Flight Gate Assignment and Proactive Flight Gate Reassignment Optimization for Hub and Spoke Airline Operations

by

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ABSTRACT

The flight gate assignment problem is encountered by gate managers at an airport on a periodic basis. This assignment should be made in such as way so as to balance the perspectives of the airline and customer simultaneously, while providing buffers for disrupting unexpected events. In this dissertation, a binary integer multi-commodity gate flow network model is presented for finding the optimum flight-gate assignment with the objective of both minimizing the fuel burn cost of aircraft taxi by type and the expected walking distance of connecting passengers magnified by time windows. While this network formulation is efficient, a heuristic approach of grouping gates into zones and sub-zones is developed for large-problem instances in which non-polynomial complexity becomes prohibitive. This formulation and heuristic application is demonstrated for the gating of scheduled flights of Continental Airlines at George W. Bush Intercontinental Airport in Houston (IAH).

Reassignments of flights occur when scheduled flight gate assignments are disrupted, causing flight gate conflicts due to flight delays. Flight delays are caused by a host of problems, such as inclement weather, tardy crews, mechanical problems, tardy passengers, airport security issues, airport congestion, delay propagation between airports, etc. In this dissertation, a Binary Integer Program is formulated for the optimal reassignment of planes to gates in response to *day-of* flight delays. This program minimizes the total walking distance of those connecting and originating passengers whose boarding passes for reassigned flights were issued prior to the gate reassignments, which can cause passenger disruption at the airport.

A numerical illustration is shown for actual operations of Continental Airlines at George W. Bush Intercontinental Airport to exhibit the speed and efficiency of the model.

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CHAPTER 1
INTRODUCTION

1.1 Flight Gate Assignment

The main purpose of flight gate scheduling is to find the optimum gate assignment for scheduled flights such that there are smooth flight operations in an airport without unnecessary inconvenience to arriving or departing passengers. Many researchers have prioritized their models to minimize operational costs or maximize revenues that drive airline business. Gates are one of the most important resources at the disposal of an airline in a hub-spoke airport. The effective use of these flight gates is extremely important with respect to operational cost reduction and passenger satisfaction. Therefore, flight gate scheduling deals with the optimum flight gate assignment policy reflective of several objectives of interest. Some of the typical and common objectives of interests are as follows:

1. Minimize the total walking distance of arriving or departing passengers
2. Minimize total walking/inter-gate distance for connecting passengers
3. Minimize ungated aircraft (at the apron) activities
4. Maximize the gate utilization
5. Maximize the preferences of certain airplanes for some gates

It is extremely challenging to make optimum flight gate assignments that minimize several objectives of interest. With an increase in air-traffic volume in recent years (nearly doubled since early 1980s), the need to use gates efficiently to reduce operating costs, increase passenger satisfaction, and alleviate congestion has become more prevalent. The flight gate assignment problem is encountered by gate managers at an airport on a frequent basis. It is very unlikely to have an optimal flight gate assignment if you do not use a proper decision support tool.

1.2 Flight Gate Reassignment

Reassignments of flights are generally done when there are conflicts with the schedule of the arriving flights. A flight schedule is said to be in conflict if the departure time of the plane is greater than the arrival time of the next flight at any particular gate. Reassigning conflicting airplanes caused by flight delays is one of the major daily tasks for airport gate managers. If flight i is delayed, then it effects the flight schedule of subsequent flight j. There are two ways we can reassign the flight to the gate: 1) reassign flight i or 2) reassign flight j. When reassigning flight i or flight j at gate k, there can be a situation that the reassigned flight is interfering with the subsequent flight at gate k', $k \neq k'$. Such a situation is known as secondary flight reassignments. If reassignments are made without a proper decision support tool, then downstream effects of those reassignments, (producing more conflicting flights requiring further reassignments) could make the airport gate managers' work more difficult. It is rare to see flight operations without airplane delays or reassignments. Therefore, considerable emphasis has been put on understanding and managing airport delays. Flight delays are caused by a host of reasons, such as inclement weather, tardy crews, mechanical problems, passengers, airport security issues, airport congestion, delay propagation between airports, etc.

1.3 Causes of Flight Delays

Flight delays are caused by inclement weather conditions (tornados, hurricanes, thunderstorms, etc), mechanical breakdowns of airplanes, airport securities, crew scheduling problems, congestion in an airport, delay propagation, etc. Whatever are the causes of flight delays, disturbance in normal flight schedules increases potential flight conflicts at gates requiring flight gate reassignments for smoother flight operations. The most important causes of flight delays are weather, congestion (volume), and equipment runways (Refer to figure 1.1).

1.3.1 Inclement Weather

Weather has a significant effect on flight delays. The Bureau of Transportation Statistics (BTS) suggests that weather is responsible for nearly 70 percent of the National Aviation System (NAS) delays (Chatterji & Sridhar, 2005). Weather conditions that impact air transportation include convective weather, ceiling and visibility, turbulence, temperature, humidity in-flight icing, ground de-icing, etc. Figure 1.1 shows that the NAS delays for Continental Airlines Inc. (CO) for January 2010 - July 2010 is 72.54%.

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Services (NWS) continuously monitors the weather conditions to respond to changing weather conditions so that any fatal accidents and flight delays due to severe convective weather conditions can be decreased. Reliable weather information is always important to various users in the aviation industry. The National Oceanic and Atmospheric Administration's (NOAA) Aviation Digital Data Services (ADDS) provides access to graphical, textual and gridded weather data including winds, temperature, turbulence, convective weather and icing, and also reports hazardous

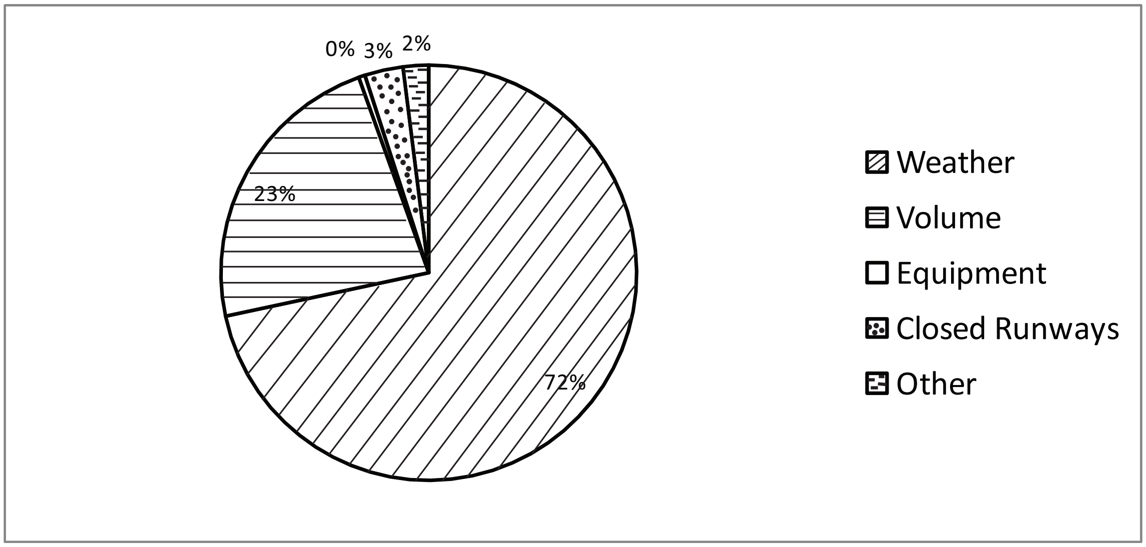


Figure 1.1. Causes of National Aviation System Delays, Houston, TX: Houston Intercontinental (Jan -July, 2010)
Source:Federal Aviation Administration OPSNET

weather to all types of aircraft via the internet. It also provides a Terminal Aerodrome Forecast (TAF) consistent with the International Civil Aviation Organization (ICAO) rules.

1.3.2 Congestion

Congestion is an another important component that contributes to flight delays. There are two kinds of congestion, i.e. airspace congestion and airport congestion. Both types of congestion have a direct or indirect implications in ground delays. The airspace is said to be congested if given airspace has more airplanes than it is allowed. If the airspace is congested, then flights are re-routed so that flights will take more time to reach their destination. An airport is said to be congested if the number of airplanes in the airport exceeds airplane handling capacity. If the predicted Airport Acceptance Rate (AAR) falls short of the scheduled AAR, traffic flow managers may implement a Ground Delay Program (GDP) in collaboration with the Federal Aviation Authority (FAA) Air Traffic Control System Command Center (ATCSCC). With the implementation of GDP, AAR is reduced and a sequence of arrival slots are created in accordance with the expected arrival capacity (Hoffman, Krozel, and Jakobavits, 2004). Therefore, the delays generated with GDP are propagative. It sometimes can propagate delays throughout the day. The main reasons for the increasing congestion trend are due to the steady growth in air travel demand (Figure 1.3) and the deregulation act of 1978, which does not limit the schedules for safety or compensate passengers for delay and cancelations (Le, 2006). The consequences of airport congestion generally result in long queue lengths for landing airplanes, long wait times for the gates, disruption of transfer passengers, and crowded airports. Moreover, it will have a ripple effect on the subsequent arriving flights.

The solution to the congestion problem is to increase an airport's capacity by building additional infrastructure, which would be a costly proposition. It may take a number of years to solve the problem. If steady growth in air traffic continues, then it cannot be guaranteed that the congestion problem will not occur in the future again. Increases in the size of the airplane will decrease the frequencies of the flights, which could be another solution to the congestion problem. This would help take some planes off the NAS. Many solutions have been proposed at the policy level, including the necessity of upgrading the current Air Traffic Control System (ATCS) and the imposition of congestion pricing, would have to pay a fee that varies at US airlines with levels of congestion at the airport. Under congestion pricing, operating costs at peak hours would rise substantially compared to off-peak costs, encouraging airlines to schedule their planes away from the peak hours (Brueckner, 2002).

1.3.3 Runways

Runways are important resources shared by arriving flights and departing flights. Runways are used not only for takeoffs and landings, but also for taxiing arrival flights to the gate or departing flights from gate to runways. Therefore, any bottleneck in the airplane flow on the runway could increase the ground delays and decrease the airport capacity. Hence, runway assignment is a strategic decision made by traffic controllers to reduce delays depending upon the traffic volume and weather conditions. Air traffic controllers choose certain runways over others depending on aircraft arrival direction, wind speed, and wind direction.

There have been studies on how to mitigate delays caused by runway mismanagement. Anagnostakis & Bohme (2001) developed an automated decision-aiding system to assist air traffic controllers in handling the departure traffic and mitigating the adverse effects of ground congestion and delays. Davis et al. (1994) developed Final Approach Spacing Tool (FAST), a decision support system that effectively manages runway systems. FAST provides landing sequences and landing runway assignments, as well as speed and heading advisories that help controllers manage arrival traffic and achieve an accurately spaced flow of traffic on final approach.

Almost all domestic airports and international airports have multiple runways. Therefore, runway operations planning and management within the Air Traffic Management (ATM) system is equally important. Some of the important responsibilities of runway operations planning and management are runway configurations, deployment of operational procedures, configuration change times due to weather conditions, expected traffic fluctuations and other regulations and constraints, runway assignments, and tactical planning of runway usage by different arriving and departing flights, according to Anagnostakis & Bohme (2001).

1.3.4 Growth in Air Travel Demand

The Federal Aviation Administration (FAA) forecasts a steady growth in Air Travel Demand. It is projected that the number of passengers carried by U.S. commercial air carriers are projected to hit the one billion mark by 2016 (FAA, 2008). Record number 741 million and 765 million passengers traveled by US commercial air carriers in 2006 and 2007 (FAA, 2007, 2008). By 2025, US commercial air carriers are projected to fly 1.3 billion passengers. Planes will remain crowded, as load factor is projected to rise to 81.7 percent by 2025 (FAA, 2008).

From figure 1.3.4, the total number of domestic flights have been steadily increasing except for in 2002 following the September 11, 2001 attack. According to the Department of Transportation's (DOT) Bureau of Transportation Statistics (BTS), air traffic volume has increased by more than 2.2 million flights in the past 19 years, jumping from 5.2 million domestic passenger flights to 7.4 million domestic passenger flights in 2007 (Schumer & Maloney, 2008).

1.3.5 Effect of High Air Traffic Demand

With the increase of air traveling passengers, airports are becoming crowded and flights are experiencing delays because of congestion in airports. This is due to limited growth in airport capacity and almost no upgrades in air traffic controlling technologies. The National Aviation System delays will only get worse if

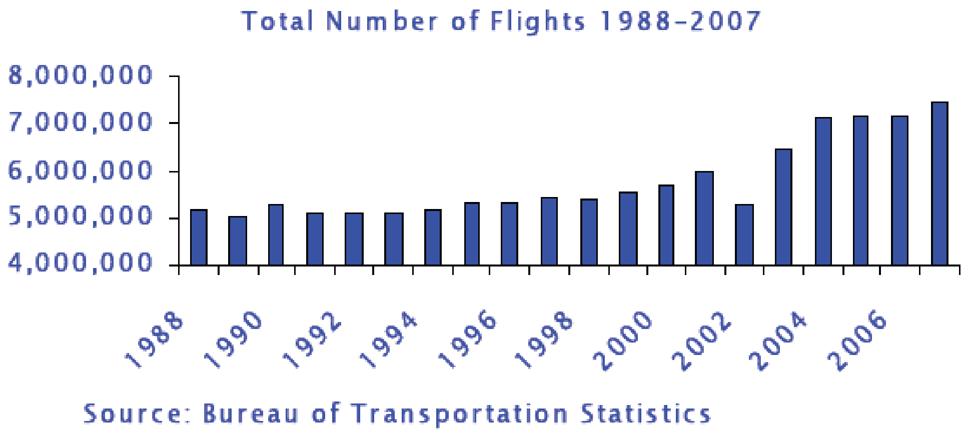


Figure 1.2. Total Domestic Flights 1988-2007

appropriate actions are not taken to increase airport capacity or to decrease the aviation delays by increasing the throughput of every airport system. Without significant reforms, forecasters predict air traffic will increase by equivalent of two major hub airports each year through 2020 (Schumer & Maloney, 2008). One of the ways to solve this problem is to use smarter gate scheduling methodologies, maximizing the utilization of the present resources.

1.3.5.1 Flight Delays

As the number of flights are increasing, the total number of flight delays are also increasing. An increasing trend of the total flight delays in hours are clearly visible in the following figure 1.3.

A Joint Economic Committee report by Schumer & Maloney (2008) stated that the total cost of domestic air traffic delays cost the US economy as much as $41 billion in 2007, including $19 billion in increased airlines' operating costs, such as additional crew, fuel, maintenance, etc; $12 billion worth in passenger time lost,

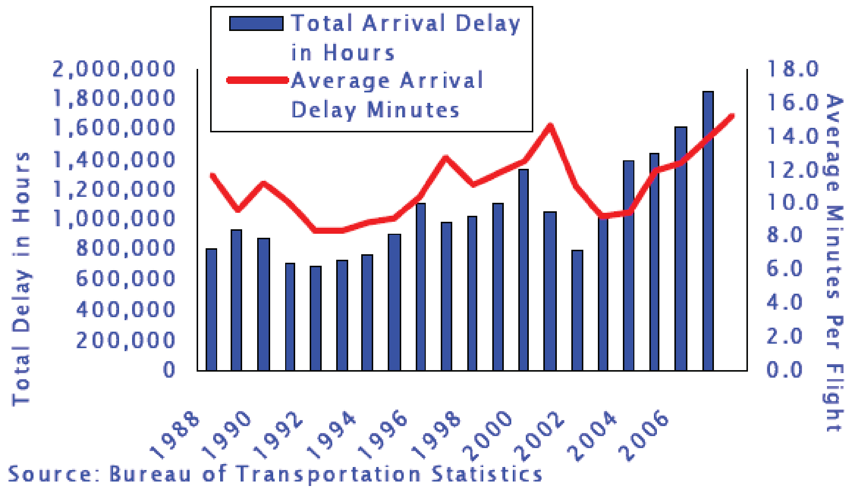


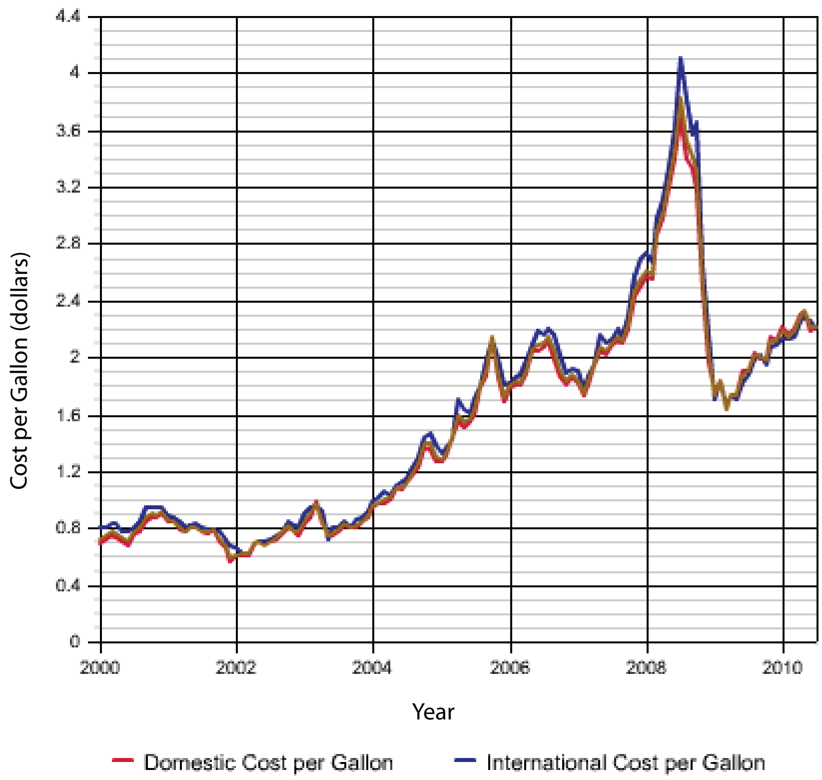
Figure 1.3. Total flight delays over 20 years

causing lower productivity and business opportunities; and $10 billion in indirect costs of delay to other industries that rely on air traffic, such as food service, lodging, public transportation, etc.

1.3.5.2 Fuel Burn

With the increasing air passengers, the total numbers of flight delays are also increasing. Predicted levels of air traffic demand raise the need for enhancements of airport capacity, the reduction of environmental impacts such as engine emissions, and the costs of operational inefficiencies that reflects more fuel burn. According to the Air Transport Association, delays costs an additional $19 billion for operations of airlines alone, whereas the airline industry earned $3.8 billion only in 2007. Higher fuel costs (refer to figure 1.4) is in part responsible for the higher operating costs. In 2007, delayed flights consumed about 740 million additional gallons of jet fuel worth $1.6 billion, assuming the average wholesale price of $2.15 per gallon. It is also estimated that additional fuel burn released 7.1 million metric tons of CO_2

(the principal green house gas responsible for global warming) into the atmosphere (Schumer & Maloney, 2008).



Source: Bureau of Transportation Statistics

Figure 1.4. Air Fuel Cost and Consumption for 2000-2010

2008 was a rough year for the aviation industry. Airlines were often operating at a loss due to high price of jet fuel. Jet fuel wholesale price increased to $3.69 per gallon in July 2008. Because of the high fuel price, American Airlines (AA) declared a charge for the first checked bag on May 21, 2008. The jet fuel price has since decreased, but it cannot be guaranteed that the same situation will not follow in the future, creating a great deal of pressure on the aviation industry once again.

1.4 Continental Airlines Hub at George Bush Intercontinental Airport

Flight gate assignment and reassignment algorithm developed in this research is directly applied to one of the largest Continental Airlines Hubs: George W. Bush Intercontinental Airport (IAH). Therefore, a brief introduction about George W. Bush Intercontinental Airport is given below:

1.4.1 A Brief Introduction to George Bush Intercontinental Airport

The George W. Bush Intercontinental Airport (IAH) is located in Houston ($95^\circ 20' 29''$W,$29^\circ 59' 4''$N), Texas and occupies more than 10,000 acres (40 sq. km). It is operated and maintained by the City of Houston Department of Aviation. Currently, IAH is ranked 3rd in the United States among U.S. airports with scheduled non-stop domestic and international service (over 170 destinations). There were more than 700 daily departures (on average) with 40 million passengers conducted through IAH in 2009 (HAS, 2009). According to Airports Council International, IAH ranked 8th (includes passengers and cargo) for 2009 in North America rankings and 16th in top world airports for 2008.

IAH is presently served by 17 scheduled passenger airlines, and is the largest hub for Continental Airlines Inc. (CO) and numerous other carriers. Over 170 domestic and international destinations are accessible through nonstop or direct flights from IAH.

IAH has 5 airport terminals namely A,B,C,D, and E. Terminal A,B,C,D are used for domestic flights, whereas terminal E is used for the international flights. All international arrivals are processed through Passport Control by U.S. Customs and Border protection officers. Terminal A has 16 gates (A1 to A34), terminal B has 38 gates (gate B50 to gate B88), terminal C has 30 gates (gate C14 to gate C45), terminal D has 14 gates (gate D1 to gate D12), and terminal E (gate E1 to gate E24) has 23 gates. Detail airport terminal diagram is shown in the figure (1.5).

There are five operational runways at IAH, which are 15L/33R, 9/27, 8R/26L, 15R/33L, and 8L/26R. All the runways are made from concrete. The runways for arrivals and departures of the flights are equipped with navigational aids and other Federal Aviation Authority (FAA)-operated facilities.These include the following:

1. Instrument Landing System for each major runway
2. Airport Surveillance Radar
3. Highly sophisticated navigational aids and lighting systems for all runways.
4. Low level alert wind shear system
5. Doppler radar to enhance weather prediction
6. Aircraft rescue and firefighting facility that meets current FAA safety standards
7. Runway 8L/26R utilizes LED Taxiway Edge Light Fixtures
8. Parallel Category III runways at IAH permit triple independent simultaneous all-weather flight operations

The runway description for IAH is given in table 1.1.

1.4.2 A Brief Introduction to Continental Airlines

Continental Airlines is a hub-spoke airlines utilizing George Bush Intercontinental Airport at Houston as its largest metropolitan airport (Hub). Most of its fleet are

Table 1.1. Description on George Bush Intercontinental Runways

Runways	Dimensions	Type
15L/33R	12,000 ft by 150 ft	R/W 33 ILS Category I
9/27	10,000 ft by 150 ft	R/W 27 ILS Category I/III
8R/26L	9,4000 ft by 150 ft	R/W 26 ILS Category I
15R/33L	10,000 ft by 150 ft	R/W 15 ILS Category I
8L/26R	9,000 ft by 150 ft	R/W 26 ILS Category III

kept and maintained at IAH. Continental Airlines operates a fleet of 337 mainline jets. More than 70 percent of the fleet consists of common rated Boeing 737 series aircraft. Other Continental Airport hubs are New York/ Newark Liberty International Airport (EWR), Cleveland Hopkins International Airport (CLE), and Guam International Airport (GUM).

Table 1.2. Continental Airlines Fleet with Seating Capacity as of 2009

Model	Seating Capacity	Fleet in CO
737-300	124	3
737-500	114	34
737-700	124	36
737-800	157	117
737-900	173	12
737-900ER	173	30
757-200	175	41
757-300	216	18
767-200ER	174	10
767-400ER	235	16
777-200ER	285	20
Total		337

Continental Airlines has 337 airplanes. Continental has installed winglets on its entire 737-500, 737-700, 737-800, 737-900, 737-900ER, 757-200 fleet and its long-range 737-300 aircraft, which reduces fuel consumption by up to 5 percent COA (2010).

On-time arrival performance of the aircraft is one of the most important factors to be considered during the scheduling of planes to respective gates. The on-time arrival performance of Continental Airlines at IAH from January 2010 - July 2010 is shown in table 1.3.

Table 1.3. On-Time Performance of Continental Airlines Inc (CO) - Houston TX: Houston Intercontinental Airport (January - July 2010)

	Number of Operations	% of Total Operations	Delayed Minutes	% of Total Delayed Minutes
On Time	34,002	83.61%	N/A	N/A
Air Carrier Delay	1,351	3.32%	86,755	28.79%
Weather Delay	149	0.37%	8,699	2.89%
National Aviation System Delay	3,280	8.07%	110,948	36.81%
Security Delay	44	0.11%	2,586	0.86%
Aircraft Arriving Late	1,496	3.68%	92,386	30.65%
Cancelled	204	0.50%	N/A	N/A
Diverted	142	0.35%	N/A	N/A
Total Operations	40,669	100.00%	301,374	100.00%

Source: Bureau of Transportation Statistics, Airline Quality Performance 234

The table 1.3 shows that on-time performance of Continental Airlines Inc. (CO) for Houston is 83.16 % for the time frame of January 2010 - July 2010. The National Aviation System delay is 8.07 %, which can be due to volume (congestion), mechanical problems such as equipment failure, closed runways, etc. Airplane arrival delays and flight cancellations can also be related to the inclement weather conditions.

As shown in figure 1.1, the National Aviation System Delays are mostly related to weather, i.e. 72 percent, whereas congestion, mechanical problems, and closed runways are among the remaining 28 percent.

