# An Intelligent Optimization System for Terminal Traffic Management

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# Dedication

This work is dedicated to my parents, you instilled in me all the values that have allowed me to reach this point; especially to my mother, you were my inspiration, I know you have been watching over me from the heaven all these years.

# Abstract

This dissertation presents the development of a terminal traffic flow management system using an intelligent optimization method. The system is in an effort to provide advisories to efficiently assign runways to cope with the unbalanced traffic flow from and/or toward different directions and computes the optimal arrival or departure time for each flight. This is a high fidelity advisory system to assist traffic managers at airports to manage the complex terminal traffic in a more efficient fashion in order to ultimately minimize the overall flight delay in the entire airport and maintain a high level of safety at the same time. Multiple objectives pertaining to overall airport throughput, system delay, maximum individual delay, and runway balance are used. The system described in this study utilizes knowledge base intelligent optimization methods and takes advantage of the self-contained mixed integer linear program. The mixed integer linear program calculates the optimal schedule for each aircraft for each runway while the intelligent optimization method is used to produce optimal runway assignment for all flights in the entire airport. The importance of improving airport efficiency is introduced in detail in this dissertation. The system explicitly considers eliminating mid-air crossings within the terminal airspace due to irrational runway assignments. This not only improves safety but also effectively reduces controller workload. The importance and contribution of the study is addressed. This system is suitable for an airport with multiple runways. Simulations were conducted based on the real traffic mix for four of the 30 busiest airports in the United States and the results of the simulation prove the feasibility of the system. Future development of the system is also discussed.

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# Nomenclatures

| | |
|---|---|
| $N_{arr}$ | Total number of arrival aircraft |
| $N_{dep}$ | Total number of departure aircraft |
| $X$ | Total number of arrival routes that are available to be assigned based on the runway configuration |
| $Y$ | Total number of departure routes that are available to be assigned based on the runway configuration |
| $P$ | Total number of scheduling points on an arrival route |
| $Q$ | Total number of scheduling points on a departure route |
| $K$ | Total number of common scheduling points between two routes |
| $i$ | Index for arriving aircraft, $\forall i \in N_{arr}$ ; sorted in ascending order of earliest un-impeded ETAs |
| $j$ | Index for departing aircraft, $\forall j \in N_{dep}$ ; sorted in ascending order of earliest un-impeded ETAs |
| $x$ | Index for arrival routes, $\forall x \in X$ , each route uniquely connects an arrival fix to the point at landing threshold of a particular runway |
| $y$ | Index for departure routes, $\forall y \in Y$ , each route uniquely connects the departure end of a particular runway to a departure fix (exit point of the TMA) |
| $p$ | Index for scheduling points on arrival routes, $\forall p \in P$ |
| $q$ | Index for scheduling points on departure route, $\forall q \in Q$ |
| $k$ | Index for common section, $\forall k \in K$ |
| M | A large positive real number |
| $T_C$ | Computational time for one scheduling window |
| $T_L$ | Look-ahead time |
| $T_W$ | Length of scheduling windows |

## Acronyms

| | |
|---|---|
| ACC | Area Control Center (center) |
| ARTCC | Air Route Traffic Control Center |
| ATC | Air Traffic Control/Air Traffic Controller |
| ATM | Air Traffic Management |
| CAD | Collaborated Arrival and Departure |
| EA | Evolutionary Algorithms |
| FAA | Federal Aviation Administration |
| FAST | Final Approach Spacing Tool |
| ETA | Estimated Time of Arrival at a Scheduling Point |
| FCFS | First Come First Serve |
| GA | Genetic Algorithms |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organization |
| IE | Implicit Enumeration |
| MILP | Mixed Integers Linear Programming |
| MITRE | The MITRE Corporation |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| NextGen | Next Generation air Transportation System - FAA |
| NM | Nautical Mile |
| OAG | Official Airline Guide |
| PSO | Particle Swarm Optimization |
| RCM | Runway configuration management |
| ROT | Runway Occupancy Time |
| SA | Simulated Annealing |
| SID | Standard Instruments Departure |
| STA | Schedule Time of Arrival at a Scheduling Point |
| STAR | Standard Terminal Arrival Route |
| TFMS | Traffic Flow Management System |
| TMA | Terminal Airspace |
| TRACON | Terminal Radar Approach Control |

