Research*, Vol.35(3), 2008, pp. 916-932.

18. Mohammadi, M., Fatemi Ghomi., S.M.T., Karimi, B., and S. A. Torabi. MIP-Based Heuristics for Lot Sizing in Capacitated Pure Flow Shop with Sequence-Dependent Setups, *International Journal of Production Research,* Vol. 48(10). 2010. pp. 2957–2973.

19. ILOG Inc., ILOG CPLEX 12.1- Users Manual.