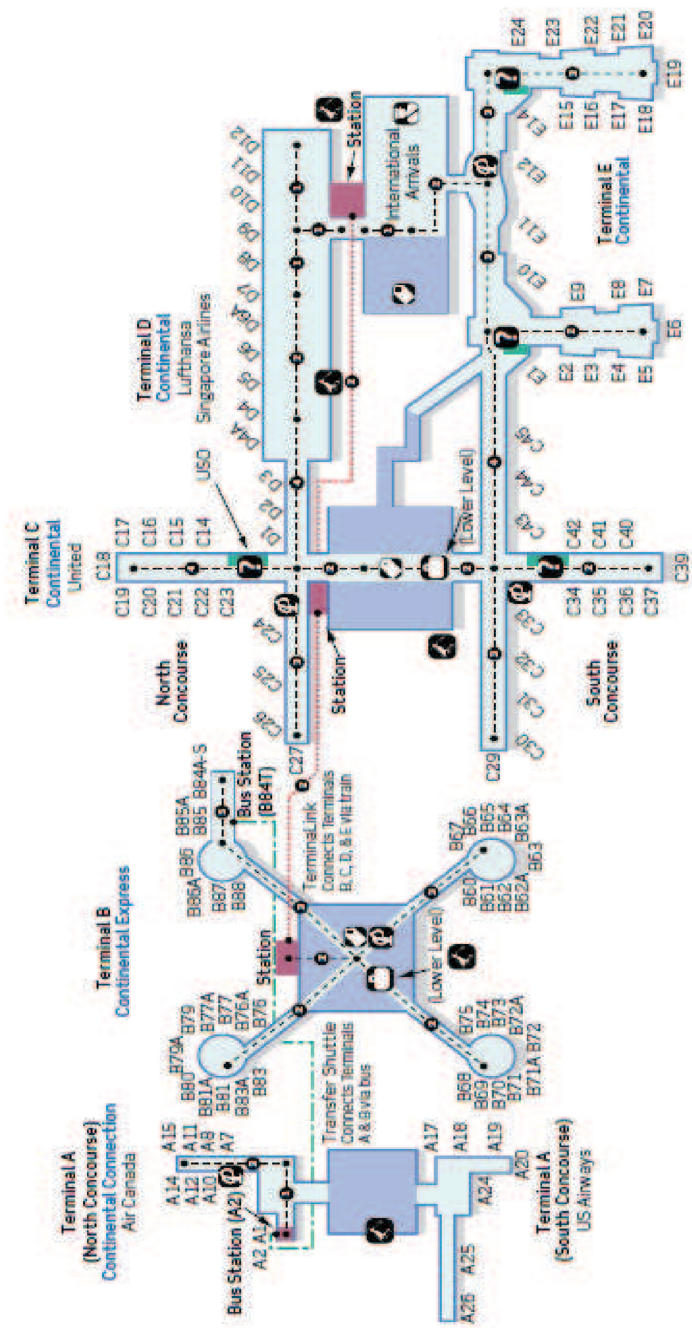


Figure 1.5. IAH Terminals and Gates

CHAPTER 2

SURVEY OF FLIGHT GATE ASSIGNMENT/REASSIGNMENT MODELS

Many researchers have investigated ways to solve efficient flight scheduling problems. Flight gate assignment and reassignment problems are one of the interesting areas of flight scheduling. It has been viewed as a prominent area for possible optimization either to minimize cost or maximize revenue associated with the problem. Flight gate assignment and reassignments problems are generally solved by mixed integer programming which has been proposed with different solution approaches by many researchers.

2.1 Flight Gate Assignment Algorithms

Research on flight gate assignment problem in an airline industry started with the paper "Aircraft Stand Assignment to Minimize Walking" (Babic et al., 1984). In this paper, Babic formulated a linear integer mathematical model to minimize walking distance for arriving and departing aircraft passengers. He used branch and bound algorithm (backtracking method) to solve the problem. The LP relaxation of integer program and the Greedy heuristic algorithm was used to extend a model to account for connecting passengers from one gate to another gate (Mangoubi & Mathaisel, 1985).

With the increasing number of air travelers, over the years, airports have started to get busier and more crowded. Due to increase in demand and moreover constant resources, flights begin to get delayed. This increasing delay trend attracted researchers to incorporate costs of flight delay into the model along with the aforementioned walking distance for arriving and departing passengers. Wirasinghe

& Bandara (1990) tried to address this problem by integrating delay cost to minimize intra-terminal traveling distances.

Obata (1979) formulated the flight gate assignment problem as a quadratic assignment problem (QAP) to minimize connecting passengers walking distances for arrival flights from one gate to departure flight at another gate. Obata (1979) also showed that QAP as a NP-hard problem. Since then, many researchers have studied this problem and proposed different techniques to solve flight gate assignment problems (Xu & Bailey, 2001; Haghani & Chen, 1998; Ding et al., 2005).

Initial research into the flight gate assignment problem was focused solely on the passenger, mainly minimizing walking distances within an airport for departing passengers or the distance to baggage claim for arrival passengers, etc. In a seminal paper, Braaksma (1977) demonstrated the possibility of reducing the walking distance through an assignment policy without changing the layout of the airport terminal, which resulted in an average distance reduction of over 100 ft per passenger. Babic et al. (1984) formulated a linear integer mathematical model to minimize walking distances for both arriving and departing passengers simultaneously, which was solved using branch and bound methodology. Mangoubi & Mathaisel (1985) also came up with a similar formulation that was solved using a LP relaxation method. Yan & Chang (1998) further extended this vein of work through a multi-commodity flow network formulation of the walking distances problem with a solution based on a Langrangian relaxation, which was shown to be much more efficient when compared to that of Mangoubi & Mathaisel (1985).

Multi-criteria optimization has received much attention recently in both theory and practice. The multi-criteria used in the flight gate assignment problems are to devise a zero-one integer program with the two objective functions of minimizing total passenger walking distances and total passenger waiting time simultaneously (Yan & Huo, 2001). A recent formulation by Drexel & Nikulin (2008) took a multi-objective point of view in which the number of flights that are not assigned to the gate and the total passenger walking distances (quadratic objective) are minimized whereas maximizing user preferences for gate assignments are solved using pareto simulated annealing developed by Kirkpatrick & Vechhi (1983).

2.2 Flight Gate Assignment/Reassignment Models with Flight Delays

Flights are generally delayed due to aviation weather conditions, mechanical failures, crew scheduling problems, airport securities, airport congestion, delay propagation, etc. These factors, especially weather conditions affecting flight delays, cannot be controlled by human beings, but they have a direct effect on the flight conflict(s) at a particular preassigned gate. Therefore, in an actual operations, flight delays are due to stochastic disturbances created by either early or late arrivals at a destination airport and late departures from the originating airport. Hence, stochastic flight delays that occur in actual operations are very important for solving the flight gate assignment problem.

With the increasing number of air travelers, research emphasis in gate modeling shifted from concentration on the passenger alone to address flight delays, with the paper by Wirasinghe & Bandara (1990). Following along this line, Bard et al. (2001) developed a transformed time-based network formulation that captures flight delays and cancelation costs for each flight in making gate assignments. Yan & Tang (2007) developed a heuristic approach for airport gate assignments that considers stochastic flight delays. Yan et al. (2002) used a simulated framework to analyze the interrelationship between static gate assignments and real-time gate assignments as affected by the stochastic flight delays that occur in real operations.

Real-time gate assignment using Robust Airport Gate Assignment (RAGA) was proposed by Lim & Wang (2005). RAGA is stochastic programming model which is transformed into a a binary programming model by introducing the unsupervised estimation functions without knowing any information on the real-time arrival and departure time of aircrafts in advance. In order to solve such problems, the authors developed hybrid meta-heuristic search combining tabu-search and local-search methods.

It is extremely difficult to incorporate all possible delay causes into the model. Therefore, there are very few models available that can adequately model stochastic delays in the National Aviation System (NAS). Hence, people still use deterministic decision support tools for solving air traffic flow management problem. Tu et al. (2005) discovered through that the deterministic approaches fail to capture the following three stochastic factors in their study:

1. Uncertainty in flight's departure time including the possibility of flight cancellation
2. Changes in a flight's route immediately before takeoff or after flight is airborne
3. Airspace queueing effect.

Disruption of a planned scheduled is always possible due to flight delays, severe aviation weather, and equipment failure that makes flying unsafe. Therefore, Air Traffic Managers (ATM) should always remain alert for the possible changes in the schedule (divert, cancel, or delay). If appropriate action to respond such changes is not taken immediately, then it can effect the subsequent flights schedule, worsening the flight delay propagation and congestion in an airport. Hence, the decision support to choose which flights to assign to which airport gates affects not only the deployment of ramp personnel and equipment, but also the time required to travel passengers from flight gates to the baggage claim area. To solve this decision support for real-time assignment addressing the stochastic flight delays, genetic algorithm (GA) based heuristic solution was studied by Gu & Chung (1999). The Genetic algorithm applies the global search techniques inspired by natural evolution (inheritance, mutation, selection and crossover) to find more effective solutions generated by experienced gate managers. The solution for the reassignment is chosen based on fitness value function represented as linear combination of flight delays and passenger walking distance of gates in the terminal. Yan & Tang (2007) have solved real time flight assignment considering stochastic flight delays using a gate flow network model. Their approach is to solve model to get planned flight gate assignment and then simulate reassignments for all scenarios, if an airplane cannot be assigned to its original gate. The best reassignment is chosen based on best estimate of reassignment objective value (passengers waiting time and time inconsistencies from previous assignment) based on simple reassignment rules. Tang et al. (2009) studies a gate reassignment framework for real time flight delays by minimizing space inconsistency and time inconsistency. Space consistency expected to occur when conflicting flight is reassigned to a different gate other than original gate whereas,time inconsistency is a difference of delayed arrival time and original arrival times of a flight. Reassignment is accomplished in two phases: 1) preprocessing phase and 2) construction phase. Arrival/Departure times and other relevant information are update in preprocessing phase and then using the planned assignments, reassignments are made in construction phase.

CHAPTER 3
RESEARCH OBJECTIVES

Day-to-day operations of scheduling airplanes are complicated without a proper decision support tool for gate assignment and gate reassignment of incoming flights. Many researchers have modeled flight gate assignment/reassignments in the past (refer to Chapter 2). It is clear that there are integer optimization models that could be used to make these assignments/reassignments while minimizing several objectives of interest, yet these models become impractical in even moderately scaled problems, which are not reflective of large-carrier operations. A model that balances the viewpoints of the consumer and carrier in making assignments that can be solved in reasonable time could have a broad impact on the airline industry.

The primary objective of this dissertation is to model flight gate assignment and develop a flight gate reassignment algorithm that can be used by gate managers or operations manager as a decision support tool for hub and spoke airline operations. The Continental Airline's hub, George W Bush Intercontinental Airport at Houston is used to test our model.

3.1 Research Objectives for Flight Gate Assignment

The research objectives for flight gate assignment models are as follows:

1. Formulate a multicommodity flow network model for flight gate assignment for hub and spoke airline operations. This model will be presented in detail by first presenting the multicommodity network structure, then followed by mathematical formulation.

2. Assign flight gates to balance the perspective of airline and customer's convenience simultaneously. Therefore, an objective to minimize fuel burn cost of aircraft used for taxi in a runways and expected walking distance of connecting passengers within a given time window will be considered for modeling flight gate assignment problem.

3. Develop a heuristic approach of solving a problem so that model can be used as decision support tool for airport gate managers to assign flights to the gates.

In order to achieve the abovementioned objectives, the following approaches are used in the model.

1. Connecting passenger penalty cost function will be applied to the model in order to discourage the assignment of a gate that requires the passenger to walk a long distance in order to make a connection from one gate to another.

2. Heuristic application of model is approached by grouping gates into zones and sub-zones will be developed for large-problem instance in which polynomial complexity becomes prohibitive.

3. There is always a chance for unexpected ground delays whether it is the arrival or departure flights. In order to absorb some of unexpected ground delays, some buffer is kept between departure time and arrival time of a flight at a same gate. This will also help assign zones to a flight sparsely to the different zones reducing the traffic congestion at a terminal.

4. The runway usage for arrival and departure flights will be assessed to compute the expected taxiing runway length to its gates for computing the fuel burn cost for given airplane type.

3.2 Research Objectives for Flight Gate Reassignment

The research objectives of flight gate reassignment models are as follows:

1. Flights can be delayed due to a host of causes. Some important ones are inclement weather, airport congestion, equipment or mechanical failure, airport security, and crew mishandling. When flights are delayed, it can conflict with schedules of other flights. Hence, conflicting flights are generally reassigned to different gates where conflict with any other flights are not expected. If proper reassignments are not made, there could be a huge impact on gate performance with domino effects on subsequent flights. These flight conflicts and gate changes can highly influence connecting passengers. These changes can lead passengers to the wrong gate, which may cause great inconvenience to the passenger. We call this phenomenon "passenger disruption". In this dissertation we will try to minimize the cumulative walking distance of disrupted passenger due to gate changes.

2. In order to minimize the cumulative walking distance of disrupted passenger, we model the reassignment problem as a binary integer program. In this dissertation detailed formulation of the model will be presented. The algorithm must be solvable in real-time, therefore it must exhibit a quick solution.

3. It is desirable to reassign conflicting flights close to the originally assigned gate. Therefore, the airport terminal will be divided into different zones and the reassignment algorithm will only reassign conflicting flights within its zone.

4. Flight delays are highly stochastic in nature. Therefore, vigilant assessment of

the conflict is required to determine the conflicting flights. Any changes in the arrival or departure times of a flight may cause gate conflict. Therefore, the algorithm must be solved as soon as any conflicts between flights are detected.

CHAPTER 4

MULTI-COMMODITY GATE FLOW NETWORK MODEL FOR FLIGHT GATE ASSIGNMENT PROBLEM FOR HUB-SPOKE AIRLINE OPERATIONS

(to be submitted for journal publication)

4.1 Introduction

Gates are one of the important resources at the disposal of an airline in a hub-spoke airport, and with air-traffic increase in recent years (nearly doubled since the early 1980s), the need to efficiently use these to reduce operating costs, increase passenger satisfaction, and alleviate congestion has become more prevalent. It is clear that there are straightforward integer optimization models that could be used to make these assignments while minimizing several objectives of interest, yet these become impractical in even moderately scaled problems, which are not reflective of large-carrier operations. A model that balances the viewpoints of the consumer and carrier in making assignments that can be solved in reasonable time could have a broad impact on airline industry.

Initial research into the flight gate assignment problem was focused solely on the passenger, particularly minimizing walking distances within an airport for departing passengers to departure gates or the distance to baggage claim for arrival passengers, etc. In a seminal paper, Braaksma (1977) demonstrated the possibility of reducing the walking distance through an assignment policy without changing the layout of the airport terminal, which resulted in an average distance reduction of over 100 ft per passenger. Babic et al. (1984) formulated a linear integer mathematical model to minimize walking distances for both arriving and departing airplane passengers simultaneously, which they subsequently solved using branch and bound methodology, upon which Mangoubi & Mathaisel (1985) provided a similar formulation that was solved using a linear relaxation. Yan & Chang (1998) further extended this vein of work through a multi-commodity flow network formulation of the walking distances problem with a solution based on a Langrangian relaxation, which was shown to be much more efficient when compared to that of Mangoubi & Mathaisel (1985). In addition to these works, several researchers have used quadratic assignment (QAP) formulations to model the gate assignment problem with an objective that includes the distances of terminating passengers to baggage claim in addition to those connecting, including Xu & Bailey (2001), Haghani & Chen (1998), and Ding et al. (2005).

With an increasing number of air travelers over time, however, due to a notable paper by Wirasinghe & Bandara (1990) research emphasis in gate modeling shifted from concentration on the passenger alone to that which addressed flight delay. Following along this line, Bard et al. (2001) developed a transformed time-based network formulation that captures flight delays and cancelation costs for each flight in making gate assignments, and Yan & Tang (2007) developed a heuristic approach for airport gate assignments that considers stochastic flight delays. A recent formulation by Drexel & Nikulin (2008) took a multi-objective point of view in which the number of flights not assigned to the gate and total passenger walking distance were minimized while simultaneously maximizing user preferences for gate assignment, which was solved using pareto simulated annealing developed by Kirkpatrick & Vechhi (1983).

In this paper, we develop a binary multi-commodity network flow formulation of the gate assignment problem model that is more efficient computationally and show how this may be applied in a practical manner for large-scale problems. In this formulation, gates are treated as a commodity that originate at a source node and flow through various arcs and intermediate nodes that represent flight demand on its way to the terminal node. The routing of these flows satisfy flight demand while simultaneously minimizing taxi in and out fuel burn costs and the distance connecting customers traverse, which is magnified by the time window of connecting flights. Buffers to compensate for variability in planes arriving and departing from gates are built into the constraints of the model, which alleviates excessive "day-of" reassignments and idling of aircraft for blocked gates. As there are multiple gates that flow through the network, this formulation is said to be a multi-commodity gate flow network model.

4.2 Model

4.2.1 Mathematical Notation

The mathematical notation that will be used throughout this paper is as follows.

4.2.1.1 Sets

F = Set of all Arrival Flights for the flight-gate assignment planning period.

D= Set of all Departure Flights for the flight-gate assignment planning period.

K= Set of all Gates available for the flight-gate assignment during planning period.

4.2.1.2 Nodes

S = Source node.

T = Terminal node.

A_j = Arrival time for the intermediate arrival node $i \in \mathbf{F}$.

D_j = Departure time for the intermediate departure node $j \in \mathbf{D}$.

4.2.1.3 Parameters

C_k = Fixed cost associated with gate k, $k \in \mathbf{K}$.

d_{k1} = Expected runway distance from arrival runway to gate $k1 \in \mathbf{K}$.

d_{k2} = Expected runway distance from departure runway to gate $k2 \in \mathbf{K}$.

$d_{kk'}$ = Intergate/Interzone distance (ft) where $k \in \mathbf{K}$ to gate $k' \in \mathbf{K}$ s.t. $k \neq k'$.

f_i = Fuel burn rate (kg/sec) for flight $i \in \mathbf{F}$.

f_s = Average runway speed for an aircraft (ft/s).

f_c = Fuel Cost ($/kg).

$C_{kk'}^{ii'}$ = Per passenger cost for transferring passenger from gate $k \in \mathbf{K}$ to gate $k' \in \mathbf{K}$. s.t. $k \neq k'$.

N'_{ii} = Number of passenger transfer from flight $i \epsilon \mathbf{F}$ to flight $i' \in \mathbf{F}$ s.t. $i \neq i'$.

$|\mathbf{K}|$ = Cardinality of set $\mathbf{K}$.

$|\mathbf{F}|$ = Cardinality of set $\mathbf{F}$.

4.2.1.4 Decision Variables

X_{Si}^{k} = Flow-in arc representing gate $k \in \mathbf{K}$ flowing from source node (S) to arrival flight $i \in \mathbf{F}$.

X_{ji}^{k} = Back flow arc representing gate $k \in \mathbf{K}$ flowing from departure flight node (D_j) to arrival flight node (A_i) s.t. $i \neq j$.

4.2.1.5 Other Variables

X^k_{jT} = Flow-out arc representing gate $k \in \mathbf{K}$ flowing from departure node (D_j) to terminal node (T).

X^k_{ST} = Flow-pass arc representing gate $k \in \mathbf{K}$ flowing from source node (S) to terminal node (T).

X^k_{ij} = Flow arc representing gate $k \in \mathbf{K}$ flowing from intermediate node $i \in \mathbf{F}$ to intermediate node $j \in \mathbf{D}$ s.t. $i \neq j$.

4.2.2 Network Flow Model

Figure 4.1 provides a graphical representation of the multi-commodity network model, where gates flow in the direction of the arrows through arcs in the network. In particular, gates (G_1, G_2, ..., G_n) are commodities that flow from a source node

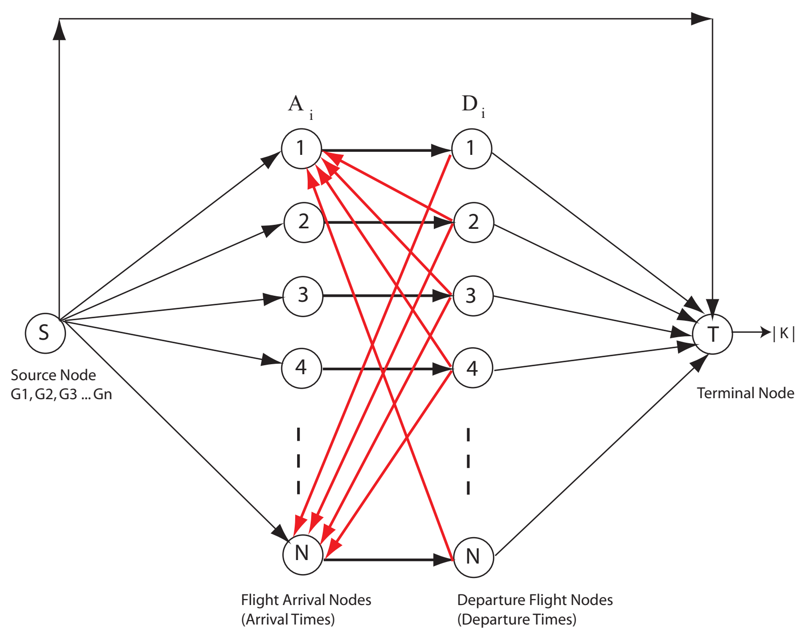


Figure 4.1. Multicommodity Network Model for Flight Gate Assignment Problem

(S) to a terminal node (T) through intermediate arrival (A_1, A_2, ..., G_N) and departure (D_1, D_2, ..., D_N) nodes using different possible combination of arcs. There are five types of arcs in the graph shown in figure 4.1, each with an integer capacity of (0, 1). A definition of these arcs is as follows.

4.2.2.1 Flow-in Arc

A flow-in arc is defined as an arc connecting a source node (S) to arrival flight nodes (A_i, $\forall\ i \in \mathbf{F}$). It is represented by arc(S, i), $\forall\ i \in \mathbf{F}$.

4.2.2.2 Serving Arc

A serving arc connects arrival node (A_i, $\forall i \in \mathbf{F}$) with departure node (D_j, $\forall i \in \mathbf{F}$). Serving arcs hold the gate from arrival of the flight until its departs. Flight service consists of deplaning passengers from the airplane, refueling, cleaning airplane, enplaning passengers, etc during the flight service time ($D_i - A_i$) of the gate. It is represented by arc(i, j) $\forall i \in \mathbf{F}$, $\forall j \in \mathbf{F}$, s.t. $i = j$.

4.2.2.3 Flow-out Arc

A flow-out arc connects departure node (D_j, $\forall j \in \mathbf{F}$) with terminal node (T). It is called a flow-out arc because it represents flights leaving from the gate assigned to them. It is represented by arc(j, T), $\forall j \in \mathbf{F}$.

4.2.2.4 Back-flow Arc

A back flow arc connects departure node $(D_j, \forall i \in \mathbf{F})$ with arrival node $(A_i, \forall i \in \mathbf{F})$ so flow direction is backwards compared to other flows. A back-flow arc is represented by arc(j, i) $\forall i \in \mathbf{F}$, $\forall j \in F$, s.t. $i \neq j$ if flight i and flight j share the same gate (k) consecutively. For example, if the arrival node (A_2) is connected by a back-flow arc with departure node (D_3), then flight 2 and flight 3 are scheduled to the same gate (k). Back-flow arc can only exist if the arrival time of flight i is greater than the departure time of flight j. Therefore, we define an Indicator variable (In_{ji}) as follows:

$$In_{ji} = \begin{cases} 1 & \text{if } (A_i - D_j) \geq p \qquad \forall i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{4.1}$$

In above equation, if In_{ji} is defined as equal to 1 if $(A_i - D_j) \geq p, \forall i \neq j$ then the flight i and flight j will share the same gate k consecutively such that arrival time of flight i and flight j is at least p hours apart.

4.2.2.5 Flow-pass Arc

A flow pass arc connects a source node (S) to a terminal node (T). It is represented by arc(S, T) . If the source node (S) is connected to the terminal node (T) by flow pass arc then gate (k) would flow through the flow pass arc without flowing through any intermediate nodes (arrival node, departure node).

4.2.3 Mathematical Formulation

In the mathematical formulation, the additional decision and supporting variables are defined based on the network model.

X_{si}^k = a binary decision variable equal to 1 if and only if there is a gate (k) flowing through a flow-in arc i.e. arc(S, i)

X_{ji}^k = a binary decision variable equal to 1 if and only if there is a gate (k) flowing through a back-flow arc i.e. arc(j, i)

X_{jT}^k= a binary variable equal to 1 if and only if there is a gate (k) flowing through a flow-out arc i.e. arc(j,T)

X_{ST}^k= a binary variable equal to 1 if and only if there is a gate (k) flowing through a flow-pass arc i.e. arc(S,T)

X_{ij}^k = a binary decision variable equal to 1 if and only if there is a gate (k) flowing through a serving arc i.e. arc(i,j)

Note that X_{si}^k, X_{ij}^k, and X_{ji}^k are decision variables that assign gates to arrival flights, and the others support the flow of gates through intermediate nodes in the network. Any flight i that is scheduled to gate k will get serviced as soon as it arrives at the gate, before it leaves the gate for its departure to another destination airport or mathematically $X_{ij}^k = 1 \forall i \in \mathbf{F}$, $\forall j \in \mathbf{D}$, s.t. $i = j$ and $|\mathbf{F}| = |\mathbf{D}|$.