# Chapter 1 Introduction

## 1.1 Background and Motivation

Since the introduction of commercial aviation, travel by air has become a more and more common way of travel. With the advent of globalization, air travel has become the dominant form of transportation in the last four decades, especially in the US and Europe. The National Airspace System (NAS) of the United States is one of the most complex aviation systems in the world; every second, there are more than 5,000 aircraft in the system, and all this traffic must takeoff and land somewhere. In 2001, September 11th made a dent in aviation traffic, but air transportation quickly rebounded and has picked up the pace and is now accelerating. Airport report (1) showed that last year, Atlanta airport serviced 114% of the traffic of 2000; Dulles airport reached 118%; and Philadelphia airport exceeded 123% of the traffic compared with year 2000. To meet the substantially increased air traffic demands, many existing airports will need to be expanded, and more airports will be needed. However, looking around in the US, the last new airport built was Denver International Airport, but even that was constructed in the 1970’s. In addition, many airport expansion plans require years if not decades to execute, such as expansion plans for John F. Kennedy and Philadelphia airports. It is extremely difficult for airports to expand in metropolitan areas where aviation demand has been driven traditionally. This makes airports the weak link in the chain of the National Airspace System. With the continuous growth of air traffic, the National Airspace System is reaching its capacity. The limitations of the current resources, such as terminal airspace and runways, are strained and improving the operational efficiency of the existing system while maintaining safety has become an urgent task.

Safety is the number one propriety in the aviation world. Professionally trained flight crews and air traffic controllers are the main work force to keep our skies safe. However, with the increase in air traffic, the complexity of the air traffic operation is growing exponentially. The current Air Traffic Management (ATM) system is restricting the growth of air transport and is a major factor in delays, longer than necessary routes and peak traffic demand levels without the capacity to accommodate these needs. Each of which has an adverse effect on the environment (2). Ultimately, we are all looking for solutions to improve the efficiency of this system without sacrificing safety.

Compared with the drastically changing technology in most other areas over the last few decades, the air traffic management system has been moving very slowly. After years of development, even in the US, the ATM system is still in a low level of automation. First, computers are still not advanced enough to be trustworthy in making good judgments in complex situations as well they are not capable of adjusting to uncertainties instantaneously. Until the day all aircraft are completely controlled by computer, we will still need a human air traffic controller (ATC) in the loop for sequencing aircraft; especially with unanticipated interruptions such as bad weather or during special situation like grounding all traffic on September 11th, 2001. Currently, only a human operator can respond to the unexpected situation in a timely manner and is able to reassign and re-sequence aircraft when it is necessary. The goal in improving the degree of automation in the ATM system is not to replace the human controller, but to produce more accurate predictions of the situation and provide more useful information to controllers to improve the efficiency of the overall ATM system. Presently, there are few airports that rely on only one or two runways; 90% of the 30 busiest airports in US (1) have multiple runways. As complexity has increased, there is a need to create a systematic method to design, evaluate and provide operational assistance in runway assignment as well as optimizing arrival/departure aircraft scheduling.

## 1.2 Overview of Past Efforts

There are several research areas that address aspects of the terminal air traffic management system. The most common one is scheduling problem, which optimizes the aircraft schedule of landings or departures on a runway in order to reduce flight time or flight delay. Many different methods have been considered for this task. Dynamic programming algorithms (3), Mixed Integer Linear Program (MILP) (4) and Generic Algorithms (5) have been applied to the scheduling problem. Among those, Shresta from MITRE approached the problem using modeling (6). Isaacson, Robinson III and Lee from NASA Ames applied various methods, such as fuzzy logic (7), knowledge-based system (8), modeling (9) to obtain a more optimal schedule (10). There were also several studies under the Next Generation (NextGen) in efforts of improving efficiency of air traffic operations (11).

Some of these studies will be further detailed in Section 3.2 Basically many of the studies focused on two completely separate topics: one for scheduling arrival aircraft only; and the other for scheduling departure aircraft only. It is easy to understand why it is important to get arrival aircraft on the ground as soon as possible (12). First, it is always safer to have the aircraft on the ground than holding or vectoring them in air, so arrivals almost always have the priority of using the runway. Secondly, for most commercial flights, an arrival leg is connected with a departure leg after landing, thus the delay of an arrival may consequentially further delay a linked departing flight using the same aircraft. This is also applied to connecting passengers and flight crews. However, if departures have been delayed for too long they will occupy gates and parking positions, and arriving flights cannot be parked after landing. Furthermore, if departures have been held on the ground after pulling out from the gate, they may block taxi paths for other aircraft and cause ground congestion; this would also cause higher emission and fuel consumption. In addition, an extensive delay may cause a chain reaction to the entire national air traffic flow system. Therefore, some approaches to the scheduling problems include collaboration of both arrival and departure. An example is the Collaborate

Arrival and Departure (CAD) approach; this aims to find available times for departures by creating additional spacing in arrival queues (13).

Many scheduling solutions attempted to optimize scheduling on a single runway, or treat the scheduling problem for a multiple runway system as a single stream of flights. Very few studies extended the focus from runway to terminal airspace that includes scheduling at arrival fixes. MITRE developed an agent based simulation model of ATC arrival operations, using traffic structures based on geometry direction of incoming arrivals (6), but the model is intended to predict the impact of operational changes to actual operations, not to optimize the operation. Clarke et al. scheduled aircraft based on the associated arrival or departure fixes in attempt to solve the problem of uneven use of runway resources due to unbalanced traffic flow from or to different directions (14). Both studies used the additional arrival routes across the airport field in order to use runways on the other side of the airport. However, it was sometimes restricted by airspace constraints; and sometimes it required more transfers from one controller to another that would cause increases in controller workload; potentially resulting in some mid-air crossovers that would also result an increase in controller workload.

## 1.3 Overview of Proposed Methods

Optimization techniques are indeed the best choices for this kind of problem. But air traffic control is a very complex system; normally it consists of many different constraints and objectives at the same time especially when considering the geometric constraints of the airfield and airspace. It is difficult for the classical optimization methods to reach the optimal solution. The intelligent optimization algorithms provide ways to overcome the complexity. That enables us to obtain the optimal solution and process the multiple tradeoffs simultaneously (5).

A closed-loop optimization system based on the intelligent optimization method and MILP scheduling techniques are capable of providing a high fidelity scheduling and runway assignment solution that considers both departure and arrival traffic flow in a terminal airspace, as well as the interaction between the two.

The intelligent algorithm starts by generating a set of individuals - runway assignments for all aircraft on the schedule. The fitness of the set is evaluated, which is decided based on airport delay and runway utilization rate, and crossover or mutation is processed to produce a healthier generation – better set of runway assignments. The process is repeated until an approximation of an optimal solution is achieved or when it reaches the pre-determined number of iterations. The MILP process computes the optimal schedule for each runway in every iteration. The system is in some degree generic and can handle various scenarios of unbalanced traffic flow.

Constraints accounted for wake turbulence separation, runway occupancy time, separation between landing and takeoff on closely spaced parallel runways are explicitly considered. An optional prioritization scheme for relevant aircraft was also applied to address the maximum delay on a single aircraft. To handle continual traffic flows, a long planning horizon is divided into a series of smaller time intervals, referred to scheduling windows. The dynamic scheduling method in each of these time intervals is sequenced to process continual traffic flows with no overlap in scheduling windows. The dynamic strategy provides a solution with a high level of fidelity in a short computation time allowing for the real-time traffic feeds. Thus the system would be more likely to be used in real-time air traffic control operations with less vulnerability to the uncertainties in actual flight plans (15).

The intelligent optimization system was built on the knowledge and experiences in air traffic management systems. This methodology could be easily adopted by practical operations because of its simplicity. This study sets the groundwork for future development of more sophisticated decision support tools for terminal traffic flow management.

## 1.4 Contributions

The study attempted to combine the knowledge base intelligent optimization algorithms with the classical optimization methods to provide a more comprehensive solution for the terminal traffic management problem. Another important step of this study is that the system considers geometric constraints of the airfield and terminal airspace when computing runway assignments due to unbalanced traffic flow. Optimizing runway assignments is important for airports with multi-runway systems. Overloading one runway while allowing another to remain underutilized will not only lower the overall airport throughput but would cause more delay in the system (6). However, in the U.S., airports on either coast and airports located far north or far south often face unevenly distributed traffic flow. By default, the most convenient runway to use would be the one nearest to the direction of traffic flow. Determining runway utilization due to unbalanced traffic flow and scheduling aircraft with a coordination of arrivals and departures within the same framework would potentially improve efficiency and throughput of the overall operation at busy airports. In this optimization framework, we aim to formulate a systematic process to optimize runway utilization. The proposed solution eliminates mid-air crossings within the terminal airspace due to irrational runway assignments. This assures minimum impact on the controller workload when aircraft have to alter runway due to capacity. The system not only improves operational safety but also makes it more appealing to controllers.