Hence, an initial mathematical formulation of the network flow model is given as follows.

$$\text{Min} Z = \sum_{i \in F} \sum_{k \in K} (C_k + 2 f_i f_c / f_s \{d_{k1} + d_{k2}\})(X_{s,i}^k + \sum_{j \in D} X_{j,i}^k) \tag{4.2}$$

$$+ \sum_{\substack{(i \in F, i=j, \\ i'=j' i \neq i', \\ j \neq j')}} \sum_{\substack{(i' \in F, i=j, \\ i'=j' i \neq i', \\ j \neq j')}} \sum_{k \in K} \sum_{k' \in K} N_{ii'} C_{kk'}^{ii'} X_{i,j}^k X_{i',j'}^{k'} \tag{4.3}$$

Subject to

$$\begin{aligned}
\sum_i X^k_{s,i} + X^k_{S,T} &= 1 && \forall k \in K; i \in F && (4.4)\\
X^k_{s,i} + \sum_j In_{ji} X^k_{j,i} &= X^k_{m,n} && \forall i, m \in F; j, n \in D; i \neq j; m = n && (4.5)\\
\sum_j In_{ji} X^k_{j,i} + X^k_{j,T} &= X^k_{m,n} && \forall i, m \in F; j, n \in D; i \neq j; m = n && (4.6)\\
\sum_j X^k_{jT} + \sum_k X^k_{ST} &= 1 && i \in F; k \in K && (4.7)\\
\sum_k X^k_{ij} &= 1 && \forall i \in A; j \in D; i = j && (4.8)\\
X^k_{s,i}, X^k_{j,i}, X^k_{jT}, X^k_{m,n}, X^k_{S,T} &= \{0, 1\} && && (4.9)
\end{aligned}$$

4.2.3.1 Objective Function

The objective function represents a linear combination of costs associated with fuel burn related to the taxi in and out of planes and the "discomfort" of passengers connecting to flights in other gates. In particular, the first term of (Eq. 4.2) represents the *expected* taxi in and out fuel burn cost of assigning a plane to a particular gate based on the expected runway distance corresponding to arrival and departure cities for the flight. Note that most airports have multiple runways and those used vary depending upon the direction of approach and departure of the aircraft, and the cost of fuel burn varies depending on aircraft type. Due to constraint Eq. (4.5) and the unit capacity of arcs connecting each node i, this fuel burn objectives summed over all arrival flight nodes and available gates gives the total taxi in fuel burn cost for a particular assignment.

The second part of Eq. (4.2) is related to the connecting passenger objective. Once again, X^k_{ij} and $X^{k'}_{i'j'}$ must be equal to 1 for $\forall k, i = j, i' = j'$ and $i \neq i'$ since a unit flow is forced through each node, and there are potentially connecting passengers if and only if arrival time of flight i is less than the departure time of flight j ($A_i < D_j$), such that $i \neq j$, as given by Eq. (4.1). The cost associated with these connections, however, is multidimensional as it is determined by both how far the connecting gates are apart and the time until the departure of the connecting flight. For example, if the time between connections is tight, the cost of passenger discomfort for assigning a gate far away is much greater than one that is close, yet as this interval of time grows, the cost differential between distances is much less. Indeed if this interval of time is long enough, the differential of discomfort for connection distances is the same, as the passenger has plenty of time to walk between gates. A functional representation of this connecting passenger cost $C_{ii'}^{kk'}$ is given in Eq. (4.16) of section (4.2.3.5). Note that the magnitude of these costs may be scaled to line up relatively with those of fuel burn in the first part of the objective.

4.2.3.2 Constraints

The first constraint indicated by Eq. (4.4) is referred to as a flow-in constraint because it deals with the gate flow from the source node to the arrival flight node. It forces a unit flow of a certain gate to the arrival flight node or any unused will then be by-passed to the terminal node via arc(S, T). The second constraint Eq. (4.5) is referred to as conservation of flow at the arrival node, i.e. flow-in from arc(S, i) and arc(j, i), $i \in \mathbf{F}$, $j \in \mathbf{D}$ is forced to flow-out from arc(i, j), $i \in \mathbf{F}, j \in \mathbf{D}$ s.t. $i = j$. The constraint defined by Eq. (4.6) is conservation of flow at the departure node, i.e. the flow in from arc(i, j), $i \in \mathbf{F}$, $j \in \mathbf{D}$ s.t. $i = j$ is forced to get out from either flow-out arc(j, T) , $j \in \mathbf{D}$ or arc(j, i), $j \in \mathbf{D}$, $i \in \mathbf{F}$. The fourth constraint Eq. (4.7) is the flow-out constraint that forces all the flow to leave the departure node and flow to the terminal node. Note that the sum of all flows to the departure node must be equal to cardinality of the set **K**. The fifth constraint Eq. (4.8) is referred to as a unit flow serving arc constraint as it allows only one unit gate k to flow through the serving arc. The sixth constraint is the binary constraints of Eq. (4.9).

4.2.3.3 Linearization of the Quadratic Objective Function

The quadratic term in Eq. (4.3) of the objective function, i.e. connecting passenger cost, is cumbersome and difficult to solve, as noted by Obata (1979) who showed that the quadratic flight gate assignment problem is an NP hard. Therefore, a linearization of the quadratic objective function is considered in this paper, similar to that of Xu & Bailey (2001) Bailey and Xu (2001) who have shown a similar method for linearizing the quadratic objective function. In particular, the quadratic cost function

$$\mathrm{Min} Z_2 = \sum_{\substack{(i \in F, i=j, \\ i'=j' i \neq i', \\ j \neq j')}} \sum_{\substack{(i' \in F, i=j, \\ i'=j' i \neq i', \\ j \neq j')}} \sum_{k \in K} \sum_{k' \in K} N_{ii'} C_{kk'}^{ii'} X_{i,j}^{k} X_{i',j'}^{k'} \tag{4.10}$$

may be linearized by replacing the quadratic term $(X_{ij}^{k} X_{i'j'}^{k'})$ with a new variable $Y_{ii'}^{kk'}$ defined as

$$Y_{ii'}^{kk'} = \begin{cases} 1 & \text{if } (X_{ij}^{k} = 1 \text{ and } X_{i'j'}^{k'} = 1 \ \forall i = j, i' = j', i \neq i', j \neq j' \ \& \ k \neq k') \\ 0 & \text{otherwise .} \end{cases} \tag{4.11}$$

The above relationship in Eq. (4.11) can be expressed with the following constraints expressed in Eq. (4.12) through Eq. (4.15) to convert the quadratic objective into an equivalent linear objective model.

$$Y_{ii'}^{kk'} - X_{ij}^{k} \leq 0 \qquad \forall i = j, i' = j', i \neq j' \& k \neq k' \tag{4.12}$$

$$Y_{ii'}^{kk'} - X_{i'j'}^{k'} \leq 0 \qquad \forall i = j, i' = j', i \neq j' \& k \neq k' \tag{4.13}$$

$$X_{ij}^{k} + X_{i'j'}^{k'} - Y_{ii'}^{kk'} \leq 1 \qquad \forall i = j, i' = j', i \neq j' \& k \neq k' \tag{4.14}$$

$$X_{ij}^{k} + X_{i'j'}^{k'} - Y_{ii'}^{kk'} \geq 0 \qquad \forall i = j, i' = j', i \neq j' \& k \neq k' \tag{4.15}$$

The inequalities of Eqns. (4.12, 4.13) represent the constraints that variable $Y_{ii'}^{kk'}$ is equal to 1 if and only if binary variable X_{ij}^{k} and $X_{i'j'}^{k'}$ is equal to 1. Eq. (4.14) specifies that $Y_{ii'}^{kk'}$ cannot be greater than 1, and Eq. (4.15) further specifies that $Y_{ii'}^{kk'}$ cannot be less than zero. Due to the binary nature of X_{ij}^{k} and $X_{i'j'}^{k'}$, with the above constraints, $Y_{ii'}^{kk'}$ is forced to be a binary variable.

4.2.3.4 Instance for Infeasibility of the Mathematical Model

In the multi-commodity gate flow model, there is the potential for infeasibility of the problem when none of the gates are flowing through at least one of the intermediate flight nodes (arrival flight node/ departure flight node). Infeasibility may only occur, however, if $|\mathbf{F}| > |\mathbf{K}|$ and the numbers of possible backward arcs is less than $|\mathbf{F}| - |\mathbf{K}|$, which is generally not the case in practice.

4.2.3.5 Connecting Passenger Cost ($C_{ii'}^{kk'}$)

The passenger connecting cost is a function of both the expectation of time available and the inter-gate distance for a passenger making a connecting flight. In particular, it is a three dimensional penalty cost function for passenger discomfort that discourages the assignment of a gates far away for tight connections. This function is represented as

$$C_{ii'}^{kk'} = \begin{cases} \sqrt{d_{kk'}}(2 - \Delta t_{ii'})^2 & \forall 0 < \Delta t_{ii'} \leq t_{max} \\ 0 & \text{otherwise} \end{cases} \tag{4.16}$$

where $d_{kk'}$ (ft) is the intergate (or interzone) distance between gates k and k', $\Delta t_{ii'}$ (hr) is the time available for making a transfer from flight i to flight i', and t_{max} is the upper limit on the time window beyond which no penalty for distance is incurred. A surface plot of the cost function defined in Eq. (4.16)is used by letting $t_{max} = 2$hrs is given in Figure (4.2). Note the non-linear nature of this surface plot,

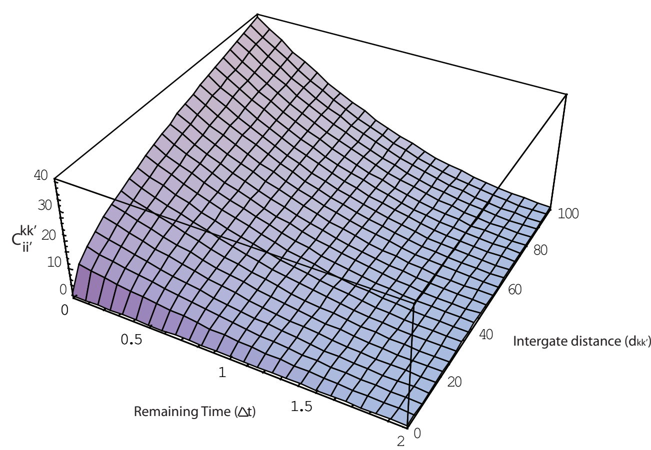


Figure 4.2. Surface Plot for the Penalty Cost Function for Transfer Passenger

which penalizes the distance between gate assignment at a more severe rate as the connecting time for passengers is reduced.

4.2.4 Mathematical Formulation using Zoning Strategies

The formulation of subsection 4.2.3 is a mixed integer program (MIP), which for larger size problems of the magnitude typically encountered in practice is difficult to solve due to 1) insufficient memory and 2) non-polynomial computational times. In particular, the branch and cut tree frequently become so large that insufficient memory is available to solve the LP sub-problems, and in the case that memory is available, the computation times are prohibitively long. Due to these pragmatic issues, an alternative approach is to breakdown the problem into a series of sub-problems, and then solve these sub-problems independently using a solution terminating criteria for "good" solution. In the case of the flight gate assignment problem, the airport gates were divided into different zones and then sub-zones, which are then solved hierarchically. The basic model described in subsection 4.2.3 remains the same, yet the definitions of parameters ($C_k, d_{k1}, d_{k2}, C_{ii'}^{kk'}$), objective function, and constraints (Eq. (4.4) and (4.8)) are modified to reflect the grouping of gates into zones.

4.2.4.1 Sets

K_z= Set of Zones/ Set of Sub-zones

F_z = Set of arrival flights at Zones / Set of Sub-zones

4.2.4.2 Parameters

d_{k1} = Expected arrival distance from runway to Zone / Sub-Zone $k, k \in K_z$

d_{k2} = Expected departure distance from runway to Zone / Sub-Zone $k, k \in K_z$

$C_{kk'}^{ii'}$= Per passenger connecting cost from zone / sub-zone $k, k \in K_z$

Note that the expected arrival (d_{k1}) and departure (d_{k2}) distances from the runway to each zone or subzone are assessed from their respective median gate.

4.2.4.3 Objective Function

A minor modification in an objective function is needed to accommodate the possible connecting passengers from gates that belong to different zones/sub-zones. Hence, the following equation sums $i \in \mathbf{F_z}$, $i' \in \mathbf{F}$, $k \in \mathbf{K_z}$, and $k' \in \mathbf{K}$ as

$$\text{Min}Z = \sum_{i \in F} \sum_{k \in K_z} (2 f_i f_c / f_s \{d_{k1} + d_{k2}\})(X^k_{s,i} + \sum_{j \in D} X^k_{j,i}) + \sum_{\substack{(i \in F_z, i=j, \\ i'=j', i \neq i', \\ j \neq j')}} \sum_{\substack{(i' \in F, i=j, \\ i'=j' i \neq i', \\ j \neq j')}} \sum_{k \in K_z} \sum_{k' \in K} N_{ii'} C^{ii'}_{kk'} X^k_{ij} X^{k'}_{i'j'} \tag{4.17}$$

There is no fixed cost associated with gates(C_k) on the first part of an objective function because this modification is done only for zone/subzone assignment only.

4.2.4.4 Constraints

The constraints of Eq. (4.4) and (4.8) are modified and replaced with

$$\sum_i X^k_{si} + X^k_{ST} = |K_z| \qquad \forall k \in K_z, i \in F \tag{4.18}$$

$$\sum_j X^k_{jT} + \sum_k X^k_{ST} = |K_z| \qquad \forall i \in F, k \in K_z \ . \tag{4.19}$$

4.3 Numerical Illustration

An illustration of the application of this multicommodity flow formulation is presented using the operations of Continental Airlines at the George Bush Intercontinental Airport in Houston (IAH). The data used in this paper is publicly accessible through various sources with only parameter values being hypothetically specified in some cases. The following assumptions are made in this paper to aid in clarity, yet may be easily relaxed or re-specified for other airports.

1. The flight gates are assumed homogenous and may be used to accommodate all sizes of airplanes.

2. Operational contraints of international arrivals, which are usually scheduled in Terminal E at IAH due to customs and immigration facilities requirements, are not included in the model.

3. The terminals A, B, and D are not operated by Continental Airlines at IAH, and hence are not considered in the model formulation.

4.3.1 Grouping of Gates into Zones and Sub-Zones

Continental Airlines schedules and operates its narrow body and wide body airplanes in terminal C and terminal E at IAH, which will be the focus of this paper[1]. Hence, the gates at terminals C and E at IAH are grouped into Zones and Sub-Zones based on their relative proximity to each other. Note that these groupings define mathematical formulations, which will be solved in hierarchical order building upon assignments made at the previous level.

1. Level 1: Zone Assignment

   The Zone assignment problem will assign flights to either the North Terminal C (Zone 1), South Terminal C (Zone 2), or Terminal E (Zone3) Zone.

2. Level 2: Sub-Zone Assignment

   The Sub-Zone assignment problem will assign flights assigned to a particular

[1] Flights at Terminal A are operated by Continental Connection, Air Canada, United, and US Airways, flights at terminal B are operated by Continental Express and flights at terminal D are operated by Lufthansa and Singapore Airlines. Adapted from http://www.continental.com/web/en-US/content/travel/airport/maps/iah.aspx.

zone in the Level 1 problem to either 2 or 3 respective Sub-Zones that are defined by gates in the same corridor.

3. Level 3: Gate Assignment

   The Gate assignment problem will assign flights assigned to a particular sub-zone in the Level 2 problem to a specific gate within the sub-zone.

A pictorial representation of terminals C and E at IAH with overlaid zoning assignments is given in figure (4.3), with a corresponding skeletal representation given in figure (4.4).

In calculating the expected runway length to zones/subzones and interzonal/subzonal distances in the Level 1 and 2 problems, the median gate [2] of the grouping is chosen. In particular, the median gates for zones 1, 2, and 3 are C21, C36, and E12 respectively, and the median gates for subzones 1 through 9 are C19, C26, C31, C39, C44, E5, E12, and E20 respectively.

[2]Median gate is a middle gate separating gates into two halves.

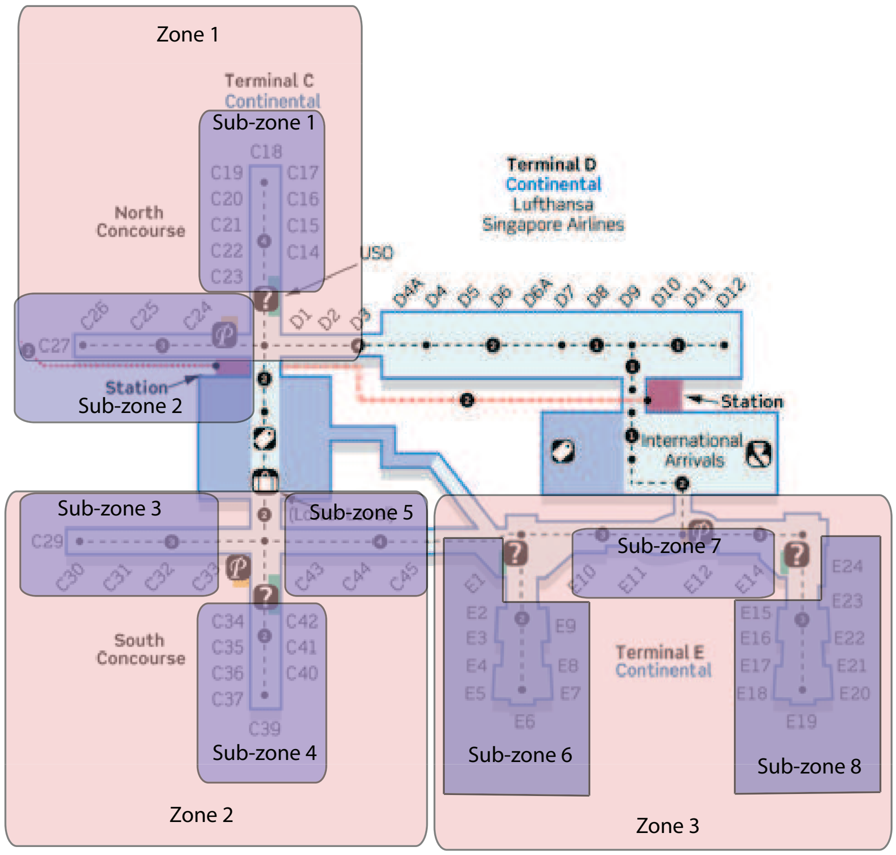


Figure 4.3. Zone and Subzones Division for Terminal C (North and South Concourse) and Terminal E

4.3.2 Specification of Parameters and Model Components

Information required to specify the multicommodity network flow model of gate assignment include arrival times, departure times, average taxi/idling fuel burn cost per unit distance, fixed cost for operating a gate, inter-gate distance, distance of gates from runways, and number of passengers connecting to departing gates. In this subsection, data collected to fully specify flight gate assignment problem for Continental Airlines at IAH is reported.

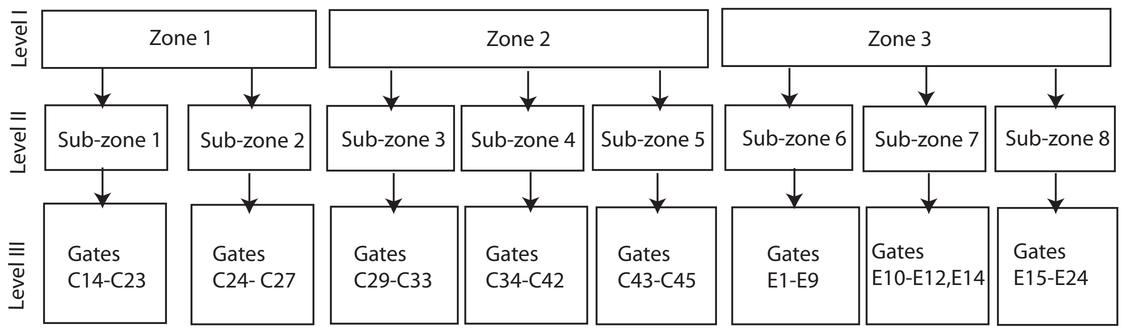


Figure 4.4. Computational Skeleton of the Flight-gate Assignment Problem

4.3.2.1 Arrival and Departure Times

The United States Department of Transportation's (DOT) Bureau of Transportation Statistics (BTS) records the arrival times (A_i), departure times (D_i), and on-time performance of domestic flights operated by large air carriers, which are made available to the general public (BTS, 2010).

4.3.2.2 Fuel Burn

The fuel burn rates differ by the size and type of aircraft. The data on amount of fuel burn during take-off, climb out, approach and idle are recorded for most aircraft, however, is maintained by the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) as the ICAO Emission Databank. It is also assumed that power remains constant at 7% thrust during taxi and idling operations as noted by Kim et al. (2005). The amount of fuel burn for wide body jets operated by Continental Airlines is reported in table (4.1)[1].

[1]*CFM International is a joint company of Snecma (SAFRAN Group) and General Electric. Note: Adapted from http://www.continental.com/web/en-US/content/travel/inflight/aircraft/default.aspx & ICAO Engine Exhaust Emissions Databank.

Table 4.1. Airplane Model Data with Jet Engine Model Taxi/Idling Fuel Burn Cost.

Model	**Engine Type**	**Engine Builder**	**Seating Capacity**	**Fleet in CO**	**Taxi/Idling Fuel per engine (kg/s)**
737-300	CFM56-3B1	CFM Intl*	124	23	0.1140
737-500	CFM56-3B1	CFM Intl	114	42	0.1140
737-700	CFM56-7B24	CFM Intl	124	36	0.1090
737-800	CFM56-7B26	CFM Intl	157	108	0.1130
737-900	CFM56-7B26	CFM Intl	173	12	0.1130
737-900ER	CFM56-7B26	CFM Intl	173	27	0.1130
757-200	RB211-535	Rolls Royce	175	41	0.2000
757-300	RB211-535E4B	Rolls Royce	216	17	0.1900
767-200ER	GECF6-80C2B4F	GE	174	10	0.1926
767-400ER	GECF6-80C2B8F	GE	235	12	0.2050
777-200ER	GE90-90B	GE	285	20	0.3130

4.3.2.3 Gate Operating Costs

The gate operations cost for each gate at Terminals C and E are assumed to be equal and fixed.

4.3.2.4 Runway Distances to Gates

There are five runways at IAH whose respective dimensions and usage are given in table (4.2). Wind flow direction is a critical factor in determining on which

Table 4.2. Runway Dimensions (adapted from HAS (2010))

Runways	Dimensions	Type
15L/33R	12,000 ft by 150 ft	R/W 33 ILS Category I
9/27	10,000 ft by 150 ft	R/W 27 - ILS Category I/III
8R/26L	9,400 ft by 150 ft	R/W 26 - ILS Category I/III
15R/33L	10,000 ft by 150 ft	R/W 15 - ILS Category I
8L/26R	9,000 ft by 150 ft	R/W 26 ILS Category III

runway an airplane will land, and there are typical departure and arrival corridors depending upon the direction of the wind flow. At IAH, there are two airport configurations due to prevailing wind conditions given by West-flow and East-flow as depicted in figures (4.5) and (4.6) respectively. According to the Final

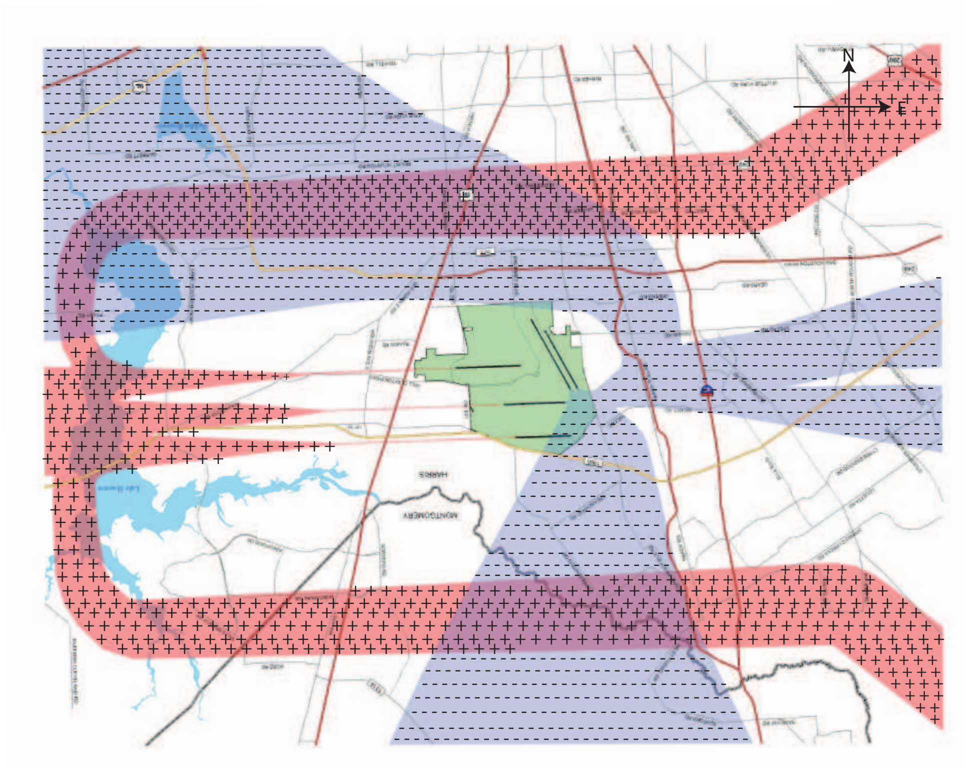


Figure 4.5. West-flow Arrival and Departure Corridor for IAH (Departures are shown in (-) pattern and arrivals are shown in (+) pattern)(HAS, 2010).