## 1.5 Thesis Structure

The rest of this dissertation is organized as following: Chapter 2 provides a detailed description of the airport geometric and the terminal airspace model used in the system. The architecture of the system is described in Chapter 4 along with the basic mathematical formulation with a description of notation and the interpretation of the expressions. The scenarios of the numerical simulation for evaluating the system are tallied in Chapter 5. This is followed by the conclusion in Chapter 6. Finally, thoughts for future research and development of the system are discussed in Chapter 7.

# Chapter 2 Modeling of Airport and Surrounding Airspace

## 2.1 Airport Geometry and Operational Rules

Terminal traffic is like a funnel, arriving traffic narrows down to runways, while departing traffic start from runways and diverge to their separate routes. Typical airports have a limited number of arrival paths, but may have many departure paths.

After years of operation and practices, the FAA established the four corner post configuration for most of the major metropolitan airports in the US effectively minimizing conflicts between arrivals and departures. Figure 2.1 shows the arrival flow during one day at the Dallas Fort Worth International airport in Texas. The arrival stream entering the terminal airspace from four corners clearly illustrates a typical Four Corner Post terminal airspace configuration. Figure 2.2 and Figure 2.3 show one-day arrival traffic and departure traffic respectively at Hartsfield Jackson Atlanta International Airport. In a Four Corner Post terminal airspace configuration, not only are arrival flows grouped into four different streams, but departures also exit the terminal airspace in approximately four different directions.

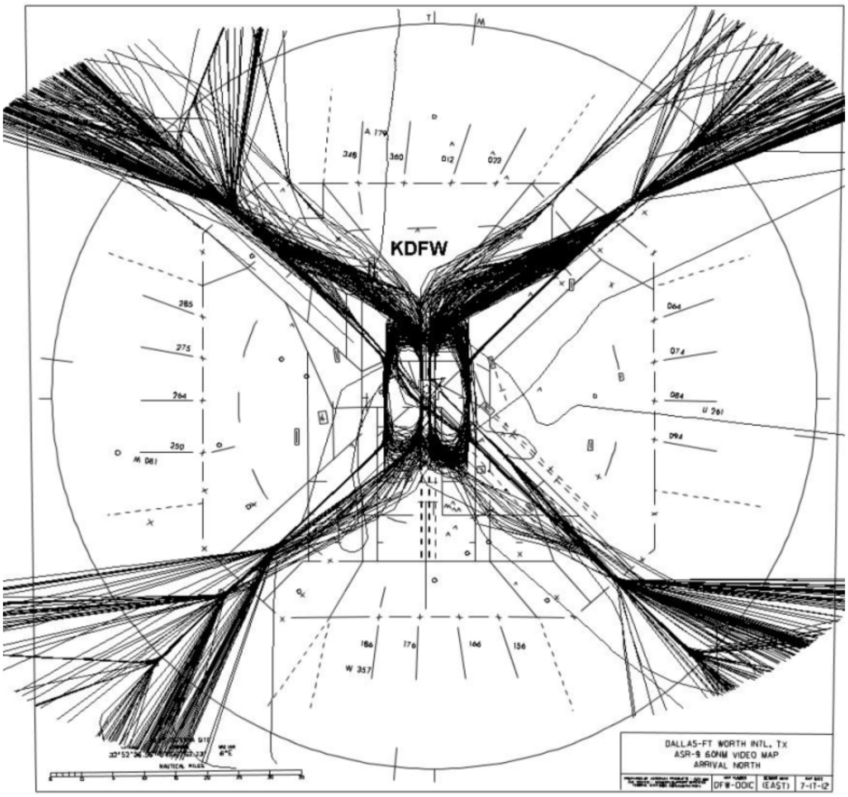


**Figure 2.1 Typical Four Corner Post Terminal Airspace Configuration – KDFW Arrival Flow (Source: DFW TRACON)**

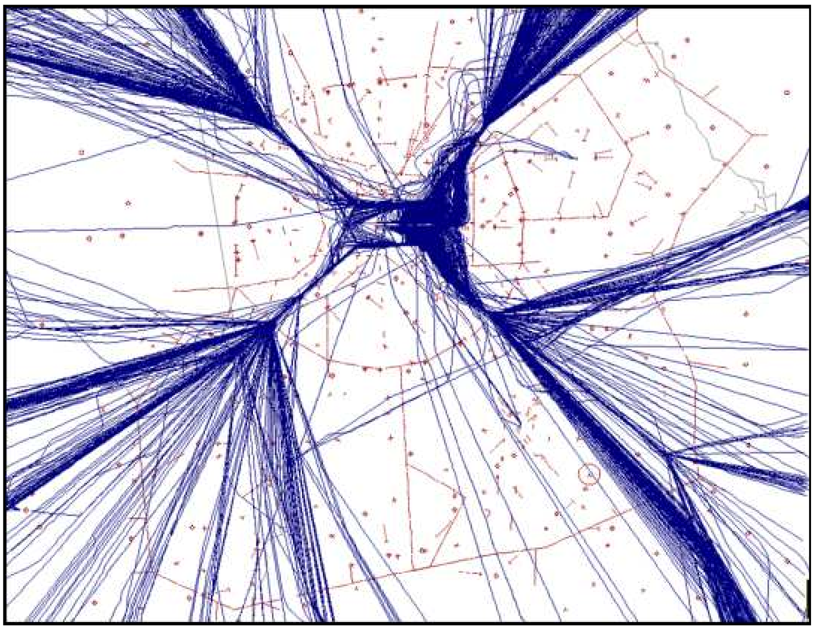


**Figure 2.2 Typical Four Corner Post Terminal Airspace Configuration – KATL Arrival Flow (Source: ATL TRACON)**

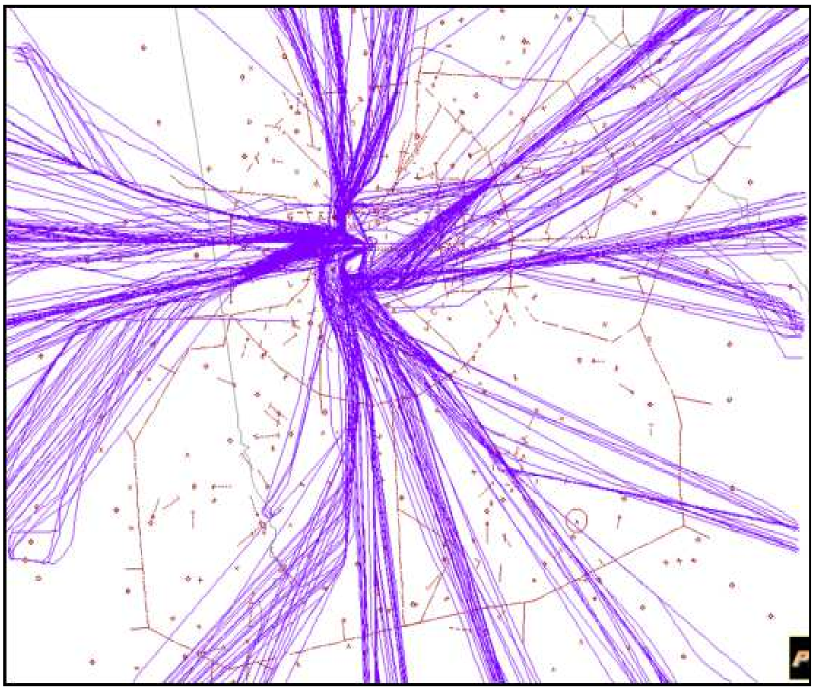


**Figure 2.3 Typical Four Corner Post Terminal Airspace Configuration – KATL Departure Flow (Source: ATL TRACON)**

Airspace in the US is classified into five classes of airspace (16). A commercial flight most likely has to fly through the national airspace system (NAS) in at least two types of airspace, Class B airspace and Class E airspace. Most of the busiest airports in the US are surrounded by Class B airspace, which extends from the surface of the airfield up to 10,000 feet above sea level. The en-route portion of the flight is through Class E airspace, which is controlled airspace outside any terminal airspace for airports and it is where most airways are defined. All these airspaces are controlled by different facilities. A commercial flight starts from a gate at an origin airport and is controlled by a ramp controller before being handed over to a ground controller for taxiing to a departure runway. Then a tower controller will take over and authorize the takeoff clearance. At most of the major airports in US, once airborne, the aircraft enters the control of the Terminal Radar Approach Control (TRACON) where a departure controller will give instructions in order to safely and quickly guide the flight through the complex terminal airspace and ultimately passes it to Air Route Traffic Control Center (ARTCC), commonly referred as “center” control. Once the aircraft approaches its destination airport, the control process is reversed until it arrives at its designated gate. Therefore intensive cooperation between neighboring facilities is very common. A typical TRACON airspace, such as Hartsfield-Jackson Atlanta International Airport, extends to 60 NM from the airport.