Environmental Impact Statement (FEIS) for IAH on July 2000, the optimal airport wind flow configuration is a West-flow, yet there can be multiple switches between West and East-flow configurations during a day. FEIS provides the guidelines for runway usage based on wind conditions for operations during the day and night as shown in table (4.3). As it is not possible to use FEIS guidelines for runway use in

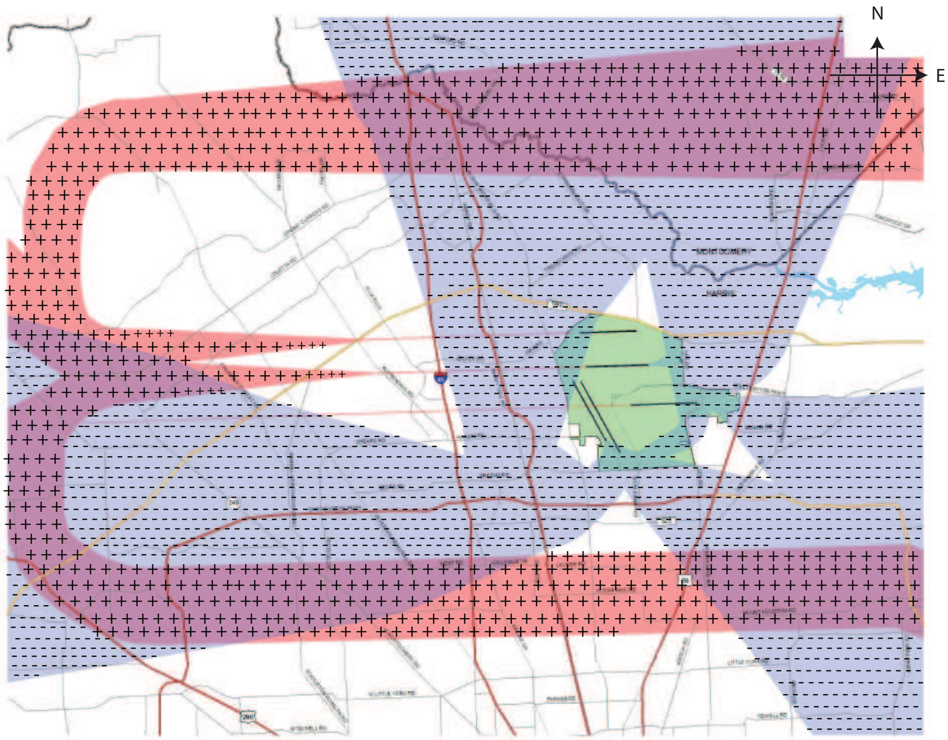


Figure 4.6. East-flow Arrival and Departure Corridor for IAH (Departures are shown in (-) pattern and arrivals are shown in (+) pattern)(HAS, 2010).

all operating scenarios, judgment is generally made by Air-Traffic Controllers (ATC) to assign and manage the airport runways. Actual runway usage at IAH from 10/1/2009 to 01/01/2010 is summarized in table (4.4).

Google Earth^{TM} Google (2009) was used to measure the physical distance from the end/beginning of runways to each gate. After these distances are assessed for arrival and departure flights, the expected runway-gate distance is calculated using the runway usage (%) as probabilities for arrival flights and departure flights as shown in table 4.4. As an example, the distances from gate C14 to runways 26L, 27, 26R, 33R, 33L, 8L, 8R, 15L, 15R, and 9 are 1.64, 2.98, 3.74, 3.63, 3.18, 4.49, 1.24,

Table 4.3. FEIS Guidelines for Runway Usage

Operation Hours	Flow Direction	Arrival Runways	Departure Runways
6:00AM-9:59PM	West Flow	26L, 26R, 27, 15L, 15R	15L, 15R, 26L, 26R, 8L
	East flow	8R, 8L, 9, 15L and 15R	15L, 15R ,9, 8R, 8L
10:00PM-5:59AM	West Flow	26L, 26R, 27, 15L, 15R	15L, 15R, 26L, 26R, 27
	East Flow	8R, 8L, 15L, 15R, and 9	15L, 15R ,9, 8R, 8L

Table 4.4. Runway Usage in Percentage of Arrival Flights, Departure Flights and Total Flights

S.N	Runway	Runway Usage (%) Arrival Flight	Runway Usage (%) Departure Flight	Total Runway Usage (%)
1	15L	0.23%	52.14%	26.18%
2	15R	0.25%	27.19%	13.72%
3	26L	35.44%	2.34%	18.89%
4	26R	7.83%	0.53%	4.18%
5	27	34.85%	1.19%	18.33%
6	9	0.60%	8.05%	3.93%
7	8R	13.87%	0.06%	7.06%
8	8L	6.89%	0.05%	3.48%
9	33L	0.00%	3.63%	1.81%
10	33R	0.03%	4.80%	2.41%
11	unknown	0.00%	0.04%	0.02%

2.77, 2.99, and 2.67 miles respectively, and hence the expected runway length (E[X]) of C14 is calculated as

$$E[x] = \sum_i x_i \times p(x_i) \quad \forall i \in \{26\text{L}, 27, 26\text{R}, 33\text{R}, 33\text{L}, 8\text{L}, 8\text{R}, 15\text{L}, 15\text{R}, \text{and}9\} = 2.43\text{mi}$$

Note that in the above equation, x_i is the runway-gate distance from each runway and $p(x_i)$ is the probability for arrival flights or departure flights which is shown in table (4.4).

4.3.2.5 Connecting Passengers

Connecting passengers are defined as passengers whose final destination is not IAH, yet rather depart on another flight originating at IAH. It is necessary to know the average number of passengers that connect from one specific flight to another, which data is maintained by Continental Airlines. In this dissertation, this data is not presented, yet that which is representative of connecting passengers for a typical airline is considered.

4.3.2.6 Parameter Specifications

Parameter specifications based on the data collected are shown in table (4.5).

Table 4.5. Tabulation of Parameters values

Parameter	Value
C_k	2450
f_i	From Table (4.1)
f_s	25 knots
f_c	\$1.614 /kg
d_{k1}	From Table (4.4) and Google Earth^{TM}
d_{k2}	From Table (4.4) and Google Earth^{TM}
$N_{ii'}$	Not shown
A_i	Not shown
D_i	Not shown

4.3.3 Computational Summary

For computational purpose, we used Intel(R) Xenon(R) CPU E5450 processors installed at High Performance Computing Center (HPCC) at the Experimental Sciences Building at Texas Tech University. Each node contains two Intel 5450 Quad Core 64bit processors with a core frequency of 3.0GHz with 16GB of memory. We used AMPL/CPLEX 11.2 to code our program, which was solved in the hierarchial zoning pattern as shown previously. As summary of the number of flights assigned to zones/subzones/gates shown in fig 4.3, total number of variables, total number of constraints, and solution elapsed time for each problem at different levels are given in table (4.6).

As a matter of reference, note that the Gap % is mathematically defined as

$$Gap\% = \left|\frac{BestNode - BestInteger}{BestInteger}\right| \times 100\% \; . \tag{4.20}$$

The optimal value of an integer program is bounded by the best integer objective value found so far and on the other side by a value deduced from all the node subproblems solved so far. Therefore, the solution search is terminated when it reaches an acceptable "Gap %" for a good solution ILOG/IBM (2008). The final assignments of flights to gates in the North and South Concourses of Terminal C and in Terminal E are given in tables (4.7-4.9) respectively. As a matter of reference, the flight numbers shown in tables (4.7-4.9) are coded flight numbers to ensure confidentiality, though most of the data used in this paper is publicly accessible.

Table 4.6. Computational Summary on Zone/Subzone/Gate Assignment

Computational Heirarachy Level	$\lvert F\rvert$	$\lvert K\rvert$ or $\lvert K_z\rvert$	Number of Variables	Number of Constraints	Optimal Objective	Solve Elapsed Time (sec)
Zone Assignment (Level-I)	226	3	767499	1221988	53878.6	36687.8
Subzone Assignment (Level-II)						
Subzones on Zone 1	54	2	23546	23170	12307.4	5.16
Subzones on Zone 2	12	3	2235	3258	2822.58	0.06
Subzones on Zone 3	160	3	384963	611686	42366.67	191723
Total	226	8				
Flight Gate Assignment (Level-III)						
Gates on Subzone 1[1]	41	10	5038090	591281	109930.18	40367.8
Gates on Subzone 2	13	4	636068	7613	35031.51	0.35
Gates on Subzone 3	3	5	183185	523	8200.19	0.05
Gates on Subzone 4	9	8	880136	16297	24193.17	0.3
Gates on Subzone 5	0	3	3	6	0	0
Gates on Subzone 6[2]	66	9	7328780	1236790	182950.31	72263.7
Gates on Subzone 7[3]	23	4	1127190	24503	62863.86	937.78
Gates on Subzone 8[4]	71	10	8767090	1790710	195808.24	53930.4
Total	226	53				

[1]Gap % = 0.71%, [2]Gap % = 1.47%, [3]Gap % = 0.52%, and [4]Gap % = 2.13

4.3.4 Optimal Assignment of Flights to Gates

The optimal assignment of flights to gates for Terminal C - North Concourse, Terminal C - South Concourse, and Terminal E is shown in table 4.7, table 4.8, and table 4.9.

Table 4.7. Flight Gate Assignment Solution for North Concourse of Terminal C

Gate	Coded Flights Number	Count
C14	42, 82, 119, 207	4
C15	85, 86, 164, 223	4
C16	15, 77, 83, 209	4
C17	68, 125, 196, 221	4
C18	46, 115, 138, 158	4
C19	32, 78, 111, 147, 212	5
C20	37, 55, 93, 165	4
C21	39, 49, 114, 123	4
C22	80, 92, 105, 226	4
C23	50, 116, 201, 204	4
C24	35, 53, 102, 129	4
C25	94, 97, 109, 120	4
C26	71, 107, 213	3
C27	110, 121	2
Total		54

Table 4.8. Flight Gate Assignment Solution for South Concourse of Terminal C

Gate	Coded Flights Number	Count
C29	58	1
C30	5	1
C31	98	1
C32	-	0
C33	-	0
C34	132	1
C35	174	1
C36	48	1
C37	47	1
C39	100	1
C40	60,199	2
C41	167	1
C42	157	1
C43	-	0
C44	-	0
C45	-	0
Total		12

Table 4.9. Flight Gate Assignment Solution for Terminal E

Gate	Coded Flights Number	Count
E1	31, 44, 57, 59, 117, 144, 166, 193, 197	9
E2	21, 26, 108, 154, 156, 163, 172	7
E3	81, 89, 118, 177, 186, 198, 217	7
E4	61, 96, 140, 171, 182, 208, 215	7
E5	24, 27, 74, 75, 155, 169, 190, 192	8
E6	7, 17, 18, 23, 30, 36, 113, 220	8
E7	6, 72, 90, 104, 145, 152, 181, 225	8
E8	63, 103, 135, 148, 159, 160, 180	7
E9	8, 14, 84, 101, 153	5
E10	2, 10, 20, 200, 210	5
E11	29, 45, 128, 137, 146, 179	6
E12	34, 66, 87, 183, 185, 189	6
E14	9, 25, 73, 122, 170, 202	6
E15	43, 99, 112, 124, 127, 168, 219	7
E16	41, 69, 139, 143, 161, 184, 218	7
E17	1, 4, 52, 64, 76, 175	6
E18	126, 149, 151, 206, 211	5
E19	3, 16, 22, 54, 70, 130, 141, 173, 176, 214	10
E20	12, 67, 91, 178, 187, 195, 203, 224	8
E21	19, 56, 142, 150, 188, 191, 194	7
E22	13, 28, 65, 95, 133, 205	6
E23	33, 79, 106, 134, 136, 162, 222	7
E24	11, 38, 40, 51, 62, 88, 131, 216	8
Total		160

4.4 Discussion and Conclusion

The specification of the indicator variable defined in Eq. (4.11) has noticeable impact on the model. For example, if $A_i - D_j \geq 0.5$ (30 min), arrival flights are scheduled to different zones satisfying the condition of a lag of 30 minutes between the departure and arrival of flights to a gate. Increasing this value will force flights to be spread across zones more uniformly, yet at a cost of increasing the objective function and possibly leading to infeasibility. Decreasing such reduces cost, yet may lead to greater congestion in a particular zone (terminal). In practice, this value will often be chosen based on operational needs, yet may be modified to balance loads within the airport. Note that in this paper, it was specified that $A_i - D_j \geq 0.5$ (30min), from whence 160 flights out of the 226 total flights are assigned to Terminal E, 12 flights are assigned to the South Concourse of Terminal C, and 54 flights are assigned to the North Concourse of Terminal C. If this were reduced to 30 mins, however, most all flights would be concentrated in Terminal E, suggesting the capacity of IAH for the increased number of flights by Continental Airlines.

4.5 Acknowledgements

This work would not be possible without the help of Continental Airlines and Mr. Manolo Centeno, Sr. Manager Operational Analyst and Operational Planning Analyst at Continental Airlines making data available along with providing valuable feedback and suggestions. The authors also acknowledge the High Performance Computing Center (HPCC) at Texas Tech University in Lubbock for providing high performance computing, visualization, database, or grid resources that have contributed to the research results reported in this paper.

CHAPTER 5

MODEL MODIFICATION FOR ASSIGNING WIDE-BODY JETS TO SPECIFIC GATES AND INTERNATIONAL FLIGHTS TO TERMINAL E

5.1 Wide-body flights

Continental Airlines uses a mix of narrow-body planes (737, 757) and wide-body planes (767, 777) for serving their passengers. Different types of planes have different specifications in length, wingspan, and height as given in table (5.1) Boeing (2010). Due to differences in physical dimensions, gates at the Intercontinental Airport in Houston cannot accommodate all types of airplanes.

Table 5.1. Length, Wingspan and Overall Height of Boeing 737, 757, 767, and 777

Plane Type	**Length**	**Wingspan**	**Tail Height**
737	94ft - 138ft	93ft - 117ft 5in	36ft 10in - 41ft 3in
757	155ft 3in - 178ft 7in	124ft 10in	44ft 6in
767 (Wide Body)	159ft 2in - 201ft 4in	156ft 1in - 170ft 4in	52ft 0in - 55ft 4in
777 (Wide Body)	209ft 1in - 242ft 4in	199ft 11in - 212ft 7in	60ft 8in - 61ft 1in

Source: http://www.boeing.com/

There are some gates that are preferred over other gates. For example, the preferred gates for wide-body flights are E4, E7, E18, E20, C14, C16, C19, and C40.

The detailed information on compatibility of flights with gates at the Terminal E is tabulated in table (5.2).

Wide-body flight constraints are added when assigning flights to the gates at Level II/Level III (refer to figure 4.4) which is shown in section 4.3.1.

Table 5.2. Terminal E Gates and its Compatibility with Plane Sizes

Gates	**Boeing 737**					**Boeing 757**		**Boeing 767**		**Boeing 777**
	300	**500**	**700**	**800**	**900**	**200**	**300**	**200**	**400**	
E1	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E2	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
E3	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N
E4	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
E5	**Y**	**Y**	N	N	N	N	N	N	N	N
E6	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E7	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
E8	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N
E9	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
E10	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E11	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E12	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E14	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
E15	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
E16	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E17	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	N	N	N	N
E18	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
E19	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E20	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
E21	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E22	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E23	**Y**	**Y**	**Y**	**Y**	**Y**	N	N	N	N	N
E24	**Y**	**Y**	N	N	N	N	N	N	N	N

*Y = Yes, N = No

5.2 International Flights

At the George Bush Intercontinental Airport (IAH), Terminal E is an international terminal. Therefore, all the Continental international flights arriving at IAH must be scheduled at Terminal E due to its ability to handle customs and immigrations protocol put in place by the Department of Homeland Security (DHS) and the Federal Aviation Authority (FAA). All the international passengers are required to go through Terminal E sothat they will be processed through U.S.

Customs and the Border Protection facility, sothat the FAA/DHS have accurate statistics on how many temporary visitors arrive in IAH. International departing passengers are allowed to fly out through any terminal at IAH. Flights from Canada are exempt from this protocol because passengers go through customs and immigration in the Canadian departing airport. However, specific Canadian cities do require passengers go through U.S. customs and immigration. A continental airline does not connect to those Canadian cities.

In order to follow FAA/DHS protocol for international arrival flights, we need to identify the international flights the day before we plan for flight gate assignment. The tabulation of international flights on Feb 01, 2010 is given in table 5.3.

Table 5.3. International Arriving Flights at IAH on February 01, 2010

Coded Flight Number	Departure Airport Code	Departing Country	Plane Type
1	NRT	Japan	777
2	CDG	France	767-400
26	CUN	Mexico	737-700
42	CUN	Mexico	737
57	POS	Trinidad and Tobago	737-800
63	GUA	Guatemala	737
65	CUN	Mexico	737-800
71	LIM	Peru	757
82	UIO	Ecuador	737-700
96	TGU	Honduras	737-700
99	SAP	Honduras	737-800
100	CUN	Mexico	737-800
103	SAL	El Salvador	737-900
104	SAL	El Salvador	737-800
105	PTY	Panama	737-700
106	GUA	Guatemala	737-800
108	PTY	Panama	737-900
110	BOG	Columbia	737-700
114	MEX	Mexico	737-800
118	MEX	Mexico	737-500
120	PVR	Mexico	737-700
121	MGA	Nicaragua	737-800
132	MEX	Mexico	737-700
137	BZE	Belize	737-800
146	MEX	Mexico	737-500
149	MEX	Mexico	737-500
165	ACA	Mexico	737-800
178	BZE	Belize	737-800
182	CUN	Mexico	737-800
183	CCS	Venezuela	737-800
189	CZM	Mexico	737-800
194	MEX	Mexico	735-500
198	CUN	Mexico	737-500
201	MGA	Nicaragua	737-800
209	PVR	Mexico	737-800
210	MID	Mexico	737-800
218	GUA	Guatemala	737-800
220	FRA	France	767-400
224	LHR	United Kingdom	767-400

While assigning zones in level I of computational hierarchy (figure 4.4), the above flights mentioned in table (5.3) are removed from the set of flights **F** because these flights will directly go to Zone 3. When we assign subzones to the flights at Zone 3, we append these international flights so that they will be assigned to Subzone 6, Subzone 7, or Subzone 8.

5.3 Wide-body flights and International Flight Constraints

Not every single flight can be assigned to any gate in Terminal E due to size limitations. Terminal E has certain gates that cannot accommodate wide body planes (767s and 777s). In Terminal E gates E1 - E23 can handle all types of 737 planes, while gate E24 can only accommodate 737-300 and 737-500 planes. Gates E2, E4, E7, E9, E14, E15, E18, and E20 can handle any size planes, whereas wide-body planes can only be scheduled at E4, E7, E18, and E20. Gates E3 and E8 can handle 737s and 757s only. The constraints 5.1 - 5.4 define the abovementioned flight to gate rules (requirements), because not all flight types can be scheduled to any gate available.

5.3.0.1 Sets

The following sets of flights and gates are defined to make modifications in order to address the special need of international arrivals:

$\mathbf{K_{737Only}}$ = Set of gates that can accommodate all 737 flights (737-300, 737-500, 737-700, 737-800, and 737-900) at Terminal E.

$\mathbf{K_{allPurpose}}$ = Set of gates that can accommodate all kinds of flights (737, 757, 767, and 777) at Terminal E.

$\mathbf{K_{737-757}}$ = Set of gates that can accommodate 737 and 757 flights at Terminal E.

$\mathbf{K_{w}}$ = Set of wide body gates that can accommodate 767 and 777 flights at Terminal E.

$\mathbf{K_{737-300-200}}$= Set of gates that can accommodate 737-300 and 737-200 flights only at Terminal E.

$\mathbf{K_{737}}$ = Set of all gates that can accommodate 737 flights at Terminal E

$\mathbf{K_{757}}$ = Set of all gates that can accommodate 757 flights at Teminal E

$\mathbf{F_{737}}$ = Set of 737 flights at Terminal E

$\mathbf{F_{757}}$ = Set of 757 flights at Terminal E

$\mathbf{F_{737-300-200}}$ = Set of 735-300 and 737-200 flights at Terminal E

Lets define $\mathbf{K_{737}}$ and $\mathbf{K_{757}}$ as follows :

$\mathbf{K_{737}}= \mathbf{K_{737Only}} \cup \mathbf{K_{allPurpose}} \cup \mathbf{K_{737-757}}$

$\mathbf{K_{757}}= \mathbf{K_{allPurpose}} \cup \mathbf{K_{737-757}}$

The following constraints are added to an existing set of constraints while assigning gate at the Zone 3 (Terminal E):

$$\sum_k X_{ij}^k = 1 \qquad \forall i = j, k \in \mathbf{K_{737}}, i \in \mathbf{F_{737}} \tag{5.1}$$

$$\sum_k X_{ij}^k = 1 \qquad \forall i = j, k \in \mathbf{K_{757}}, i \in \mathbf{F_{757}} \tag{5.2}$$

$$\sum_k X_{ij}^k = 1 \qquad \forall i = j, k \in \mathbf{K_w}, i \in \mathbf{F_w} \tag{5.3}$$

$$\sum_k X_{ij}^k \leq 1 \qquad \forall i = j, k \in \mathbf{K_{737-300-200}}, i \in \mathbf{F_{737-300-200}} \tag{5.4}$$

All the flights in set $\mathbf{F_{737}}$, $\mathbf{F_{757}}$, and $\mathbf{F_w}$ must be assigned to the set of gates $\mathbf{K_{737}}$, $\mathbf{K_{757}}$, and $\mathbf{K_w}$ respectively. The constraint 5.1 will limit flights in set $\mathbf{F_{737}}$ to the gates in set $\mathbf{K_{737}}$. The constraint 5.2 will limit flights in set $\mathbf{F_{757}}$ to gates in set $\mathbf{K_{757}}$. The constraint 5.3 will put the wide body flights in set $\mathbf{F_w}$ in the gates in set $\mathbf{K_w}$. There are gates that can only accommodate 737-200 and 737-300 (refer to table 5.2). The inequality constraint in constraint 5.4 will specify 737-200 and 737-300 to those gates that can accommodate all 737s.

5.3.1 Computational Summary with Wide-body/International Flight Constraints

For computational purposes, the Intel(R) Xenon(R) CPU E5450 processors installed at the High Performance Computing Center (HPCC) in the Experimental Sciences Building at Texas Tech University were used. Each node contains two Intel 5450 Quad Core 64bit processors with a core frequency of 3.0GHz with 16GB of memory. We used AMPL/CPLEX 11.2 to code our program, which was solved in the hierarchial zoning pattern as shown previously (refer figure 4.3). A summary of number of flights assigned to zones/subzones/gates, total number of variables, total number of constraints, and solution elapsed time for each problem with an addition of constraints 5.1 - 5.4 at different levels are given in table (5.4). Gap % (refer 4.20)

Table 5.4. Computational Summary on Zone/Subzone/Gate Assignment

Computational Heirarachy Level	$\|F\|$	$\|K\|$ or $\|K_z\|$	Number of Variables	Number of Constraints	Optimal Objective	Solve Elapsed Time (sec)
Zone Assignment (Level I)	226	3	520059	827148	47208.56	145518
Subzone Assignment (Level II)						
Subzones on Zone 1	93	2	69566	68918	23465.16	57.5
Subzones on Zone 2	67	3	67740	106604	17252.18	6036.33
Subzones on Zone 3	66	3	65739	103312	9970.10	80.42
Total	226	8				
Flight Gate Assignment (Level III)						
Gates on Subzone 1[1]	70	10	8484010	1740290	193760.73	151889
Gates on Subzone 2	23	4	1106400	24503	62487.91	39.29
Gates on Subzone 3	20	5	1202000	30630	54588.06	1498.11
Gates on Subzone 4[2]	35	8	3374010	267172	97590.67	155618
Gates on Subzone 5	12	3	432147	3258	32442.87	1.25
Gates on Subzone 6	10	9	1080010	26137	26931.22	0.31
Gates on Subzone 7	4	4	191812	624	10665.42	0.02
Gates on Subzone 8[3]	52	10	6283690	955859	139822.23	93600.5
Total	226	53				

[1]Gap % = 2.37%, [2]Gap % = 2.64%, [3]Gap % = 0.38%

for subzone 1, subzone 4, and subzone 8 are 2.37%, 2.64%, and 0.38% respectively. The low "Gap %" reported in table 5.4 shows that it is a good solution to consider for a flight gate assignment.

5.3.2 Optimal Assignment of Flights to Gates with Wide-body/ International Flight Constraints to Terminal E

The optimal assignment of flights to gates with Wide-body/International flights constraints for Terminal C - North Concourse, Terminal C - South Concourse, and

Terminal E is shown in table 5.5, table 5.6, and table 5.7.

Table 5.5. Flight Gate Assignment Solution for North Concourse of Terminal C with Wide-body/International Flight Constraints

Gate	Coded Flights Number	Count
C14	161, 188	2
C15	16, 32, 56, 66, 81	5
C16	33, 37, 52, 84, 219	5
C17	4,21,70, 88, 91, 136, 172, 180, 215	9
C18	27, 41, 130, 148, 170, 171, 177	7
C19	72, 134, 160, 193, 205	5
C20	12,20,115,141, 155, 176, 187, 191	8
C21	7,18,31,61,122,145,186,225	8
C22	3, 28, 34, 45, 126, 128, 131, 144, 147, 163, 169, 175, 179	13
C23	36, 43, 150, 166, 168, 181, 195, 206	8
C24	30, 77, 95, 135, 142, 203	6
C25	6, 14, 86, 156, 185, 213	6
C26	19, 48, 90, 140, 152, 223	6
C27	24, 46, 112, 204, 222	5
Total		93

When wide-body/international flight constraints are considered with $A_i - D_j \geq 0.75$ (45min), out of 226 flights, 93 flights are assigned to Terminal C - North Concourse, 67 flights are assigned to Terminal C- South Concourse, and 66 flights are assigned to Terminal E (International Terminal).