The two following figures illustrate the structure of arrival routes and departure routes in a typical Four Corner Post terminal airspace. Figure 2.4 shows four arrival routes. Usually there are more than four arrival routes, but as described earlier, arrival aircraft will be "funneled" or merged to fewer routes once they enter the terminal airspace. Based on the number of available landing runways, eventually the arrival routes on final will connect to the landing runways straightly at the final segment of the approach. For instance, if there are two landing runways, there will only be two arrival paths on final aligned with the extended centerline of landing runway.

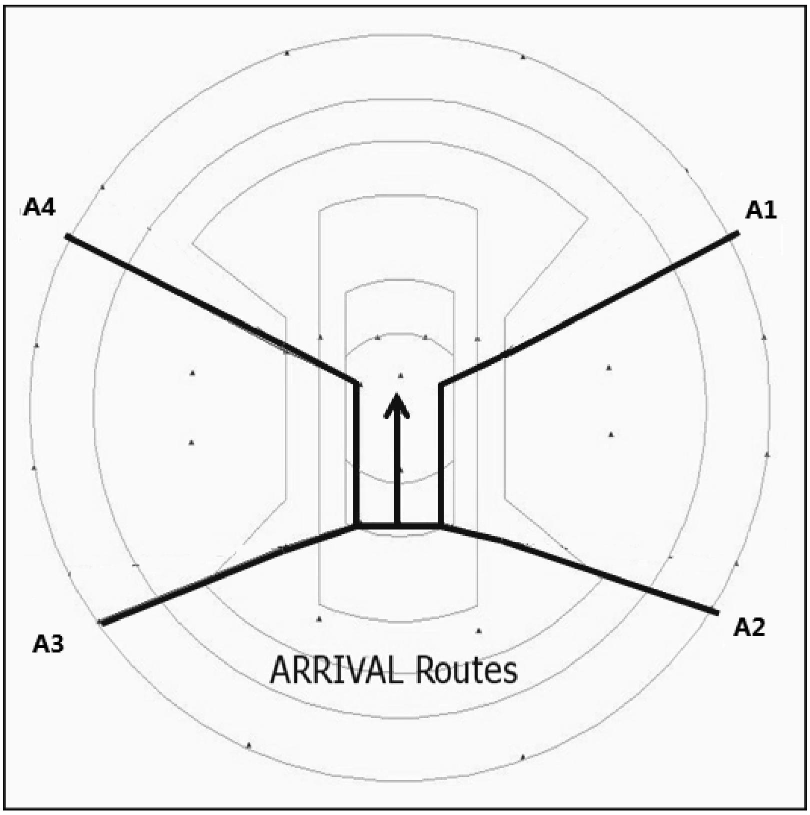


**Figure 2.4 Typical Four Corner Post Terminal Airspace Configuration – Typical Arrival Routes**

The Figure 2.5 below shows eight departure routes which illustrate the basic concepts of the departure paths in a typical Four Corner Post terminal airspace.  In fact, many major airports may have more than eight.  For instance, Atlanta (KATL) has up to 16 departure routes.

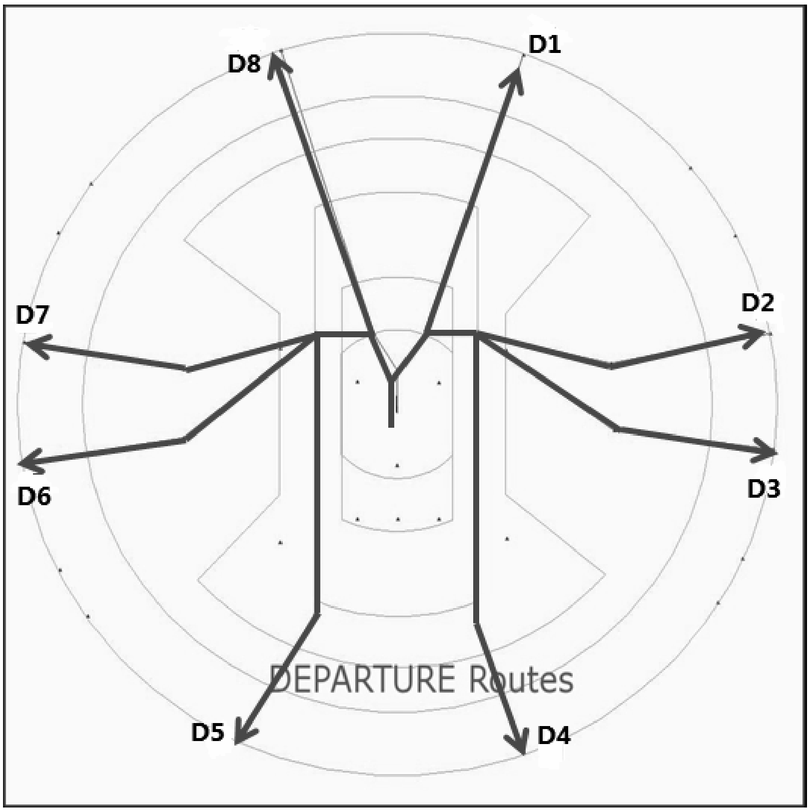


**Figure 2.5 Typical Four Corner Post Terminal Airspace Configuration – Typical Departure Routes**

### 2.1.1    In practical operations, controllers make decisions based on their own scopes:

The inbound traffic is transferred from an Area Control Center (ACC or center) controller to a feeder controller at TRACON.  In some major airport, one feeder controller may control only one corner point of entrance. The controller then hands over the arrival aircraft to an approach controller who would accept traffic coming in from different feeders then sequence the stream of arrival aircraft to line-up at a particular runway. Usually aircraft coming in using runways on the left side of the airport are controlled by a different approach controller than the one controls aircraft aim to the runways on the right side of the airport. Finally, a tower controller would take over and direct the aircraft to land and exit the runway after touching down. At most of the busy airports, one tower controller only controls aircraft landing/departing on one runway.

For departures, a tower controller would consider the sequence with other takeoff and landing aircraft, then issues a departure clearance when the proper separation is achieved. After takeoff, the aircraft is guided by a departure controller all the way to its departure fix or transfer altitude and then will hand it over to an ACC controller.

On top of all that, a traffic flow manager at the TRACON will oversee all inbound and outbound aircraft and instruct adjustments in traffic flow when runway configurations change, or when certain ATC sectors or runways gets overload. The system we are attempting to develop here is in hope of providing operational advice to the traffic flow manager in optimizing traffic planning within the terminal airspace.

## 2.2 Multiple-point Scheduling Scheme

In a scheduling problem, scheduling points present locations where the time of aircraft crossing or arriving are recorded and are used to measure scheduling performance. In a multiple-point system, each scheduling point represents a location of the aircraft in the system, such as arrival fix, departure fix, runway landing threshold, departure end of the runway (15).

For inbound traffic, our arrival fixes A1, A2, A3, A4 (Figure 2.4) are the first scheduling points, and the runway thresholds on each runway are the second scheduling points. For the outbound traffic, the departure thresholds of each runway are the first scheduling points, and the eight departure fixes, D1, D2, D3,…, D8 (Figure 2.5) are the second scheduling points. When there is a dual use runway, runway used for both takeoff and landing aircraft, the departures and arrivals share the same scheduling point. This is conveniently applied to sequence the departure stream and arrival stream.

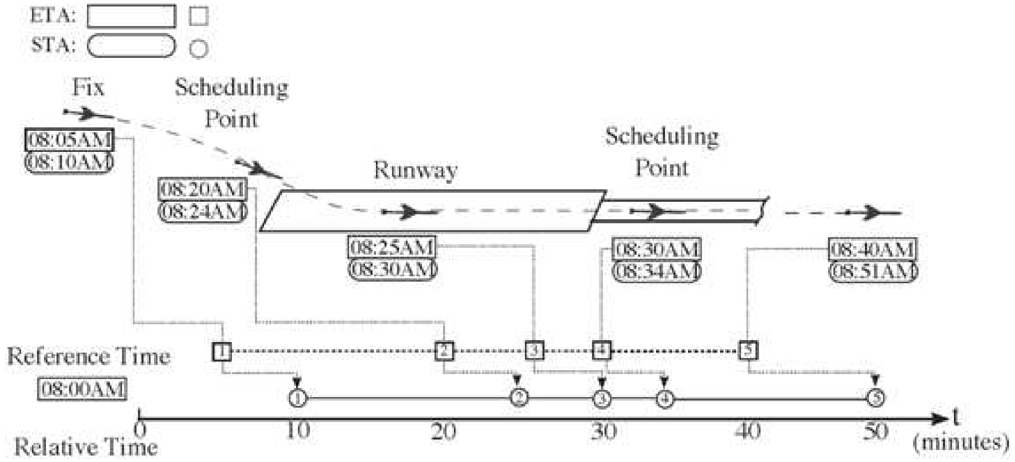


**Figure 2.6 An example of multiple-point scheduling (Chen, 2012)**

Figure 2.6 illustrates the relationship of the estimated time of arrival (ETA) and scheduled time of arrival (STA) of an aircraft at each of its scheduling points. The original ETAs are derived directly from traffic sample, and the STAs are the time produced by the system after going through the scheduling process. In our system, the STAs in the first iteration of the calculation would become the ETAs for the next cycle of iteration, and so on, until the system reaches its point of termination.