Table 5.6. Flight Gate Assignment Solution for South Concourse of Terminal C with Wide-body/International Flight Constraints

Gate	Coded Flights Number	Count
C29	8, 15, 76, 200	4
C30	49, 50, 60, 74, 143	5
C31	9, 54, 101, 133	4
C32	59, 92, 116, 151	4
C33	10, 162, 196	3
C34	40, 51, 211	3
C35	62, 117, 167, 202	4
C36	13, 109, 139, 159, 190, 197	6
C37	75, 154, 208	3
C39	68, 93, 123, 124, 192	5
C40	17, 25, 38, 44, 67, 89, 158	7
C41	29, 113, 127, 153	4
C42	73, 87, 173	3
C43	11, 55, 64, 199, 207	5
C44	23, 39, 174, 184	4
C45	22, 69, 80	3
Total		67

Table 5.7. Flight Gate Assignment Solution for Terminal E with Wide-body/International Flight Constraints

Gate	Coded Flights Number	Count
E1	96	1
E2	106	1
E3	121	1
E4	220	1
E5	157	1
E6	100, 110, 149	3
E7	224	1
E8	165	1
E9	-	0
E10	182	1
E11	209	1
E12	218	1
E14	132	1
E15	102, 42, 71, 103	4
E16	94, 217, 78, 114, 178	5
E17	47, 79, 138, 63, 99, 194	6
E18	83, 111, 214, 221, 2, 82, 210	7
E19	5, 97, 119, 129, 226, 104, 108, 118, 120, 137	10
E20	58, 125, 1, 26, 183, 201	6
E21	35, 216, 57, 65, 189, 198	6
E22	107, 105, 146	3
E23	53, 85, 212	3
E24	98, 164	2
Total		66

CHAPTER 6

COMPARISON BETWEEN UN-OPTIMIZED AND OPTIMIZED FLIGHT GATE ASSIGNMENT SCENARIOS

In this chapter, a comparison of flight assignments and objective function (fuel-burn & connecting passenger cost) between un-optimized and optimized flight gate assignment scenarios solved in section 4.3.3 and section 5.3.1 are made. In both cases, the multicommodity gate flow network model is used to optimize flight gate assignment. In section 4.3.3, the model is optimized without wide-body/international flight constraints whereas, in section 5.3.1, the model is optimized with wide-body/international flight constraints. February 01, 2010 data from the Continental Airlines Inc. is used to solve the model.

Airlines directly pay for the fuel used by the airplanes; therefore, fuel-burn cost is the direct cost. Connecting passenger cost, representing connecting passenger inconvenience, is the indirect cost for an airline. The taxi fuel-burn cost is calculated for expected runway distance used by taxiing a flight using an Eq. (4.2) and the connecting passenger cost is computed for number of connecting passengers using an (Eq. 4.3).

6.1 Un-optimized/Optimized Gate Assignment Without Wide-body/ international Flight Constraints Case

6.1.1 Gate assignment comparisons

The comparison of assignments for un-optimized flight gate assignment and optimized flight gate assignment is given in table 6.1, table 6.2, and table 6.3.

Table 6.1. Comparison of Un-optimized/Optimized Gate Assignment for February 01, 2010 at Terminal C - North Concourse

Gate	Optimized Assignment		Unoptimized Assignment	
	Coded Flight Number	Count	Coded Flight Number	Count
C14	42, 82, 119, 207	4	-	-
C15	85,86,164,223	4	-	-
C16	15,77,83,209	4	-	-
C17	68,125,196,221	4	-	-
C18	46,115,138,158	4	56, 212	2
C19	32,78,111,147,212	5	51, 211	2
C20	37,55,93,165	4	77, 150	2
C21	39,49,114,123	4	66, 204	2
C22	80,92,105,226	4	92	1
C23	50,116,201,204	4	8, 153	2
C24	35,53,102,129	4	214	1
C25	94,97,109,120	4	-	-
C26	71,107,213	3	-	-
C27	110,121	2	-	-
	Total	54		12

There are 12 flights assigned to Terminal C - North Concourse by Continental Airlines on February 01, 2010 in an un-optimized assignment (as existed). After optimization, there are 54 flights assigned to Terminal C-North Concourse.

There are 95 flights assigned to Terminal C - South Concourse by Continental Airlines on February 01, 2010. After optimization, only 12 flights assigned to Terminal C-South Concourse.

Similarly, there are 119 flights assigned to Terminal E by the Continental Airlines on February 01, 2010. After optimization, we have only 160 flights assigned to Terminal C-South Concourse.

Table 6.2. Comparison of Un-optimized/Optimized Gate Assignment for February 01, 2010 at Terminal C - South Concourse

Gate	Optimized Assignment		Unoptimized Assignment	
	Coded Flight Number	Count	Coded Flight Number	Count
C29	58	1	3, 6, 10, 89, 101, 156, 175, 179	8
C30	5	1	23, 97, 144, 154, 170, 177	6
C31	98	1	49, 73, 85, 95, 172	5
C32	-	0	9, 28, 39, 44, 222	5
C33	-	0	35, 41, 64, 69, 80, 102, 191	7
C34	132	1	15, 27, 46, 94, 208	5
C35	174	1	68, 116, 125, 157, 193, 203	6
C36	48	1	21, 161, 164, 174, 186, 187	6
C37	47	1	31, 37, 160, 176	4
C39	100	1	24, 29, 61, 195, 205, 213, 221	7
C40	60,199	2	7, 50, 55, 134, 207, 217	6
C41	167	1	19, 47, 72, 122, 142, 151, 152	7
C42	157	1	40, 58, 75, 93, 223	5
C43	-	0	14, 139, 181, 199	4
C44	-	0	4, 34, 83, 123, 168, 180	6
C45	-	0	43, 54, 62, 84, 98, 128, 163, 225	8
total		12		95

Table 6.3. Comparison of Un-optimized/Optimized Gate Assignment for February 01, 2010 at Terminal E

Gate	Optimized Assignment		Unoptimized Assignment	
	Coded Flight Number	Count	Coded Flight Number	Count
E1	31,44,57,59,117,144,166,193,197	9	5, 36, 104, 149, 183, 189	6
E2	21,26,108,154,156,163,172	7	32, 91, 112, 117, 218, 226	6
E3	81,89,118,177,186,198,217	7	71, 126, 137	3
E4	61,96,140,171,186,198,217	7	17	1
E5	24,27,74,75,155,169,190,192	8	70, 113, 146, 148, 190	5
E6	7,17,18,23,30,36,113,220	8	42, 57, 59, 121, 124, 141, 158, 216	8
E7	6, 72, 90, 104, 145, 152, 181, 225	8	1, 220	2
E8	63, 103, 135, 148, 159, 160, 180	7	22, 30, 88, 127, 145, 188, 206, 219	8
E9	8, 14, 84, 101, 153	5	18, 78, 96, 135, 143, 162, 171, 215	8
E10	2, 10, 20, 200, 210	5	11, 79, 119, 133, 138, 147, 197	7
E11	29, 45, 128, 137, 146, 179	6	48, 99, 155, 166, 185, 196, 198	7
E12	34, 66, 87, 183, 185, 189	6	60, 81, 87, 178, 202	5
E14	9, 25, 73, 122, 170, 202	6	16, 53, 108, 165, 209, 210	6
E15	43, 99, 112, 124, 127, 168, 219	7	100, 105, 111, 136, 173, 192, 201	7
E16	41, 69, 139, 143, 161, 184, 218	7	25, 26, 67, 82, 103, 159, 200	7
E17	1, 4, 52, 64, 76, 175	6	13, 74, 109, 130, 169, 182	6
E18	126, 149, 151, 206, 211	5	2	1
E19	3, 16, 22, 54, 70, 130, 141, 173, 176, 214	10	115, 131	2
E20	12, 67, 91, 178, 187, 195, 203, 224	8	52, 110, 224	3
E21	19, 56, 142, 150, 188, 191, 194	7	33, 38, 63, 65, 132, 184, 194	7
E22	13, 28, 65, 95, 133, 205	6	90, 107, 114	3
E23	33, 79, 106, 134, 136, 162, 222	7	20, 76, 106, 120, 129, 167	6
E24	11, 38, 40, 51, 62, 88, 131, 216	8	12, 45, 86, 118, 140	5
Total		160		119

6.1.2 Comparison of Fuel-burn Costs and Connecting Passenger Costs

The comparisons of objective function by fuel-burn costs and connecting passenger costs for un-optimized and optimized flight gate assignment summarized by subzones are given in table 6.4 and table 6.5 below :

Table 6.4. Un-optimized (as existed) Flight Gate Assignment for February 01, 2010

Subzones	Fuel Burn Cost	Gate Cost	Connecting Passenger Cost	Total Cost
Gates on Subzone 1	$2,505.10	$26,950.00	$18,035.01	$47,490.11
Gates on Subzone 2	$233.85	$2,450.00	$318.20	$3,002.05
Gates on Subzone 3	$7,464.21	$75,950.00	$50,770.55	$134,184.76
Gates on Subzone 4	$12,199.68	$112,700.00	$77,948.80	$202,848.48
Gates on Subzone 5	$4,730.69	$44,100.00	$31,038.72	$79,869.42
Gates on Subzone 6	$11,571.85	$115,150.00	$62,815.39	$189,537.24
Gates on Subzone 7	$5,390.28	$61,250.00	$37,028.00	$103,668.29
Gates on Subzone 8	$11,418.05	$115,150.00	$123,057.33	$249,625.38
Total	$55,513.71	$553,700.00	$401,012.02	$1,010,225.73

Table 6.5. Optimized Flight Gate Assignment for February 01, 2010 Without Wide-body Flight Constraints/international Flight Constraints

Optimized	Fuel Cost	Gate Cost	Passenger	Total
Gates on Subzone 1	$9,594.67	$100,450.00	$1,019.33	$111,064.00
Gates on Subzone 2	$3,044.00	$31,850.00	$225.35	$35,119.35
Gates on Subzone 3	$1,164.36	$12,250.00	$154.57	$13,568.93
Gates on Subzone 4	$5,293.61	$51,450.00	$88.88	$56,832.49
Gates on Subzone 5	$724.40	$7,350.00	$0.00	$8,074.40
Gates on Subzone 6	$13,224.85	$137,200.00	$2,236.15	$152,661.00
Gates on Subzone 7	$2,347.98	$24,500.00	$0.00	$26,847.98
Gates on Subzone 8	$18,696.67	$188,650.00	$7,754.07	$215,100.74
Total	$54,090.53	$553,700.00	$11,434.03	$619,268.88

From the comparison of table 6.4 and table 6.5 above, there is an observable 38.7% decrease in total cost. The connecting passenger cost undergoes the greatest reduction, which is approximately 97.14%. There has been 2.56% reduction in fuel burn cost when compared between an un-optimized scenario and an optimized flight gate assignment without any restriction on wide-body flights/international flights. The huge reduction in connecting passenger costs signifies a greater convenience achieved by shortening the connection distance between arrival gates and departure gates.

6.2 Un-optimized/Optimized Gate Assignment with Wide-body/ International Flight Constraints Case

6.2.1 Gate Assignment comparisons

The comparison of assignments for un-optimized flight gate assignment and optimized flight gate assignment with wide-body/international flight gate constraints for Terminal C- North Concourse, Terminal C -South Concourse, and Terminal E are given in table 6.6, table 6.7, and table 6.8.

Table 6.6. Comparison of Un-optimized/Optimized Gate Assignment for February 01, 2010 at Terminal C - North Concourse

Gate	Optimized Assignment		Unoptimized Assignment	
	Coded Flight Number	Count	Coded Flight Number	Count
C14	161, 188	2	-	-
C15	16, 32, 56, 66, 81	5	-	-
C16	33, 37, 52, 84, 219	5	-	-
C17	4,21,70, 88, 91, 136, 172, 180, 215	9	-	-
C18	27, 41, 130, 148, 170, 171, 177	7	56, 212	2
C19	72, 134, 160, 193, 205	5	51, 211	2
C20	12,20,115,141, 155, 176, 187, 191	8	77, 150	2
C21	7,18,31,61,122,145,186,225	8	66, 204	2
C22	3, 28, 34, 45, 126, 128, 131, 144, 147, 163, 169, 175, 179	13	92	1
C23	36, 43, 150, 166, 168, 181, 195, 206	8	8, 153	2
C24	30, 77, 95, 135, 142, 203	6	214	1
C25	6, 14, 86, 156, 185, 213	6	-	-
C26	19, 48, 90, 140, 152, 223	6	-	-
C27	24, 46, 112, 204, 222	5	-	-
	Total	93		12

There are 12 flights assigned to Terminal C - North Concourse by Continental Airlines on February 01, 2010 in an un-optimized assignment (as existed) . After optimizing with wide-body/international flight constraints, there are 93 flights assigned to the Terminal C-North Concourse.

Table 6.7. Comparison of Un-optimized/Optimized Gate Assignment for February 01, 2010 at Terminal C - South Concourse

Gate	Optimized Assignment		Unoptimized Assignment	
	Coded Flight Number	Count	Coded Flight Number	Count
C29	8, 15, 76, 200	4	3, 6, 10, 89, 101, 156, 175, 179	8
C30	49, 50, 60, 74, 143	5	23, 97, 144, 154, 170, 177	6
C31	9, 54, 101, 133	4	49, 73, 85, 95, 172	5
C32	59, 92, 116, 151	4	9, 28, 39, 44, 222	5
C33	10, 162, 196	3	35, 41, 64, 69, 80, 102, 191	7
C34	40, 51, 211	3	15, 27, 46, 94, 208	5
C35	62, 117, 167, 202	4	68, 116, 125, 157, 193, 203	6
C36	13, 109, 139, 159, 190, 197	6	21, 161, 164, 174, 186, 187	6
C37	75, 154, 208	3	31, 37, 160, 176	4
C39	68, 93, 123, 124, 192	5	24, 29, 61, 195, 205, 213, 221	7
C40	17, 25, 38, 44, 67, 89, 158	7	7, 50, 55, 134, 207, 217	6
C41	29, 113, 127, 153	4	19, 47, 72, 122, 142, 151, 152	7
C42	73, 87, 173	3	40, 58, 75, 93, 223	5
C43	11, 55, 64, 199, 207	5	14, 139, 181, 199	4
C44	23, 39, 174, 184	4	4, 34, 83, 123, 168, 180	6
C45	22, 69, 80	3	43, 54, 62, 84, 98, 128, 163, 225	8
total		67		95

There are 95 flights assigned to Terminal C - South Concourse by Continental Airlines on February 01, 2010 in an un-optimized assignment (as existed). After optimizing with wide-body /international flight constraints, there are only 67 flights assigned to Terminal C-South Concourse.

Table 6.8. Comparison of Un-optimized/Optimized Gate Assignment for February 01, 2010 at Terminal E

Gate	Optimized Assignment		Unoptimized Assignment	
	Coded Flight Number	Count	Coded Flight Number	Count
E1	96	1	5, 36, 104, 149, 183, 189	6
E2	106	1	32, 91, 112, 117, 218, 226	6
E3	121	1	71, 126, 137	3
E4	220	1	17	1
E5	157	1	70, 113, 146, 148, 190	5
E6	100,110,149	3	42, 57, 59, 121, 124, 141, 158, 216	8
E7	224	1	1, 220	2
E8	165	1	22, 30, 88, 127, 145, 188, 206, 219	8
E9	-	0	18, 78, 96, 135, 143, 162, 171, 215	8
E10	182	1	11, 79, 119, 133, 138, 147, 197	7
E11	209	1	48, 99, 155, 166, 185, 196, 198	7
E12	218	1	60, 81, 87, 178, 202	5
E14	132	1	16, 53, 108, 165, 209, 210	6
E15	102, 42, 71, 103	4	100, 105, 111, 136, 173, 192, 201	7
E16	94, 217, 78, 114, 178	5	25, 26, 67, 82, 103, 159, 200	7
E17	47, 79, 138, 63, 99, 194	6	13, 74, 109, 130, 169, 182	6
E18	83, 111, 214, 221, 2, 82, 210	7	2	1
E19	5, 97, 119, 129, 226, 104, 108, 118, 120, 137	10	115, 131	2
E20	58, 125, 1, 26, 183, 201	6	52, 110, 224	3
E21	35, 216, 57, 65, 189, 198	6	33, 38, 63, 65, 132, 184, 194	7
E22	107, 105, 146	3	90, 107, 114	3
E23	53, 85, 212	3	20, 76, 106, 120, 129, 167	6
E24	98, 164	8	12, 45, 86, 118, 140	5
Total		66		119

There are 119 flights assigned to Terminal E by Continental Airlines on February 01, 2010 in an un-optimized assignment (as existed). After optimizing with wide-body/international flight constraints, there are 66 flights assigned to Terminal E.

6.2.2 Comparison of Fuel-burn Costs and Connecting Passenger Costs

The comparisons of objective function by fuel-burn costs and connecting passenger costs are summarized by subzones table 6.9. Table 6.9, as shown below, exhibits optimized flight gate assignments considering international flights at terminal E and wide-body flights at E4, E7, E18, E24, C14, C16, C19, and C40.

Table 6.9. Optimized Flight gate assignment for February 01, 2010 with wide-body flight constraints/international flight constraints

Optimized	Fuel Cost	Gate Cost	Passenger	Total
Gates on Subzone 1	$17,836.61	$171,500.00	$4,424.13	$193,760.73
Gates on Subzone 2	$6,094.01	$56,350.00	$43.90	$62,487.91
Gates on Subzone 3	$5,169.67	$49,000.00	$418.39	$54,588.07
Gates on Subzone 4	$8,905.80	$85,750.00	$2,934.87	$97,590.67
Gates on Subzone 5	$2,935.59	$29,400.00	$107.28	$32,442.87
Gates on Subzone 6	$2,637.06	$26,950.00	$206.09	$29,793.15
Gates on Subzone 7	$865.42	$9,800.00	$0.00	$10,665.42
Gates on Subzone 8	$11,661.71	$124,950.00	$187.85	$136,799.56
Total	$56,105.86	$553,700.00	$8,322.51	$618,128.37

When comparing un-optimized fight gate assignment (refer to table 6.4) with optimized flight gate assignment with wide-body/international flight constraints (refer to table 6.9), fuel burn cost increased by 3.6% compared to an un-optimized flight gate assignment scenario. However, the connecting passenger cost is reduced by 97.9%, with a reduction of 38.81 % in total cost.

6.3 The Comparison of Costs for Un-optimized, Optimized, and Optimized with Wide-body/ International Flight Constraints

The comparison of costs for un-optimized, optimized and optimized with wide-body/international flight constraints at Terminal E are shown in figure 6.1:

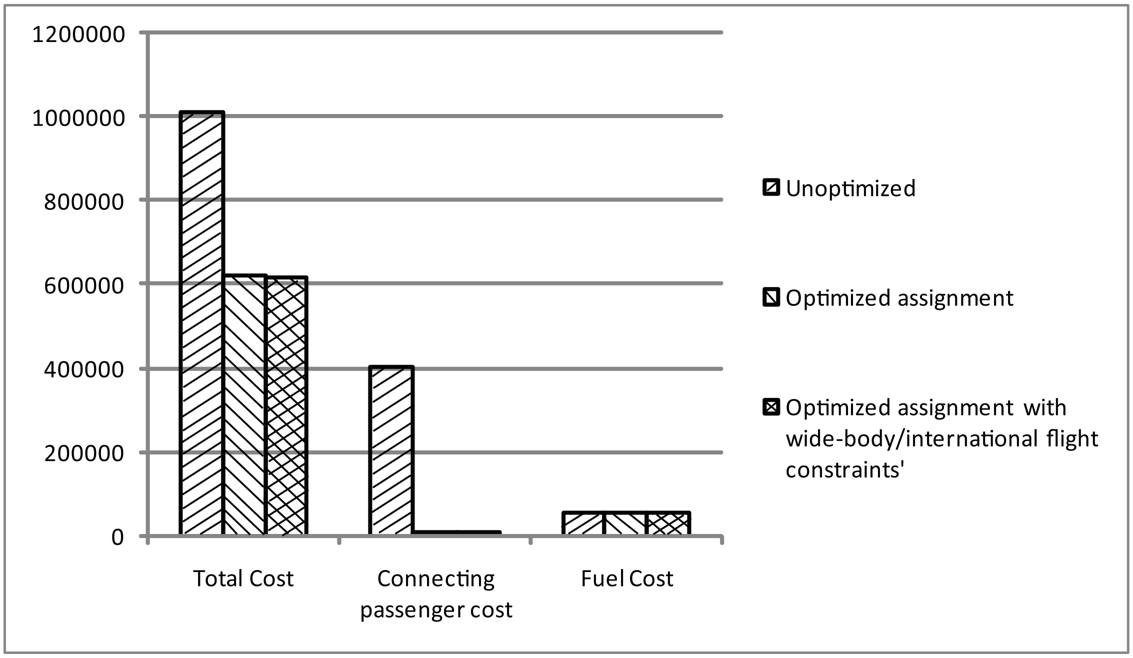


Figure 6.1. Cost Comparison with Flight Gate Assignment Model

The increase in the fuel burn cost for optimized assignment with international flights/wide-body flights in specific gates also has to do with the buffer threshold (p) (refer to Eq. 4.1) specified in the model. The values of the buffer used in the model to solve both models are tabulated in table 6.10 and table 6.11:

Table 6.10. Value of buffer (p) Used to Optimize Flight Gate Assignment Model

	Zone assignment	Subzone Assignment	Gate Assignment
p	0.5 (30 min)	0.5 (30 min)	0.5 (30 min)*

* except for subzone 4 ($p = 0.15$ (9 min)).

A higher buffer (p) value will limit the number of back-flow arcs (arc(j,i)), which then reduces the flight congestions at gates. On the other hand, low values of p

Table 6.11. Value of buffer (p) Used to Optimize Flight Gate Assignment Model with Wide-body/International Flight Constraints

	Zone assignment	Subzone Assignment	Gate Assignment
p	0.75 (45 min)	0.75 (45 min)	0.75 (75 min)*

* except for subzone 8 ($p = 0.1$ (6min)

increase the flight congestion at gates. Since, the higher p values are used in the model with wide-body/international flight constraints, the model tries to spread flights into distant gates, thus incurring more fuel burn. A lower p value will let multiple flights use the same gates but if flight conflicting situations arise due to arrival or departure delays, it increases the chance of reassignment and vice versa.

The average buffer we observed with the assignments are presented in table 6.12.

Table 6.12. Average Buffer (p) Observed with Assignment Model

	Un-optimized	Optimized	Optimized with Modifications
P (observed)	1 hr 46 min	1 hr 26 min	1 hr 7 min

Optimized gate assignments and optimized gate assignments with modifications (international flights at terminal E/wide-body flights at specified gates) have lower average buffer times compared to un-optimized assignments, which indicates better gate utilizations.

CHAPTER 7
AN OPTIMIZATION MODEL FOR GATE REASSIGNMENT IN RESPONSE TO FLIGHT DELAYS

(to be submitted for journal publication)

7.1 Introduction

With the multitude of tightly scheduled air traffic operating in a highly variable natural environment, it is not uncommon for flights to experience delays. A sampling of the on-time performance of major airlines for the first half of the year 2010 has been 83.61%, 77.1%, 77.1%, 80.2%, 83.3%, and 82.2% for Continental Airlines, American Airlines, JetBlue Airways, Southwest Airlines, United Airlines , and US Airways respectively as reported by AviationDatabase (2010). The source of these delays stem from a host of causes such as inclement weather, tardy crews, mechanical problems, passengers, airport security issues, airport congestion, delay propagation between airports, etc., with some of these being more predictable with lead time than others. As an example, a snapshot of the sources of delay experienced by Continental Airlines (CO) at Intercontinental Airport (IAH) in the first half of 2010 is given in table 7.1 as reported by RITA-BTS (2010).

Note that while CO Airlines is one of the best airlines in terms of on-time performance, roughly 38 flights per day experience some sort of delay going into or out of IAH on average. The estimated yearly cost of airline delays was estimated to be a staggering $41 billion in 2007 as noted in a Joint Economic Committee report

Table 7.1. Delay Statistics for Continental Airlines at Intercontinental Airport for the First Half of the Year 2010

Source of Delay	Number of Operations	% of Total Operations	Delayed Minutes	% of Total Delayed Minutes
No Delay (On Time)	34002	83.61%	N/A	N/A
Air Carrier Delay	1351	3.32%	86755	28.79%
Weather Delay	149	0.37%	8699	2.89%
National Aviation System Delay	3280	8.07%	110948	36.81%
Security Delay	44	0.11%	2586	0.86%
Aircraft Arriving Late	1496	3.68%	92386	30.65%
Cancelled	204	0.50%	N/A	N/A
Diverted	142	0.35%	N/A	N/A
Total Operations	40669	100%	301374	100%

by Schumer & Maloney (2008), which includes $19 billion in increased airlines' operating costs such as, additional crew, fuel, maintenance etc; $12 billion in passenger time lost, causing lower productivity and business opportunities; and $10 billion in indirect costs of delay to other industries that rely on air traffic, such as food service, lodging, public transportation etc. From an environmental perspective, this report also noted that additional fuel burned released 7.1 million metric tons of CO2 into the atmosphere.

Our interest in this paper is the effect that delayed flights will have on the initial assignment of flights to gates at an airport, specifically the development of a practical method by which gate reassignments may be made to minimize passenger disruption in response to these delays. It is our experience that these reassignments are generally made with little quantitative support by gate managers in a "real time" and reactive manner, yet we will show the formulation of a integer program that will provide fast optimal gate reassignments within an airport zoning strategy. In general, a gate schedule is said to be in conflict if there is an overlap of planes scheduled to reside at a particular gate due to realized or anticipated flight delay. If flight i is the source of gate conflict and in response some combination of flight i and other flights j are reassigned to accommodate this delay, it follows that the connecting passenger coming in on this flight i and connecting and originating passengers going out on all other flights j will experience disruption if this reassignment is not made with sufficient lead time for the respective flight. Hence, when it becomes known that a flight will be delayed, the reassignment should be made as soon as possible to disrupt as few passengers as possible, both on the offending and other flights, which is a function of both the number of passengers and lead time of all potential reassigned flights.

The gate reassignment problem has received recent, yet somewhat limited attention in the literature. Specifically, Yan & Huo (2001) studied the real time gate reassignment problem considering stochastic flight delays using a gate flow network model. Their approach is to first solve a model to get planned flight gate assignment, and then simulate reassignments for all scenarios when an airplane cannot be assigned to its original gate. The best reassignment is chosen based on the objective value which minimizes passengers waiting time and time inconsistencies from previous assignment based on simple reassignment rules. Gu & Chung (1999) address the reassignment issue by implementing a Genetic Algorithm. The algorithm applies the global search techniques inspired by natural evolution (inheritance, mutation, selection and crossover) to find better solutions in an iterative fashion. The best solution for the reassignment is chosen based on fitness value function represented as linear combination of flight delays and passenger walking distance gates in the terminal. Tang et al. (2009) developed a gate reassignment framework for real time flight delays by minimizing space inconsistency and time inconsistency. Space inconsistency occurs when conflicting flights are reassigned to a different gate other than the original gate, and time inconsistency is the difference of the delayed and original arrival times of a flight. Reassignment is accomplished in two phases, those being a preprocessing followed by construction phase. Arrival and departure times as well as all other relevant information are updated in preprocessing phase, and then using the planned assignments, reassignments are made in construction phase.

7.2 Model Development

The integer programming formulation of the reassignment model is given in this section together with an implementation strategy in a zoning context. Note that the number of connecting passengers between all flights is assumed to be known, which our experience has shown is a quantity that may be extracted in real time from an airline's database.

7.2.1 Mathematical Notation

The mathematical notation that will be used throughout this paper is given in this section. Letting $|\mathbf{X}|$ denote the cardinality of an arbitrary set $\mathbf{X}$, note that in the defined sets below $|\mathbf{VF}|=|\mathbf{VD}|=|\mathbf{K}|$ and $|\mathbf{H}|=|\mathbf{D}|$. The addition of *virtual* flights at both the beginning and end of the day and for passengers originating at the airport is necessary to ensure the feasibility of the model.

7.2.1.1 Sets

F =Set of arrival flights with arrival times greater than current time t

D =Set of departure flights with departure times greater than current time t

VF =Set of virtual flights preceding the first arrival of a flight at gate k

VD=Set of virtual flights following the last departure of a flight at gate k

H =Set of virtual flights for passengers originating at the airport

K =Set of gates available for gate reassignment

C =Set of terminal check in counters

$\mathbf{K_C} = \mathbf{K} \cup \mathbf{C}$

$\mathbf{U} = \mathbf{F} \cup \mathbf{VF} \cup \mathbf{VD}$

$\mathbf{U_H} = \mathbf{F} \cup \mathbf{VF} \cup \mathbf{VD} \cup \mathbf{H}$

$\mathbf{U_F} = \mathbf{F} \cup \mathbf{VF}$

$\mathbf{U_D} = \mathbf{F} \cup \mathbf{VD}$

7.2.1.2 Parameters

A_i =Arrival time for flight i, $i \in \mathbf{F}$

D_j =Departure time for flight j, $j \in \mathbf{D}$

A_{ik} =Arrival time of flight i at gate k, $i \in \mathbf{F}$, $k \in \mathbf{K}$

D^s_{jk}=Scheduled departure time of flight i from gate k,$i \in \mathbf{D}$, $k \in \mathbf{K}$

$N_{ii'}$=Number of connecting passengers from flight $i \in \mathbf{F}$ to flight $i' \in \mathbf{F}$, $i \neq i'$

$d_{kk'}$=Distance from gate k to gate k'

M =sufficiently large number (999999)

l =lead time before flight departure for which reassignment does not disrupt passengers

t =Current time in U.S. Central Time

f_i =Duration of flight i, $i \in \mathbf{F}$

Y_{ik} =Binary parameter equal to 1 *iff* flight i was assigned to gate k on previous run

7.2.1.3 Variables

X_{ik} =Binary decision variable equal to 1 *iff* flight i is assigned to gate k, $i \in \mathbf{F}$, $k \in \mathbf{K}$

Z_{ijk}=Binary variable equal to 1 *iff* both flight i and j are assigned to gate k, and flight j immediately follows flight i, $i \in \mathbf{F}$, $j \in \mathbf{D}$, $k \in \mathbf{K}$

7.2.2 Mathematical Model

The arrival (A_i) and departure (D_j) times for all flights are updated throughout the day as flight delays become known. With each updating of these times, the mathematical model is rerun to determine if such causes a conflict at a gate and what optimal reassignment should be made to accommodate such. Note that the mathematical formulation is a binary integer program (BIP), yet as only one or possibly a very limited number of planes will be updated at each evaluation, it will be shown in a latter section of this paper that the program solves in a matter of seconds for full scale models when implemented in a zoning strategy.

$$\mathrm{Min}Z = \sum_{\substack{i\in\mathbf{U}\\ i\neq i'}} \sum_{\substack{i'\in\mathbf{U}\\ i\neq i'}} \sum_{\substack{k\in\mathbf{K}\\ k\neq k'}} \sum_{\substack{k'\in\mathbf{K}\\ k\neq k'}} (Y_{ik}-X_{ik})^2 N_{ii'} d_{kk'} I_{ik}^{(1)} \tag{7.1}$$

$$+ \sum_{\substack{i\in\mathbf{U}\\ i\neq i'}} \sum_{\substack{i'\in\mathbf{U_H}\\ i\neq i'}} \sum_{\substack{k\in\mathbf{K}\\ k\neq k'}} \sum_{\substack{k'\in\mathbf{K_C}\\ k\neq k'}} (Y_{ik}-X_{ik})^2 N_{i'i} d_{k'k} I_{i'k'}^{(2)} \tag{7.2}$$

subject to

$$\sum_k X_{ik} = 1 \qquad \forall i \in \mathbf{U}, k \in \mathbf{K} \tag{7.3}$$

$$\sum_j Z_{ijk} = X_{ik} \qquad \forall i \in \mathbf{U_F}, j \in \mathbf{U_D}, k \in \mathbf{K}, i \neq j \tag{7.4}$$

$$\sum_i Z_{ijk} = X_{jk} \qquad \forall i \in \mathbf{U_F}, j \in \mathbf{U_D}, k \in \mathbf{K}, i \neq j \tag{7.5}$$

$$A_j + (1 - Z_{ijk})M \geq D_i \qquad \forall i \in \mathbf{U_F}, j \in \mathbf{U_D}, k \in \mathbf{K}, i \neq j \tag{7.6}$$

$$X_{ik} = 1 \qquad \forall \mathrm{i} \in \mathbf{VF}, \mathrm{k} \in \mathbf{K} \tag{7.7}$$

$$X_{ik} = 1 \qquad \forall \mathrm{i} \in \mathbf{VD}, \mathrm{k} \in \mathbf{K} \tag{7.8}$$

$$X_{ik}, Y_{ik}, Z_{ijk} = \{0, 1\} \tag{7.9}$$

where

$$I_{ik}^{(1)} = \begin{cases} 1 & \text{if } (A_{ik} - f_i - l) < t \\ 0 & \text{otherwise} \end{cases} \tag{7.10}$$

$$I_{i'k'}^{(2)} = \begin{cases} 1 & \text{if } (A_{i'k} - f_{i'} - l) < t \text{ and } i' \in \mathbf{F} \\ 1 & \text{if } (D_{i'k}^{s} - l) < t \text{ and } i' \in \mathbf{H} \\ 0 & \text{otherwise} \end{cases} \tag{7.11}$$

7.2.2.1 Objective Function

The objective function seeks to minimize the total distance that connecting passengers walk from their arriving gate to a reassigned departing gate and that originating passengers walk from the originally assigned departing gate to the reassigned gate if in either instance the reassigned gate was not known by the passenger prior to receiving their boarding pass for the reassigned flight. Indeed, most airlines print boarding passes for passengers connecting domestically at their originating airport with the gate information printed on the pass for the connecting airport in an effort to help passengers navigate around the connecting airport efficiently. If a gate reassignment occurs after the departing gate at the connecting airport is printed on the boarding pass at the originating airport, however, then passengers have to go through the unpleasant process of finding their connecting gates. Note that the parameter l denotes the lead time prior to departure of the originating flight prior to which reassignment must occur for those passengers to have the correct information on their connecting boarding pass. In a similar fashion, last minute reassignments for passengers originating at the airport in question and that receive their boarding pass at the terminal check-in counter with the wrong gate information must walk from the originally assigned gate to the reassigned gate for the departing flight. This distance, together with that of connecting passengers from their arrival to reassigned gate, is sought to be minimized by this program.

The first part of the objective function given by Eq. (7.1) denotes the cumulative distance walked by connecting passengers arriving on a reassigned flight to the departing gate of their connecting flights. The second part of the objective function given by Eq. (7.2) denotes the cumulative distance walked from the arrival gate of the originating flight for connecting passengers or the originally assigned gate of the reassigned flight for originating passengers to the reassigned gate of the reassigned flight. Note that in both equations, the indicator function only imposes this distance on the objective if the passenger has the wrong gate information printed on their boarding pass due to a reassignment without sufficient lead time l prior to the trip origination.

7.2.2.2 Constraints

The first constraint (Eq. (7.3)) implies that each flight i must be scheduled to gate k. The second and third constraints (Eqns. (7.4,7.5)) expand the decision variables (X_{ik} and X_{jk}) in terms of decision variable (Z_{ijk}) to represent the precedence of flights at gate k. The fourth constraint (Eq. (7.5)) ensures that the assignments are not made on top of each other at a gate, i.e. flight j can only arrive at gate k when the previous flight i has already departed from gate k. The fifth and sixth constraints given by Eqns. (7.6, 7.7) assign virtual flight prior to the first arrival and following last departure at each gate respectively for completeness of the constraint set. Note that the number of passengers on these flights are set to zero and hence do not contribute to the objective.

7.2.3 Zoning Strategy

In many instances, the gates at an airport are restricted to be able to accommodate only certain types of planes. As an example, international flights often must pass through a subset of all possible flights, as do regional jets, etc. In addition, it is most often desirable to make reassignments within the same terminal as which the original assignment was made to avoid extremely long walking distances for customers. In that regard, the implementation of this mathematical program will be to subset of gates corresponding to the type of plane and/or the originally assigned terminal of the delayed aircraft. This subset of gates is said to form a zone in the airport, and hence all possible reassignments will be restricted to this zone.

7.3 Numerical Illustration

A numerical implementation of this mathematical program is given for a snapshot of CO airlines at IAH on February 1, 2010. The distances between gates ($d_{kk'}$) that were used in this example are accurate, yet the number of passengers transferring from one flight to another ($N_{ii'}$) on this day is only reflective of the true values for confidentiality purposes. The original actual assignment of planes to gates on this day was used as a basis for evaluation, upon which a series of hypothesized delays were generated at various times throughout the day. Specific attention is focused on Terminal E of IAH, as this is the busiest terminal in operation by CO airlines, which is denoted as zone 3 in figure (7.1). For computational purposes, two Intel 5450 Quad Core 64bit processors with a core frequency of 3.0GHz that were

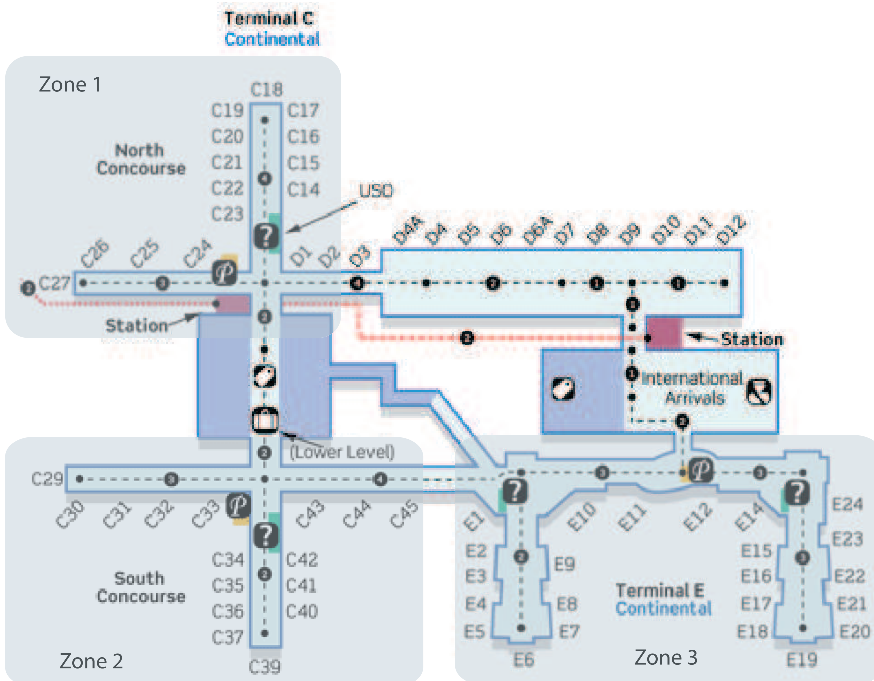


Figure 7.1. Terminal C-North Concourse, Terminal C-South Concourse, and Terminal E Divided into Zone 1, Zone 2, and Zone 3 Respectively

installed at the High Performance Computing Center (HPCC) in the Experimental Sciences Building at Texas Tech University were used in this experiment, and AMPL/CPLEX 11.2 was used to code the program.

A visualization of the original assignment of CO planes to gates in zone 3 of IAH between 17:00 and 22:00 hours is given in figure (7.2). It is hypothesized that at time $t = 17:00$hrs, the set of delays summarized in table 7.2 become known, which is visualized in figure (7.3). An evaluation of the rescheduling BIP given in this paper for these hypothesized delays in zone 3 of IAH required 0.734 seconds of CPU time yielding an optimal objective value of 2046474.5. A summary of the optimal gate reassignments in response to the delays given in figure (7.3) is given in figure

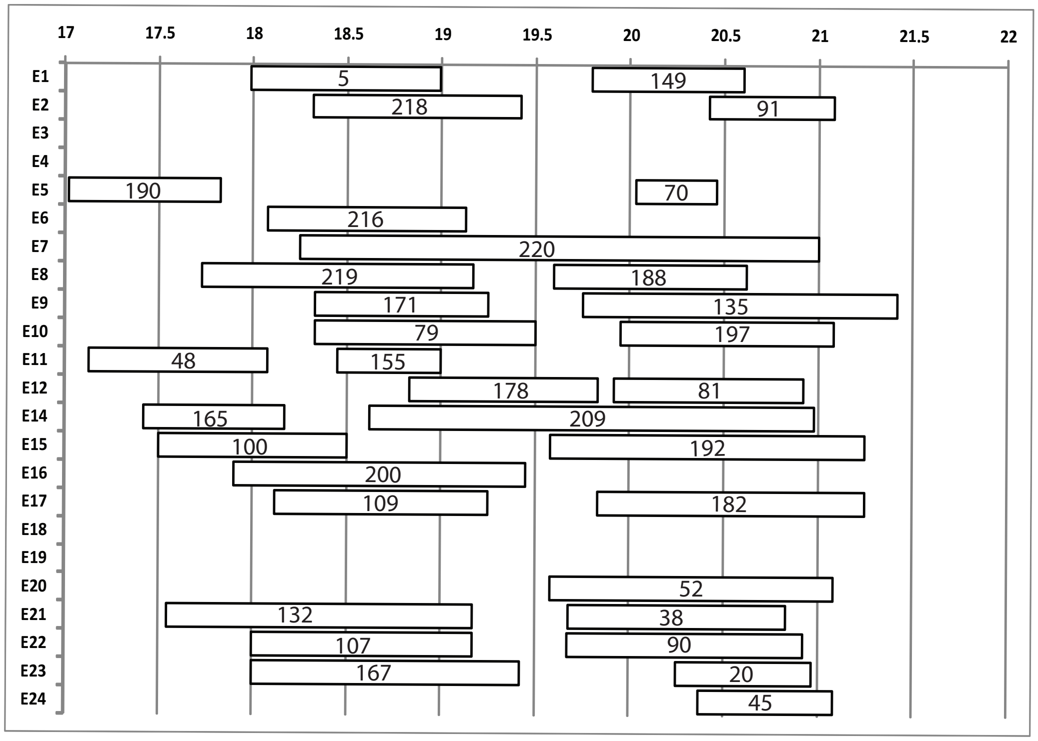


Figure 7.2. Original Gate Schedule of CO Airlines by Tail Number in Terminal E at IAH on Feb 1, 2010

(7.4) and visualized in figure (7.4). In this reassignment, there was no delay propagation beyond first order changes in the schedule due to the sparse utilization of gates by CO airlines at IAH, yet this may occur in other instances.

Table 7.2. Hypothesized Delays of Flights at Time 17:00 hours in Decimal Hours

Tail Number	Original Arrival Time	Delayed Arrival Time	Original Departure Time	Delayed Departure Time	Original Assigned Gate
5	17.99	20.25	18.99	21.25	E1
219	17.73	18.30	19.17	19.74	E8
90	19.67	19.05	20.92	20.30	E22

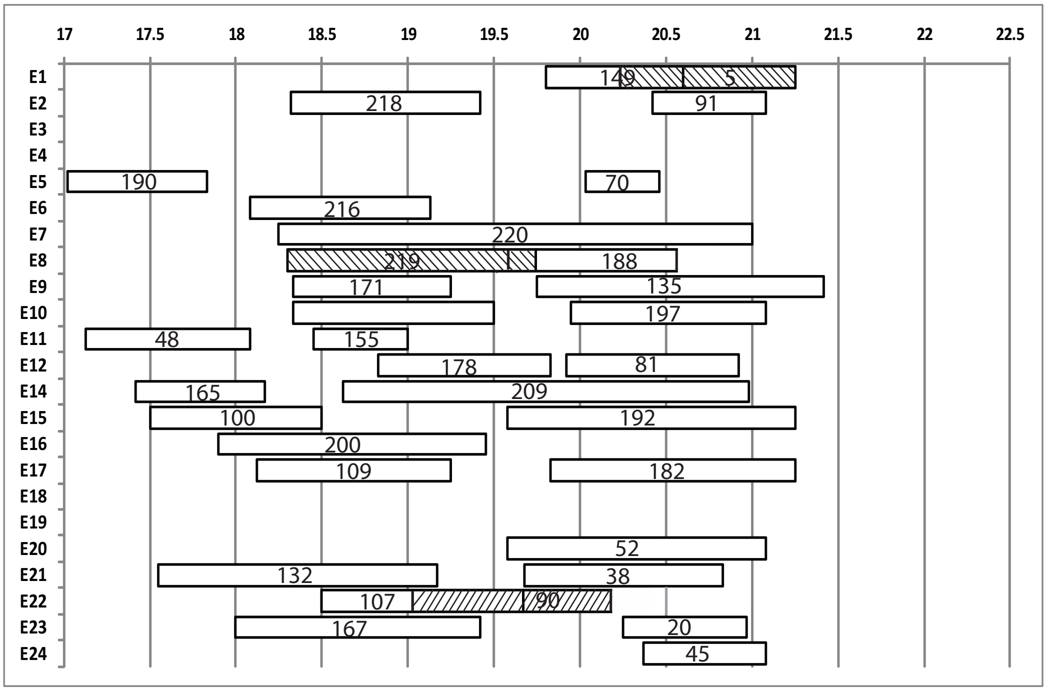


Figure 7.3. Original Gate Schedule with Shaded Conflicting Flights at Time 17:00 hrs

7.4 Acknowledgement

We would like to extend our gratitude to Continental Airlines and Mr. Manolo Centeno, Sr. Manager Operational Analyst and Operational Planning Analyst at Continental Airlines, for making data available along with valuable feedback and suggestions. The authors also acknowledge the High Performance Computing

Table 7.3. Optimal Gate Reassignment Schedule at Time 17:00 hrs

Conflicting Flights	Conflicting Gate	Reassigned Gate
149	E1	E6
5	E1	E1
219	E8	E5
188	E8	E8
107	E22	E4
90	E22	E22

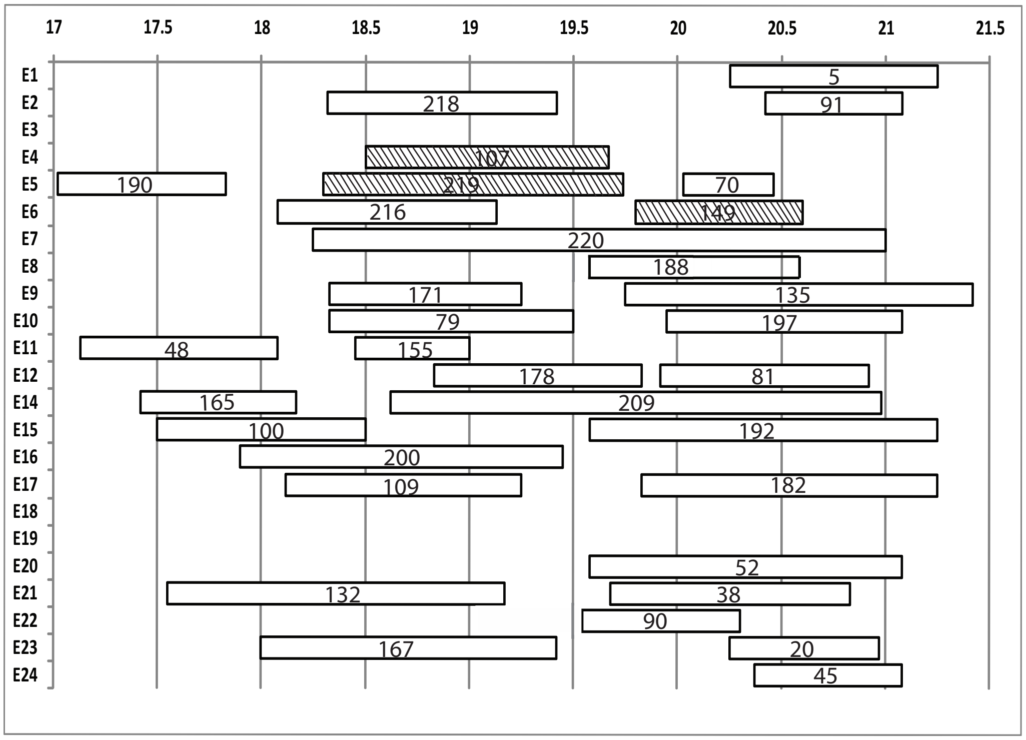


Figure 7.4. Optimal Reassigned Gate Schedule with Shaded Reassigned Flights at Time 17:00 hours

Center (HPCC) at Texas Tech University in Lubbock for providing high performance computing, visualization, database, and grid resources that have contributed to the research results reported in this paper.

CHAPTER 8
DISCUSSION AND CONCLUSION

8.1 Model Discussion

8.1.1 Multicommodity Network Flow Model

In this dissertation, multicommodity gate flow network model is used to find an optimal flight gate assignment. Many researchers have solved the flight gate assignment problem as an integer program (Babic et al., 1984; Mangoubi & Mathaisel, 1985), a quadratic integer program (Obata, 1979; Xu & Bailey, 2001; Ding et al., 2005), a multi-objective mixed integer program (Drexel & Nikulin, 2008) and a simulated approach (Yan et al., 2002), etc. Due to computational complexity in those formulations, it is extremely difficult to solve such problems for large instances. The multicommodity gate flow network model is computationally efficient compared to other procedures. Therefore, an attempt to solve a large scale flight gate assignment model is made in this research with multicommodity gate flow network formulation that groups gates into zones and subzones.

Buffer, represented by Eq. (4.1), plays an important role in solving the model. Buffer is a time allowed for two consecutive flights to share gate p hours apart. If flight j follows flight i consecutively at gate k, then flight j is allowed to share gate k after p hours of flight i's departure. An airline can choose the value of p according to its needs to customize the model accordingly. Low p values may increase congestion at certain gates but increases gate utilization. Therefore, in order to manage the congestion in the gates, p values must be chosen appropriately. High p values limit the number of back-flow arcs (refer to figure 4.1), which can make the model infeasible (refer to section 4.2.3.4).

The connecting passenger cost function is a novel approach for quantifying passenger discomfort or inconvenience caused by longer connecting gate distance. It is a function of time available (or remaining) and inter-gate distance for a passengers that are making a connection. The connecting passenger cost function (refer to section 4.2.3.5) is a three dimensional non-linear penalty cost function for passenger discomfort that discourages the assignment of a gate far away for tight connections.

Flight gates at the George W. Bush Intercontinental Airport (IAH) are not homogeneous, hence available gates cannot accommodate all airplane types. Some gates can be used for all plane sizes, whereas others cannot be used for wide-body aircraft (767,777s) etc. Terminal E is an international terminal at the IAH. International flights arriving at IAH are always scheduled in terminal E due to the availability of customs and immigration facilities. Such operational constraints of wide-body/international flights can be handled by adding a set of constraints as shown in section 5.3.

Assignments of flights in Continental Airlines Inc (CO) at IAH are currently made manually on an ad hoc basic by just following simple assignment rules. Gate managers do not have any scientific tools to assign the flights to the gates (Huda, 2007). Due to unavailability of a scientific decision support system, Continental Airlines Inc is paying a high price in fuel consumption, longer delays, higher connecting passengers cost, etc.

8.1.2 Computational Discussion for Multicommodity Network Flow Model

The state-of-the-art solver (AMPL/CPLEX 11.2) is used to solve the assignment models. The solution methods for solving the multicommodity network flow model for gate assignment used the Simplex Algorithm and the Branch and Bound Algorithm. Appendix “A” and Appendix “B” exhibit the model and data for zone assignment(Level I).The CPLEX solver used 382800 MIP simplex iterations on 49 branch and bound nodes to solve a problem that has 767499 variables and 1221990 constraints. It took 36687.8 sec (10.19 hrs) for Quad Core, 64bit 3 GHz processor with 16GB of RAM to make a zone assignments for 226 flights. Flights assigned to zones are then solved again for sub-zone assignments. After sub-zone assignments are made, gate assignments to flights are made that are assigned to sub-zones. The code for gate assignment for sub-zone 1 is given in Appendix “C” (model) and Appendix “D” (data). It took the total computational time of 3.5 days (approx) to find the complete assignment for 226 flights.

8.1.3 Flight Gate Reassignment Model

There are many uncertainties causing flight delays that arise in actual airline operations which are not planned during the flight gate assignment process. The main causes of delays are weather, tardy crews, mechanical breakdown of aircraft, airport security, tardy passengers, airport congestion, airspace congestions, ground delay program, etc. There are many other causes that can potentially disturb the normal schedule of the flights. If the normal schedule of the flights is disturbed, then flights may conflict at gates, which would require the reassignment of the flights to a different gate.

Due to the recent trend of increasing demand in air-transportation services, flight reassignment has gained much popularity in recent years. Many researchers have shown their interest in solving such problems (refer section 2.2). Flight gate reassignment can be very challenging for gate managers, if flights are delayed specially on peak time or busy days to maintain smooth airport operations. It is extremely difficult to predict when the flights will be delayed. Therefore, whenever flights are delayed and conflict with other flights, they have to be reassigned immediately. Therefore, real-time solution based algorithms/heuristics are extremely important. In this dissertation, we proposed a binary integer mathematical programming procedure to solve such problems quickly and can be utilized to make real-time reassignments.

In this dissertation, virtual flights are used to precede flights at the beginning of the day and follow flights at the end of the day. These virtual flights are assigned to gates in such a way that they will not conflict with the first flights or the last flights. The objective of flight gate reassignment is to minimize the number of passengers disrupted because of the gate changes. Originating passengers at IAH also can be disrupted due to a last minute change of the gates. In order to reflect this phenomenon in our model, a set of virtual flights is visualized that brings an originating passenger into IAH.

A zoning strategy similar to the flight gate assignment model is used in the reassignment model. The zoning strategy helps the reassignment model in two ways: 1) It helps to reduce the computational complexity by reducing the size of the problem, and 2) It reassigns flights within the zones reducing the connecting gate distance for the connecting passengers.

The reassignment model looks for all the inbound flights that have not landed at IAH for a particular reassignment day (February 01, 2010). If any potential conflicts are expected due to continuous arrival/departure time updates, the flight reassignment will take place immediately with an execution of the reassignment model. For smooth flight operation, the reassignment must occur before the conflicting flight lands at IAH. Therefore, this model is also called a proactive flight gate reassignment model. As the day progresses, the number of flights that have not landed becomes fewer allowing the reassignment model to run even quicker, if gate conflicts are expected.

8.1.3.1 Computational Discussion for Flight Gate Reassignment Model

The state-of-the-art solver (AMPL/CPLEX 11.2) is once again used to solve the flight gate assignment models. It used Simplex Iterations to solve the binary integer programming problem for the gate reassignment model. In a numerical illustration, (section 7.3), there are 6 flights conflicting at different gates (refer to table 7.3). These flight conflicts are caused due to hypothesized gate delays based on original assignments of Continental Airlines at Terminal E of Intercontinental Airport at 17:00 hrs on February 01, 2010. When solved, it took CPLEX 0.734 seconds to complete the solution with 407 MIP simplex iterations. The solver only took a fraction of seconds to make a reassignment of the conflicting flights. The codes for flight gate reassignment model are given in Appendix “G” and Appendix “H”.

8.2 Conclusion

The emphasis of this dissertation is to develop a decision support tool that can assist airport gate managers in assigning and reassigning flight gates. A multicommodity gate flow network model is proposed for flight gate assignments, and a binary integer programming model is proposed for flight gate reassignments.

The multicommodity gate flow network model has some important components. The allowance of buffer for two consecutive flights to share a gate with p hours apart helps the model to lower the congestion in the gates. Connecting passenger cost function is used to quantify a passenger discomfort or inconvenience caused by longer connecting gate distance for remaining connecting time. In this dissertation, it is shown that a multicommodity network formulation is a better model to solve the flight gate assignment problems, minimizing taxi fuel-burn cost and connecting passenger cost. Heuristic application of the multicommodity gate flow network model by grouping gates into zones and subzones as demonstrated in figure 4.4. The model took approximately 3.5 days to find the optimal flight gate assignment for 226 flights.

When connecting passenger cost is compared between the un-optimized and optimized gate assignments (without wide-body/international flight constraints), the connecting passenger cost is reduced by 94.14%, whereas, taxi fuel burn is reduced by 2.54%. Similarly, when connecting passenger cost is compared between the un-optimized and optimized gate assignments with wide-body/international flight constraints, the connecting passenger cost is reduced by 97.9% and taxi fuel-burn cost is increased by 3.6%. This means that huge passenger convenience is achieved through the multicommodity gate flow network model.

The flight gate reassignment model reassigns flights if there are any conflicts assessed due to changes in arrival/departure times. The changes in the gate information due to reassignment of flights can cause passenger disruption. Therefore, the main objective of the flight gate reassignment model is to minimize total distance walked by disrupted passenger caused by gate changes due to conflicting flights. The procedure of grouping gates into zones (refer to figure 7.1) and reassigning gates within the zones allows the model to quickly solve large problems. It only took 0.747 sec to solve a binary integer program for the flight gate reassignment model for the numerical illustration presented in section 7.3.

8.3 Future Work

Further research can make this work even more valuable. It would be interesting to see the following research in the optimization of flight gate assignment area:

1. The results from multicommodity gate flow network model formulation with an inclusion of minimization of crew scheduling cost in addition to taxiing fuel-burn cost and connecting passenger cost would be an interesting to see.

2. A multi-objective formulation to see how flight gate assignments will respond to crew scheduling in terms of scalability of different costs (fuel-burn, connecting passengers, crew scheduling cost etc).

3. The multicommodity gate flow network model and flight-gate reassignment model are decision support tools for gate managers who are responsible for making assignments/reassignments to the flights. Gate managers may not know much about network flow modeling or integer programming. Therefore, it would be a good idea to develop Graphical User Interfaces (GUIs) that link to Continental Airline's database to make CPLEX work seamlessly to make necessary flight gate assignments and reassignments.

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APPENDIX A: AMPL/CPLEX MODEL FOR MULTICOMMODITY GATE FLOW NETWORK MODEL FOR ZONE(LEVEL I)/SUBZONE (LEVEL II) ASSIGNMENT)

The following code denotes the AMPL/CPLEX model file used for multicommodity gate flow network model for zone assignment (Level I) used in Chapter 4. The model for subzone assignments (Level II) are not shown. Subzone assignment uses the same model as shown below with very little adaption to reflect zones to subzones.

```
####################################################
# Multicommodity data for Flight Gate Assignment   #
# Written by: Binod Maharjan            #
# Department of Industrial Engineering        #
# Texas Tech University               #
####################################################
#Zone Assignment
#Defining a set
set OrigZone;
set ProdZone;
set ArrivalFlights;
set DepartFlights;
set Terminal;
set Zone{ProdZone};
#Defining a Parameters
param ArrivalTimes{ArrivalFlights};
param DepartTimes{DepartFlights};
param fb{ArrivalFlights}; #fuel burn rate in kg/s
param d1{ProdZone}; #Expected arrival runway length  in ft.
param d2{ProdZone}; #Expected departure runway length in ft.
param N{ArrivalFlights, DepartFlights}; #Connecting passenger
param ID{ProdZone, ProdZone}; #Inter-zone/Inter-gate distance
param RT{ArrivalFlights, DepartFlights}; # Time Remaining for
 making any connection
param fc; #Fuel cost
param fs; #Expected flight runway speed

set abc := { i in ArrivalFlights, j in ArrivalFlights, k in ProdZone,
```

```
 kp in ProdZone: i<>j and (ArrivalTimes[i]+0.25) < DepartTimes[j] and
 DepartTimes[j] < (ArrivalTimes[i] + 1) and k<>kp};

#Parameters for connecting passengers objective function
param NC{i in ArrivalFlights, ip in ArrivalFlights};
param NC1{k in ProdZone, kp in ProdZone} = sqrt(ID[k,kp]);

#parameter to calculate (d1[k]+d2[k]) where d1[k] = E[arrival runway length]
and d2[k]= E[departure runway length]
param fbd{k in ProdZone} = d1[k]+d2[k];
# (fuel cost)/(flight runway speed) for fuel burn objective
param fp = 2*fc/fs; #Airplanes have 2 jet engines

#Indicator function will be equal to 0 if the following condition is not meet.
#Airplane in the same gate can only follow if Aj>Di by 30 min.
param In{j in DepartFlights, i in ArrivalFlights} = if
 ArrivalTimes[i] > DepartTimes[j]+0.5 then 1 else 0;

#Declaration of Variables
var X{OrigZone, ArrivalFlights, ProdZone} binary;
var X2{OrigZone, Terminal, ProdZone} binary;
var X3{DepartFlights, Terminal, ProdZone} binary;
var X4{DepartFlights, ArrivalFlights, ProdZone} binary;
var X5{ArrivalFlights, ArrivalFlights, ProdZone} binary;
var Z{ArrivalFlights, ArrivalFlights, ProdZone, ProdZone}>=0;

#Objective Function
minimize Total_cost:
sum{(i,ip,k,kp) in abc}NC[i,ip]*NC1[k,kp]*Z[i,ip,k,kp] +
 sum{s in OrigZone, i in ArrivalFlights, k in ProdZone}
 ((fp*fb[i]*fbd[k])*(X[s,i,k]+sum{j in DepartFlights} X4[j,i,k]));

#Constraints
subject to FlowIn{s in OrigZone, k in ProdZone, t in Terminal}:
sum{j in ArrivalFlights} X[s,j,k] + X2[s,t,k]<=card(Zone[k]);

subject to ArrivalCs{s in OrigZone, i in ArrivalFlights, k in ProdZone}:
X[s,i,k] + sum{j in DepartFlights:i<>j} In[j,i]*X4[j,i,k]=X5[i,i,k];

subject to DepartureCs{j in DepartFlights, t in Terminal, k in ProdZone}:
```

```
sum{i in ArrivalFlights:i<>j} In[j,i]*X4[j,i,k]+X3[j,t,k]=X5[j,j,k];

subject to FlowOut{s in OrigZone, t in Terminal, k in ProdZone}:
sum{j in DepartFlights} X3[j,t,k] + X2[s,t,k]<=card(Zone[k]);

subject to cons2{i in ArrivalFlights}:
sum{k in ProdZone} X5[i,i,k]=1;
#Following constraints are added for linearizing the objective function
subject to lin1{i in ArrivalFlights, ip in ArrivalFlights, k in ProdZone,
 kp in ProdZone: i<>ip and k<>kp}:
Z[i,ip,k,kp]-X5[i,i,k]<=0;

subject to lin2{i in ArrivalFlights, ip in ArrivalFlights, k in ProdZone,
 kp in ProdZone: i<>ip and k<>kp}:
Z[i,ip,k,kp]-X5[ip,ip,kp]<=0;

subject to lin3{i in ArrivalFlights, ip in ArrivalFlights, k in ProdZone,
 kp in ProdZone: i<>ip and k<>kp}:
X5[i,i,k]+X5[ip,ip,kp]-Z[i,ip,k,kp]<=1;

subject to lin4{i in ArrivalFlights, ip in ArrivalFlights, k in ProdZone,
 kp in ProdZone: i<>ip and k<>kp}:
X5[i,i,k]+X5[ip,ip,kp]+Z[i,ip,k,kp]>=0;
```

APPENDIX B: AMPL/CPLEX DATA FOR MULTICOMMODITY GATE FLOW NETWORK MODEL FOR ZONE/SUBZONE ASSIGNMENT

The following code denotes the AMPL/CPLEX data file used for multicommodity gate flow network model for zone /subzone assignment used in Chapter 4. The data for subzone assignments (Level II) are not shown. Subzone assignment uses the same data as shown below with very little adaption to reflect zones to subzones. The complete data table has many columns and rows, therefore only partial data are shown below.

```
#####################################################
# Multicommodity data for Flight Gate Assignment    #
# Written by: Binod Maharjan                        #
# Department of Industrial Engineering              #
# Texas Tech University                             #
#####################################################

#In this data set, the zone1 has 8 gates and zone 2 has 7 gates
set OrigZone:= S;
set ProdZone:=Zone1 Zone2 Zone3;
set ArrivalFlights:=1 .. 226;
set DepartFlights:= 1 .. 226;
set Terminal:= T;
set Zone[Zone1]:=C14 C15  C16 C17 C18 C19 C20 C21 C22 C23 C24 C25 C26 C27;
set Zone[Zone2]:=C29 C30 C31 C32 C33 C34 C35 C36 C37 C38 C39 C40 C41 C42
C43 C44 C45;
set Zone[Zone3]:=E1 E2 E3 E4 E5 E6 E7 E8 E9 E10 E11 E12 E14 E15 E16 E17
E18 E19 E20 E21 E22 E23 E24;

#Expected Zone - Arrival Runway distance in feet
# C21 as median gate for Zone1
# C36 as median gate for Zone2
# E12 as median gate for Zone3
param d1:=
Zone1 12517.46
Zone2 15598.49
Zone3 11529.04;
#Expected Zone - Departure Runway distance in feet

param d2:=
```

```
Zone1 14096.18
Zone2 12002.93
Zone3 13534.06;

param ArrivalTimes:=
1 13.83
2 13.42
3 22.27
.   .
.   .
.   .
224 16.58
225 7.75
226 9.50;

param DepartTimes:=
1 16.42
2 15.67
3 23.27
.   .
.   .
.   .
224 18.25
225 8.83
226 10.42;

#NC = Nii*(2-(DepartTime[j]-ArrivalTimes[i]))^2
param NC:1  2   3   ... 226:=
        1   0   0   ... 0
        2   0   0   ... 0
        3   0   0   ... 0
        .   .   .   ... .
        .   .   .   ... .
        .   .   .   ... .
        226 .   .   ... 0;

#Inter-zonal distance (ID) in feet
param ID: Zone1 Zone2 Zone3:=
Zone1 0 1417.5 2397.5
Zone2 1417.5 0 1697.5
```

```
Zone3 2397.5 1697.5 0;

#Fuel Burn rate for a flight(kg/sec)
param fb:=
1 0.313
2 0.205
3 0.114
.   .
.   .
.   .
226 0.113;
```

APPENDIX C: AMPL/CPLEX MODEL FOR MULTICOMMODITY GATE FLOW NETWORK MODEL FOR GATE ASSIGNMENT

The following code denotes the AMPL/CPLEX model file used for multicommodity gate flow network model for gate assignment used in Chapter 4.

```
#####################################################
# Multicommodity Model for Flight Gate Assignment    #
# Written by: Binod Maharjan              #
# Department of Industrial Engineering            #
# Texas Tech University                  #
#####################################################
#Gate Assignment
#Defining a set
set OrigGates;
set ProdGates;
set ArrivalFlights;
set DepartFlights;
set Terminal;
set All_ProdGates;
set All_ArrivalFlights;
set All_DepartFlights;

#Defining Parameters
param ArrivalTimes{All_ArrivalFlights};
param DepartTimes{All_DepartFlights};
param fb{ArrivalFlights};
param d1{ProdGates};
param d2{ProdGates};
param Cost{ProdGates};  #Fixed cost for a gate
param N{All_ArrivalFlights, All_DepartFlights};
param ID{All_ProdGates, All_ProdGates}; #Inter-gate distance
param RT{All_ArrivalFlights, All_DepartFlights}; # Time Remaining for
    making any connection
param fc; #Fuel cost
param fs; #Expected flight runway speed

set abc := {i in ArrivalFlights, j in All_ArrivalFlights, k in ProdGates,
 kp in All_ProdGates: i<>j and (ArrivalTimes[i]+0.25) < DepartTimes[j] and
 DepartTimes[j] < (ArrivalTimes[i] + 1) and k<>kp};
```

```
#Parameters for connecting passengers objective function
param NC{i in All_ArrivalFlights, ip in All_ArrivalFlights};
param NC1{k in All_ProdGates, kp in All_ProdGates} = sqrt(ID[k,kp]);

#parameter to calculate (d1[k]+d2[k]) where d1[k] = E[arrival runway length]
    and d2[k]= E[departure runway length]
param fbd{k in ProdGates} = d1[k]+d2[k];

# (fuel cost)/(flight runway speed) for fuel burn objective
param fp = 2*fc/fs; #Airplanes have 2 jet engines

param In{j in DepartFlights, i in ArrivalFlights} = if
    ArrivalTimes[i] > DepartTimes[j]+0.5 then 1 else 0;

#Declaration of Variables
var X{OrigGates, ArrivalFlights, ProdGates} binary;
var X2{OrigGates, Terminal, ProdGates} binary;
var X3{DepartFlights, Terminal, ProdGates} binary;
var X4{DepartFlights, ArrivalFlights, ProdGates} binary;
var X5{ArrivalFlights, ArrivalFlights, ProdGates} binary;
var Z{ArrivalFlights, All_ArrivalFlights, ProdGates, All_ProdGates}>=0;# binary;

#Objective Function
minimize Total_cost:
sum{(i,ip,k,kp) in abc} NC[i,ip]*NC1[k,kp]*Z[i,ip,k,kp] +
 sum{s in OrigGates, i in ArrivalFlights, k in ProdGates}
 ((Cost[k] + fp*fb[i]*fbd[k])*(X[s,i,k]+sum{j in DepartFlights} X4[j,i,k]));


#Constraints
subject to FlowIn{s in OrigGates, k in ProdGates, t in Terminal}:
sum{j in ArrivalFlights} X[s,j,k] + X2[s,t,k]=1;

subject to ArrivalCs{s in OrigGates, i in ArrivalFlights, k in ProdGates}:
X[s,i,k] + sum{j in DepartFlights:i<>j} In[j,i]*X4[j,i,k] =X5[i,i,k];

subject to DepartureCs{j in DepartFlights, t in Terminal, k in ProdGates}:
sum{i in ArrivalFlights:i<>j} In[j,i]*X4[j,i,k]+X3[j,t,k]=X5[j,j,k];
```

```
subject to FlowOut{s in OrigGates, t in Terminal, k in ProdGates}:
sum{j in DepartFlights} X3[j,t,k] + X2[s,t,k]=1;

subject to cons2{i in ArrivalFlights}:
sum{k in ProdGates} X5[i,i,k]=1;

subject to lin1{i in ArrivalFlights, ip in ArrivalFlights, k in ProdGates,
    kp in ProdGates: i<>ip and k<>kp}:
Z[i,ip,k,kp]-X5[i,i,k]<=0;

subject to lin2{i in ArrivalFlights, ip in ArrivalFlights, k in ProdGates,
    kp in ProdGates: i<>ip and k<>kp}:
Z[i,ip,k,kp]-X5[ip,ip,kp]<=0;

subject to lin3{i in ArrivalFlights, ip in ArrivalFlights, k in ProdGates,
    kp in ProdGates: i<>ip and k<>kp}:
X5[i,i,k]+X5[ip,ip,kp]-Z[i,ip,k,kp]<=1;

subject to lin4{i in ArrivalFlights, ip in ArrivalFlights, k in ProdGates,
    kp in ProdGates: i<>ip and k<>kp}:
X5[i,i,k]+X5[ip,ip,kp]+Z[i,ip,k,kp]>=0;
```

APPENDIX D: AMPL/CPLEX DATA FOR MULTICOMMODITY GATE FLOW NETWORK MODEL FOR GATE ASSIGNMENT

The following code denotes the AMPL/CPLEX data file used for multicommodity gate flow network model for gate assignment used in Chapter 4. The following code is only for gate assignment for subzone 1 that consists of gates C14 - C23. The data for other subzones are not shown. The complete data table has many columns and rows, therefore only partial data are shown below.

```
####################################################
# Multicommodity data for Flight Gate Assignment    #
# Written by: Binod Maharjan                        #
# Department of Industrial Engineering              #
# Texas Tech University                             #
####################################################
set OrigGates:= S;
set ProdGates:=C14 C15 C16 C17 C18 C19 C20 C21 C22 C23;
set ArrivalFlights:=15 32 37 39 42 46 49 50 55 68 77 78 80 82 83 85 86 92
93 105 111 114 115 116 119  123 125 138 147 158 164 165  196 201 204 207
209 212 221 223 226;
set DepartFlights:=15 32 37 39 42 46 49 50 55 68 77 78 80 82 83 85 86 92
93 105 111 114 115 116 119  123 125 138 147 158 164 165  196 201 204 207
209 212 221 223 226;
set Terminal:= T;
set All_ProdGates:= C14 C15 C16 C17 C18 C19 C20 C21 C22 C23 C24 C25 C26
C27 C29 C30 C31 C32 C33 C34 C35 C36 C37 C38 C39  C40 C41 C42 C43 C44 C45
E1  E2 E3 E4 E5 E6 E7 E8 E9 E10 E11 E12 E14 E15 E16 E17 E18 E19 E20 E21
E22 E23 E24;
set All_ArrivalFlights:=1 ... 226;
set All_DepartFlights:=1 ... 226;
#cost of the fuel in $/kg (Airnav Source: March 31, 2010 price $4.94/gallon
    (Full-Service at IAH), 1 gallon = 3.78 liters, density = 0.81 kg /liter)
param fc:=1.614;
#aircraft runway speed ft/sec
param fs:= 42.25; #42.25ft/sec = 25 knots

param Cost:=
C14 2450
C15 2450
C16 2450
```

```
C17 2450
C18 2450
C19 2450
C20 2450
C21 2450
C22 2450
C23 2450;

#Expected Gate- Arrival Runway distance in feet
param d1:=
C14 12804.64
C15 12664.18
C16 12521.34
C17 12395.92
C18 12135.93
C19 12119.13
C20 12361.59
C21 12517.46
C22 12689.83
C23 12788.03;
#Expected Gate- Departure Runway distance in feet
param d2:=
C14 15090.08
C15 14850.09
C16 14771.65
C17 14559.48
C18 14109.85
C19 13826.75
C20 13929.82
C21 14096.18
C22 14203.66
C23 14338.17;

param ArrivalTimes:=
1 13.83
2 13.42
3 22.27
.   .
.   .
.   .
```

```
224 16.58
225 7.75
226 9.50;
param DepartTimes:=
1 16.42
2 15.67
3 23.27
.   .
.   .
.   .
224 18.25
225 8.83
226 10.42;

#NC = Nii*(2-(DepartTime[j]-ArrivalTimes[i]))^2
param NC:1  2   3   ... 226:=
        1   0   0   ... 0
        2   0   0   ... 0
        3   0   0   ... 0
        .   .   .   ... .
        .   .   .   ... .
        .   .   .   ... .
        226 .   .   ... 0;
#Inter-gate distance (ID) in feet
param ID: C14   C15 C16 ... E24:=
C14    0    105  175 ... 2653
C15    105  0    105  ... 2723
C16    175  105  0    ... 2793
    .       .    .    .    ... .
    .       .    .    .    ... .
    .       .    .    .    ... .
    E24   2653 2723 2793 ... 0;
#Fuel Burn rate for a flight(kg/sec)
param fb:=
1 0.313
2 0.205
3 0.114
.   .
.   .
.   .
```

```
226 0.113;
```

APPENDIX E: AMPL/CPLEX MODEL FOR MULTICOMMODITY GATE FLOW NETWORK MODEL FOR GATE ASSIGNMENT WITH WIDE-BODY/INTERNATIONAL FLIGHT CONSTRAINTS AT TERMINAL E

The following codes denotes the AMPL/CPLEX model used for Multicommodity Gate Flow Network Model for gate assignment with wide-body/International flight constraints at Terminal E. The code for zone and subzone assignment uses the same model with little adaptation to reflect zones instead of gates. The modified code of gate assignment for Terminal E subzones are given below.

```
####################################################
# Multicommodity Model for Flight Gate Assignment    #
# for Terminal E with wide-body/International flight #
# constraints                                        #
# Written by: Binod Maharjan                         #
# Department of Industrial Engineering               #
# Texas Tech University                              #
####################################################
#Gate Assignment
#Defining sets
set OrigGates;
set ProdGates;
set ArrivalFlights;
set DepartFlights;
set Terminal;
# added lines of codes to comprehend connecting passenger#
set All_ProdGates;
set All_ArrivalFlights;
set All_DepartFlights;
#added lines of codes finish#
# added lines of code for international#
set ProdGatesInt;
set TermESubzoneArrvflights;
set TermESubzoneDeptflights;
set ArrvFlights = ArrivalFlights union TermESubzoneArrvflights;
set DeptFlights = DepartFlights union TermESubzoneDeptflights;

#sets for flight types
set 737_300_flights;
set 737_500_flights;
```

```
set 737_700_flights;
set 737_800_flights;
set 737_900_flights;
set 757_300_flights;
set 757_X_flights;
set 767_200_flights;
set 767_400_flights;
set 777_flights;
set 737_only_gates;
set all_purpose_gates;
set 737_757_only_gates;
set 737_300_200gates;
set widebodygates;
set 767_777_flights:=767_200_flights union 767_400_flights union 777_flights;
set 737_flights:=737_300_flights union 737_500_flights union 737_700_flights
    union 737_800_flights union 737_900_flights;
set 737_termE:= 737_flights inter TermESubzoneArrvflights;
set 757_flights:=757_300_flights union 757_X_flights;
set 757_termE:=757_flights inter TermESubzoneArrvflights;
set 767_777_termE:=767_777_flights inter TermESubzoneArrvflights;
set 737_300_200termE:= 737_300_flights inter TermESubzoneArrvflights;
set 737_gates:=737_only_gates union all_purpose_gates union 737_757_only_gates;
set 757_gates:= all_purpose_gates union 737_757_only_gates;
#defining parameters;
param ArrivalTimes{All_ArrivalFlights};
param DepartTimes{All_DepartFlights};
param fb{ArrvFlights};
param d1{ProdGates};
param d2{ProdGates};
param Cost{ProdGates};  #Fixed cost for a gate
param N{All_ArrivalFlights, All_DepartFlights};
#param C{All_ProdGates, All_ProdGates};
param ID{All_ProdGates, All_ProdGates}; #Inter-gate distance
param RT{All_ArrivalFlights, All_DepartFlights}; # Time Remaining for making
    connection
param fc; #Fuel cost
param fs; #Expected flight runway speed

set abc := {i in ArrvFlights, j in All_ArrivalFlights, k in ProdGates,
    kp in All_ProdGates: i<>j and (ArrivalTimes[i]+0.25) < DepartTimes[j]
```

```
    and DepartTimes[j] < (ArrivalTimes[i] + 1) and k<>kp};

#Parameters for connecting passengers objective function
param NC{i in All_ArrivalFlights, ip in All_ArrivalFlights};
param NC1{k in All_ProdGates, kp in All_ProdGates} = sqrt(ID[k,kp]);

#parameter to calculate (d1[k]+d2[k]) where d1[k] = E[arrival runway length]
    and d2[k]= E[departure runway length]
param fbd{k in ProdGates} = d1[k]+d2[k];

# (fuel cost)/(flight runway speed) for fuel burn objective
param fp = 2*fc/fs; #Airplanes have 2 jet engines

param In{j in DeptFlights, i in ArrvFlights} = if
    ArrivalTimes[i] > DepartTimes[j]+0.75 then 1 else 0;

#Declaration of Variables
var X{OrigGates, ArrvFlights, ProdGates} binary;
var X2{OrigGates, Terminal, ProdGates} binary;
var X3{DeptFlights, Terminal, ProdGates} binary;
var X4{DeptFlights, ArrvFlights, ProdGates} binary;
var X5{ArrvFlights, ArrvFlights, ProdGates} binary;
var Z{ArrvFlights, All_ArrivalFlights, ProdGates, All_ProdGates}>=0;# binary;

#Objective Function
minimize Total_cost:
sum{(i,ip,k,kp) in abc} NC[i,ip]*NC1[k,kp]*Z[i,ip,k,kp] +
    sum{s in OrigGates, i in ArrvFlights, k in ProdGates}
    ((Cost[k] + fp*fb[i]*fbd[k])*(X[s,i,k]+sum{j in DeptFlights} X4[j,i,k]));

#Constraints
subject to FlowIn{s in OrigGates, k in ProdGates, t in Terminal}:
sum{j in ArrvFlights} X[s,j,k] + X2[s,t,k]=1;

subject to ArrivalCs{s in OrigGates, i in ArrvFlights, k in ProdGates}:
X[s,i,k] + sum{j in DeptFlights:i<>j} In[j,i]*X4[j,i,k] =X5[i,i,k];

subject to DepartureCs{j in DeptFlights, t in Terminal, k in ProdGates}:
sum{i in ArrvFlights:i<>j} In[j,i]*X4[j,i,k]+X3[j,t,k]=X5[j,j,k];
```

```
subject to FlowOut{s in OrigGates, t in Terminal, k in ProdGates}:
sum{j in DeptFlights} X3[j,t,k] + X2[s,t,k]=1;

subject to cons2{i in ArrvFlights}:
sum{k in ProdGates} X5[i,i,k]=1;

subject to lin1{i in ArrvFlights, ip in ArrvFlights, k in ProdGates,
    kp in ProdGates: i<>ip and k<>kp}:
Z[i,ip,k,kp]-X5[i,i,k]<=0;

subject to lin2{i in ArrvFlights, ip in ArrvFlights, k in ProdGates,
    kp in ProdGates: i<>ip and k<>kp}:
Z[i,ip,k,kp]-X5[ip,ip,kp]<=0;

subject to lin3{i in ArrvFlights, ip in ArrvFlights, k in ProdGates,
    kp in ProdGates: i<>ip and k<>kp}:
X5[i,i,k]+X5[ip,ip,kp]-Z[i,ip,k,kp]<=1;

subject to lin4{i in ArrvFlights, ip in ArrvFlights, k in ProdGates,
    kp in ProdGates: i<>ip and k<>kp}:
X5[i,i,k]+X5[ip,ip,kp]+Z[i,ip,k,kp]>=0;

subject to 737cons{i in 737_termE}:
sum{k in 737_gates} X5[i,i,k]=1;

subject to 757cons{i in 757_termE}:
sum{k in 757_gates} X5[i,i,k]=1;

subject to 767_777cons{i in 767_777_termE}:
sum{k in widebodygates} X5[i,i,k]=1;

subject to 737_300_200cons{i in 737_300_200termE}:
sum{k in 737_300_200gates} X5[i,i,k]<=1;
```

APPENDIX F: AMPL/CPLEX DATA FOR MULTICOMMODITY GATE FLOW NETWORK MODEL FOR GATE ASSIGNMENT WITH WIDE-BODY/INTERNATIONAL FLIGHT CONSTRAINTS AT TERMINAL E

The following codes denotes the AMPL/CPLEX data used for Multicommodity Gate Flow Network Model for Gate Assignment with wide-body/International flight constraints for subzone 6 that consists of gates E1-E9. The data for other subzones for Terminal E are not shown. The complete data table has many columns and rows, therefore only partial data are shown below.

```
####################################################
# Multicommodity Data for Flight Gate Assignment     #
# for Terminal E with wide-body/International flight #
# constraints                                        #
# Written by: Binod Maharjan                         #
# Department of Industrial Engineering               #
# Texas Tech University                              #
####################################################
set OrigGates:= S;
set ProdGates:=E1 E2 E3 E4 E5 E6 E7 E8 E9;
set ProdGatesInt:=E1 E2 E3 E4 E5 E6 E7 E8 E9;
set TermESubzoneArrvflights:=96 100 106 110 121 149 165 220 224;
set TermESubzoneDeptflights:=96 100 106 110 121 149 165 220 224;

# ArrivalFlights listed as set below must be flights assigned to subzone6
in the prior subzone assignment without international flights
set ArrivalFlights:=157;
set DepartFlights:=157;
set Terminal:= T;

set All_ProdGates:= C14 C15 C16 C17 C18 C19 C20 C21 C22 C23 C24 C25 C26
C27 C29 C30 C31 C32 C33 C34 C35 C36 C37 C39 C40  C41 C42 C43 C44 C45 E1
E2  E3 E4 E5 E6 E7 E8 E9 E10 E11 E12 E14 E15 E16 E17 E18 E19 E20 E21 E22
E23 E24;

set All_ArrivalFlights:=1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
20 21 22 23 24  25 26 27 28 29 30 31  32 33 34 35 36 37 38 39 40 41 42 43
44 45 46 47 48 49 50 51 52 53  54 55 56 57 58 59 60 61 62 63 64 65 66 67
68 69  70 71 72 73 74 75 76 77 78 79 80 81 82 83  84 85 86 87 88 89 90 91
92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107  108 109 110 111
```

```
112 113  114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129
130 131 132 133 134 135 136 137 138 139 140 141 142 143  144 145 146 147
148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165
166 167 168 169 170 171 172 173  174 175 176 177 178 179 180  181 182 183
184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201
202 203  204 205 206 207 208 209 210 211 212 213 214 215 216 217  218 219
220 221 222 223 224 225 226;

set All_DepartFlights:=1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
21 22 23 24  25 26 27 28 29 30 31  32 33 34 35 36 37 38 39 40 41 42 43 44
45 46 47 48 49 50 51 52 53  54 55 56 57 58 59 60 61 62 63 64 65 66 67 68
69  70 71 72 73 74 75 76 77 78 79 80 81 82 83  84 85 86 87 88 89 90 91 92
93 94 95 96 97 98 99 100 101 102 103 104 105 106 107  108 109 110 111 112
113  114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130
131 132 133 134 135 136 137 138 139 140 141 142 143  144 145 146 147 148
149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166
167 168 169 170 171 172 173  174 175 176 177 178 179 180  181 182 183 184
185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202
203  204 205 206 207 208 209 210 211 212 213 214 215 216 217  218 219 220
221 222 223 224 225 226;

set 737_300_flights:=18 59 62 66;
set 737_500_flights:=3 6 22 23 45 54 56 67 68 70 75 91 95 97 113 115 118
128 140 142 144 146 148 150 161  168 174 175 177 181 186 187  190 193 194;
set 737_700_flights:=5 8 12 21 25 26 32 34 35 51 53 58 73 79 82 83 85 94
96 98 105 110 111 120 125  129 131 132 157 163 164 197  212;
set 737_800_flights:=4 9 10 15 16 20 27 28 36 37 38 41 43 46 47 48 50 57
60 61 63 64 65 69 76  77 78 80 81 86 87 89 92  93 99 100 101 104 106 107
109 112 114 117 119 121 122 123 127 133 134 135 136 137 138  143 145 149
152 153 154 156 158 159 162 165 166 170 171 172  173 178 182 183 184 185
189 191 192 195 198 200 201 202 203  204 206 207 208 209 210 211 213 214
215 218 223 225 226 84;
set 737_900_flights:=11 29 33 39 40 42 44 49 55 90 102 103 108 116 124 141
147 155 160 167 179 180 196 199 205  216 221 222;
set 757_300_flights:=7 14 19 30 72 88 126 151 176 188 217 219;
set 757_X_flights:=13 24 31 71 74 130 139 169;
set 767_200_flights:=17 52;
set 767_400_flights:=2 220 224;
set 777_flights:=1;
```

```
set 737_only_gates:=E1 E6;
set all_purpose_gates:=E2 E4 E7 E9;
set 737_757_only_gates:=E3 E8;
set 737_300_200gates:=E5;

set widebodygates:=E4 E7;

param fc:=1.614;

#aircraft runway speed ft/sec
param fs:= 42.25; #42.25ft/sec = 25 knots

param Cost:=
E1 2450
E2 2450
E3 2450
E4 2450
E5 2450
E6 2450
E7 2450
E8 2450
E9 2450;

#Expected Gate- Arrival Runway distance in feet
param d1:=
E1 12102.21
E2 12064.48
E3 12040.92
E4 11907.41
E5 11803.51
E6 11420.56
E7 11322.74
E8 11413.99
E9 11520.45;


#Expected Gate- Departure Runway distance in feet
param d2:=
E1 12809.97
E2 12758.40
```

```
E3 12624.06
E4 12441.58
E5 12530.33
E6 12665.40
E7 13116.40
E8 13284.47
E9 13485.27;

param ArrivalTimes:=
1 13.83
2 13.42
3 22.27
.   .
.   .
.   .
224 16.58
225 7.75
226 9.50;

param DepartTimes:=
1 16.42
2 15.67
3 23.27
.   .
.   .
.   .
224 18.25
225 8.83
226 10.42;

param NC:1  2   3   ... 226:=
        1   0   0   ... 0
        2   0   0   ... 0
        3   0   0   ... 0
        .   .   .   ... .
        .   .   .   ... .
        .   .   .   ... .
        226 .   .   ... 0;
#Inter-gate distance (ID) in feet
```

```
param ID: C14   C15 C16 ... E24:=
C14    0    105  175 ... 2653
C15    105  0   105  ... 2723
C16    175  105  0   ... 2793
    .       .   .   .    ... .
    .       .   .   .    ... .
    .       .   .   .    ... .
    E24   2653 2723 2793 ... 0;

#Fuel Burn rate for a flight(kg/sec)
param fb:=
1 0.313
2 0.205
3 0.114
.   .
.   .
.   .
226 0.113;
```

APPENDIX G: AMPL/CPLEX MODEL FOR FLIGHT GATE REASSIGNMENT MODEL

The following codes denotes the AMPL/CPLEX data used for Flight gate reassignment model for Terminal E. The codes are as follows:

```
###################################################
# Model for Flight Gate Reassignment Problem     #
# Program written by Binod Maharjan              #
# Department of Industrial Engineering           #
# Texas Tech University                          #
###################################################
# Defining sets
set rflights;            # Defines the set of real flights)
set inivirtual;            # Defines the set of initial virtual flights
set finvirtual;            # Defines the set of later virtual flights
set flights:=rflights union inivirtual union finvirtual;
set gates; # Defines the set named "gates"
param CurT;         # Define the Current Time
param arrvtime{flights}; # arrival time of the flights
param depttime{flights}; # departure time of the flights
set FliGrCurT={i in rflights: arrvtime[i]>CurT};
set newflights:=FliGrCurT union inivirtual union finvirtual;
set init={FliGrCurT, FliGrCurT, gates};
set viniwflight:= inivirtual union FliGrCurT;
set vfinwflight:= finvirtual union FliGrCurT;
set Hflights;                       # Virtual Houston Flights for passengers
     originating at Houston
set newHflights:=newflights union Hflights;
set Cgate;                          #Check-in Counter
set Ugates:=gates union Cgate;

# Declaration of parameters
param arrival{newflights, gates}; # Arrival time of the flights at gates
param depart{newflights, gates}; # Departure time of the flights at gates
param vg > 0;
param duration{newHflights};     # defines the duration of flight
param M; # sufficiently big number
param l; # level of reassignment
param arrivalH{i in newHflights, k in Ugates};
```

```
param Y{i in newflights, k in Ugates}= if abs(arrivalH[i,k])>0 then 1 else 0;

param Gap0 {i in newflights, j in newflights, k in gates} =
    if i<>j and arrival[i,k] < arrival[j,k] then
    (depart[i,k] - arrival [j,k]);
param Gapf {i in newflights, j in newflights, k in gates} =
    if arrival[i,k]>CurT and Gap0[i,j,k]>0 then
    depart[i,k]-arrival [j,k] else 0;
param ngap{i in newflights, j in newflights, k in gates} =
    if Gapf[i,j,k]>vg then 1 else 0;
param n = sum{i in newflights, j in newflights, k in gates} ngap[i,j,k];

set cnft={i in newflights, j in newflights, k in gates: Gapf[i,j,k]>vg};

param d{k in Ugates, kp in Ugates}; # gate to gate distance
param N{i in newHflights, ip in newflights};
param Eg{i in newflights, k in gates} = arrivalH[i,k]-1;
param Ig{i in newflights, k in gates} = if Eg[i,k]-duration[i] < CurT
    and Eg[i,k]-duration[i]>0 then 1 else 0;
param Ec{i in newHflights, k in Ugates} = arrivalH[i,k]-1;
param Ic{i in newHflights, k in Ugates} = if Ec[i,k]-duration[i] < CurT
    and Ec[i,k]-duration[i]>0 then 1 else 0;

# Declaration of variables
var X{newflights, Ugates} binary;
var Z{i in newflights, j in newflights, k in gates} binary;

#Objective Function
minimize Total_Cost:
sum{i in newflights, ip in newflights, k in gates, kp in gates: i<>ip}
    N[i,ip]*d[k,kp]*Ig[i,k]*(Y[i,k]+X[i,k]-2*Y[i,k]*X[i,k]) +
    sum{i in newflights, ip in newHflights, k in Ugates, kp in gates: i<>ip}
    N[ip,i]*d[kp,k]*Ic[i,k]*(Y[i,k]+X[i,k]-2*Y[i,k]*X[i,k]);

#Constraints
subject to Flightgate{i in newflights}:
sum{k in gates} X[i,k]=1;

subject to abs:
sum{i in newflights, k in gates} (Y[i,k]-X[i,k])^2<=2*n*l;
```

```
subject to Z1ijk{i in viniwflight, k in gates}:
 sum{j in vfinwflight} if i<>j then Z[i,j,k]=X[i,k];

subject to Z2ijk{j in vfinwflight, k in gates}:
sum{i in viniwflight} if i<>j then Z[i,j,k]=X[j,k];

subject to arrv{i in newflights, j in newflights, k in gates: i<>j}:
arrvtime[j]+(1-Z[i,j,k])*M >= depttime[i];

subject to HardConstraints1:
X['V1','E1']=1;
subject to HardConstraints2:
X['V2','E2']=1;
subject to HardConstraints3:
X['V3','E3']=1;
subject to HardConstraints4:
X['V4','E4']=1;
subject to HardConstraints5:
X['V5','E5']=1;
subject to HardConstraints6:
X['V6','E6']=1;
subject to HardConstraints7:
X['V7','E7']=1;
subject to HardConstraints8:
X['V8','E8']=1;
subject to HardConstraints9:
X['V9','E9']=1;
subject to HardConstraints10:
X['V10','E10']=1;
subject to HardConstraints11:
X['V11','E11']=1;
subject to HardConstraints12:
X['V12','E12']=1;
subject to HardConstraints13:
X['V13','E14']=1;
subject to HardConstraints14:
X['V14','E15']=1;
subject to HardConstraints15:
X['V15','E16']=1;
```

```
subject to HardConstraints16:
X['V16','E17']=1;
subject to HardConstraints17:
X['V17','E18']=1;
subject to HardConstraints18:
X['V18','E19']=1;
subject to HardConstraints19:
X['V19','E20']=1;
subject to HardConstraints20:
X['V20','E21']=1;
subject to HardConstraints21:
X['V21','E22']=1;
subject to HardConstraints22:
X['V22','E23']=1;
subject to HardConstraints23:
X['V23','E24']=1;

subject to HardConstraints54:
X['V54','E1']=1;
subject to HardConstraints55:
X['V55','E2']=1;
subject to HardConstraints56:
X['V56','E3']=1;
subject to HardConstraints57:
X['V57','E4']=1;
subject to HardConstraints58:
X['V58','E5']=1;
subject to HardConstraints59:
X['V59','E6']=1;
subject to HardConstraints60:
X['V60','E7']=1;
subject to HardConstraints61:
X['V61','E8']=1;
subject to HardConstraints62:
X['V62','E9']=1;
subject to HardConstraints63:
X['V63','E10']=1;
subject to HardConstraints64:
X['V64','E11']=1;
subject to HardConstraints65:
```

```
X['V65','E12']=1;
subject to HardConstraints66:
X['V66','E14']=1;
subject to HardConstraints67:
X['V67','E15']=1;
subject to HardConstraints68:
X['V68','E16']=1;
subject to HardConstraints69:
X['V69','E17']=1;
subject to HardConstraints70:
X['V70','E18']=1;
subject to HardConstraints71:
X['V71','E19']=1;
subject to HardConstraints72:
X['V72','E20']=1;
subject to HardConstraints73:
X['V73','E21']=1;
subject to HardConstraints74:
X['V74','E22']=1;
subject to HardConstraints75:
X['V75','E23']=1;
subject to HardConstraints76:
X['V76','E24']=1;
```

APPENDIX H: AMPL/CPLEX DATA FOR FLIGHT GATE REASSIGNMENT MODEL

The following codes denotes the AMPL/CPLEX data used for Flight gate reassignment model for Terminal E. The complete data table has many columns and rows, therefore only partial data are shown below:

```
####################################################
# Data for Flight Gate Reassignment Problem        #
# Program written by Binod Maharjan                #
# Department of Industrial Engineering             #
# Texas Tech University                            #
####################################################
# Set Data
set rflights :=F1 F2 F5 F11 F12 F13 F16 F17 F18 F20 F22 F25 F26 F30 F32
F33 F36 F38 F42 F45 F48 F52 F53 F57 F59 F60  F63 F65 F67 F70 F71 F74 F76
F78 F79 F81 F82 F86 F87 F88 F90 F91 F96 F99 F100 F103 F104 F105 F106 F107
F108 F109 F110 F111 F112 F113 F114 F115 F117 F118 F119 F120 F121 F124 F126
F127 F129 F130 F131 F132 F133 F135 F136 F137 F138 F140 F141 F143 F145 F146
F147 F148 F149 F155 F158 F159 F162 F165 F166 F167 F169 F171 F173 F178 F182
F183 F184 F185 F188 F189 F190 F192 F194 F196 F197 F198 F200 F201 F202 F206
F209 F210 F215 F216 F218 F219 F220 F224 F226;

set inivirtual:= V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16
V17 V18 V19 V20 V21 V22 V23;#
set finvirtual:= V54 V55 V56 V57 V58 V59 V60 V61 V62 V63 V64 V65 V66 V67
V68 V69 V70 V71 V72 V73 V74 V75 V76;#
set gates := E1 E2 E3 E4 E5 E6 E7 E8 E9 E10 E11 E12 E14 E15 E16 E17 E18
E19 E20 E21 E22 E23 E24;#
set Cgate:=C0; #counter as gate

param vg := 0.001;
#param vp := 0;
param CurT :=17;
#param Pnty := 50;
param M:=9999;
param l:=1;         #level of assignment

set Hflights := H1 H2 H5 H11 H12 H13 H16 H17 H18 H20 H22 H25 H26 H30 H32
H33 H36 H38 H42 H45 H48 H52 H53 H57 H59 H60  H63 H65 H67 H70 H71 H74 H76
```

```
H78 H79 H81 H82 H86 H87 H88 H90 H91 H96 H99 H100 H103 H104 H105 H106 H107
H108 H109 H110 H111 H112 H113 H114 H115 H117 H118 H119 H120 H121 H124 H126
H127 H129 H130 H131 H132 H133 H135 H136 H137 H138 H140 H141 H143 H145 H146
H147 H148 H149 H155 H158 H159 H162 H165 H166 H167 H169 H171 H173 H178 H182
H183 H184 H185 H188 H189 H190 H192 H194 H196 H197 H198 H200 H201 H202 H206
H209 H210 H215 H216 H218 H219 H220 H224 H226;

#Inter-Gate distance (ID) in feet
param d: E1     E2     E3       ...  E24    C0:=
        E1  0       119     294      ... 1913.5  1913.5
        E2  119     0       175      ... 2032.5  2032.5
        E3  294     175     0        ... 2207.5  2207.5
        .   .       .       .        ... .       .
        .   .       .       .        ... .       .
        E24 1039.5  2032.5  2207.5   ... 0       2953
        C0  1913.5  2032.5  2207.5   ... 2949.5  0;

param arrivalH: E1     E2     E3       ... E24    C0:=
            V1  -5      0       0        ... 0      -30
            V2  0       -5      0        ... 0      -30
            V3  0       0       -5       ... 0     -30
            .   .       .       .        ... .       .
            .   .       .       .        ... .       .
            F1  0       0       0        ... 0      -30
            F2  0       0       0        ... 0      -30
            F3  0       0       0        ... 0      -30
            .   .       .       .        ... .       .
            .   .       .       .        ... .       .
            H1  0       0       0        ... 0      -30
            H2  0       0       0        ... 0      -30
            H3  0       0       0        ... 0      -30
            .   .       .       .        ... .       .
            .   .       .       .        ... .       .
            V54  38     0       0        ... 0      -30
            V55  0      38      0        ... 0      -30
            V56  0      0       38       ... 0      -30
            .   .       .       .        ... .       .
            .   .       .       .        ... .       .
            V76 0       0       0        ... 0       -30;
```

```
param arrival: E1     E2     E3        ... E24    C0:=
            V1  -5      0       0         ... 0      -30
            V2  0       -5      0         ... 0      -30
            V3  0       0       -5        ... 0      -30
            .   .       .       .         ... .       .
            .   .       .       .         ... .       .
            F1  0       0       0         ... 0      -30
            F2  0       0       0         ... 0      -30
            F3  0       0       0         ... 0      -30
            .   .       .       .         ... .       .
            .   .       .       .         ... .       .
            V54  38     0       0         ... 0      -30
            V55  0      38      0         ... 0      -30
            V56  0      0       38        ... 0      -30
            .   .       .       .         ... .       .
            .   .       .       .         ... .       .
            V76 0       0       0         ... 0       -30;

param depart: E1     E2     E3        ... E24    C0:=
            V1  -5      0       0         ... 0      -30
            V2  0       -5      0         ... 0      -30
            V3  0       0       -5        ... 0      -30
            .   .       .       .         ... .       .
            .   .       .       .         ... .       .
            F1  0       0       0         ... 0      -30
            F2  0       0       0         ... 0      -30
            F3  0       0       0         ... 0      -30
            .   .       .       .         ... .       .
            .   .       .       .         ... .       .
            V54  38     0     0           ... 0      -30
            V55  0      38    0           ... 0      -30
            V56  0      0     38          ... 0      -30
            .   .       .       .         ... .       .
            .   .       .       .         ... .       .
            V76 0       0       0         ... 0     -30;

param N:
    F1    F2    F3     ...  F226    H1 H2  H3   ... V1   V2    ...  V76:=
V1  -5      0       0        ... 0     0     0     0  ... 0     0    ...  0
V2  0      -5       0        ... 0     0     0     0  ... 0     0    ...  0
```

```
V3   0      0      -5      ...0   0   0   0  ... 0   0  ...  0
.    .      .      .       ... .  .   .   .  ... 0   0  ...  0
.    .      .      .       ... .  .   .   .  ... 0   0  ...  0
F1   0     0       0       ... 0  0   0   0  ... 0   0  ...  0
F2   0     0       0       ... 0  0   0   0  ... 0   0  ...  0
F3   0     0       0       ... 0  0   0   0  ... 0   0  ...  0
.    .      .      .       ... .  .   .   .  ... 0   0  ...  0
.    .      .      .       ... .  .   .   .  ... 0   0  ...  0
H1   29     0      0       ... 0  0   0   0  ... 0   0  ...  0
H2   0     28      0       ... 0  0   0   0  ... 0   0  ...  0
H3   0     0      29       ... 0  0   0   0  ... 0   0  ...  0
.    .      .      .       ... .  .   .   .  ... 0   0  ...  0
.    .      .      .       ... .  .   .   .  ... 0   0  ...  0
V1   0      0      0       ... 0  0   0   0  ... 0   0  ...  0
V2   0      0      0       ... 0  0   0   0  ... 0   0  ...  0
V3   0      0      0       ... 0  0   0   0  ... 0   0  ...  0
.    .      .      .       ... .  .   .   .  ... 0   0  ...  0
.    .      .      .       ... .  .   .   .  ... 0   0  ...  0
V76   0      0     0       ... 0  0   0   0  ... 0   0  ...  0;

param duration:=
V1 0
V2 0
V3 0
.   .
.   .
F1 11.03
F2 10.28
F3 2.97
.   .
.   .
H1 0
H2 0
H3 0
.   .
.   .
V54 0
V55 0
V56 0;
```

```
param arrvtime:=
V1 -5
V2 -5
V3 -5
.    .
.    .
F1 13.83
F2 13.42
F3  22.27
.    .
.    .
V54 38
V55 38
V56 38
.    .
.    .
V76 38;

param depttime:=
V1 -5
V2 -5
V3 -5
.    .
.    .
F1 16.42
F2 15.67
F3  23.27
.    .
.    .
V54 38
V55 38
V56 38
.    .
.    .
V76 38;
```