The separation requirements between aircraft are achieved and maintained by adjusting the time when aircraft in sequence cross at the common scheduling point. Once the appropriate scheduled time has been computed, the aircraft is free to adjust its speed, and/or interim path (in real world, it would be vectoring for arrivals, and line-up and wait or ground delay for departures) to meet its time of arrival at the scheduling point.

By performing a multiple-point scheduling, it allows the flexibility of scheduling to be conducted at any given point of interest.

# Chapter 3 Problem Statement and Related Work

## 3.1 Problem Statement

The ultimate goal of this study is to provide an automated and optimized solution to assist terminal traffic flow managers in managing air traffic within a terminal airspace environment. In order to achieve this, we developed a system with multiple objectives that minimizes overall airport delays and maximizes airport throughput.

### 3.1.1 Decision variables:

#### 3.1.1.1 Route assignments which imply to runway assignment

Route connects a given “fix” to all usable runways at the airport. Every route is unique.

Arrival routes are established from each arrival fix to each runway threshold. For example, assuming there are only two runways, 36R and 36L. Aircraft entering the terminal airspace from A1 would have at least two routes to choose from, a route guides the aircraft from A1 to land on runway 36R; and a route leads the aircraft from A1 to land on runway 36L. Since each arrival fix (e.g. A1) can be link to different runways (e.g. 36R and 36L), the total number of arrival routes is the product of the total number of arrival fixes multiple the total number of arrival runways.

As stated in the previous chapter, there are eight departure fixes in our airport model (Figure 2.5), D1 through D8. There are departure routes linking each runway end to all eight departure fixes. For example, an aircraft heading to D1 would have two routes to choose from: takeoff from runway 36R, it would follow the route from the departure end of runway 36R to D1; or takeoff from runway 36L and follow the route guides from runway 36L to D1. Each runway (e.g. runway 36R) can be linked to different departure fixes (D1, D2, …Dn), thus, the total number of departure routes is the product of the total number of departure fixes multiple the total number of departure runways.

This setting illustrates a picture where each given route corresponds with one runway, and therefore by choosing the route, runway selection is processed.

Runway assignment is often altered to expedite the operation. Relaxing the notion of runway configuration to all flights to be assigned to any usable runway will increase the possibility to find the most optimized schedule. Sometime, changing the runway assignment for arrivals is done by re-routing the aircraft to a different entrance gate, but this usually results in a much longer fly distance and higher fuel burn. Otherwise, aircraft can still be re-routed to a different runway once entering the terminal airspace. However, the terminal area is a very compacted airspace, especially at metropolitan airports. Changing runway assignments within the terminal airspace may cause mid-air crossing, which would result in additional coordination with departure controllers. Even though in most cases, the aircraft have established vertical separation, controllers would still have to monitor those crossings, particularly when aircraft have to cross over the airfield to land on the opposite side of the airport. All the extra monitoring activities would increase controller workload. When the ground movement is considered as well, relaxing the runway choice may cause more taxi time on the ground, it could be less fuel economical, and most importantly, it could contribute to ground congestion.

Some runways are explicitly assigned for departure only. Those runways would only have routes linked to departure fixes. Some runways are explicitly used for arrival only. Those runways would only have routes linked with arrival fixes. And there are dual-use runways that have routes connect with departure fixes and routes connect with arrival fixes. With the uniqueness of route settings, runway usage can be implicitly defined by using the route structure.

In many cases, the number of departure fixes could be as many as 16, as at Atlanta TMA, but according to FAA and ICAO regulations, the different departure tracks need to have at least 15° divergent angle (KATL has the FAA wavier to reduce this to 10°), otherwise the separation for simultaneous departures on different paths will have to be increased. Thus, in our numerical simulation for the four corner post TMA configuration, we bundled some of the routes from/to the same direction, and defined A=4, and D=8.  At any time, an aircraft can only take the route assigned to it.

The following two figures show the situations of potential mid-air crossings when runway assignment changes from the default.

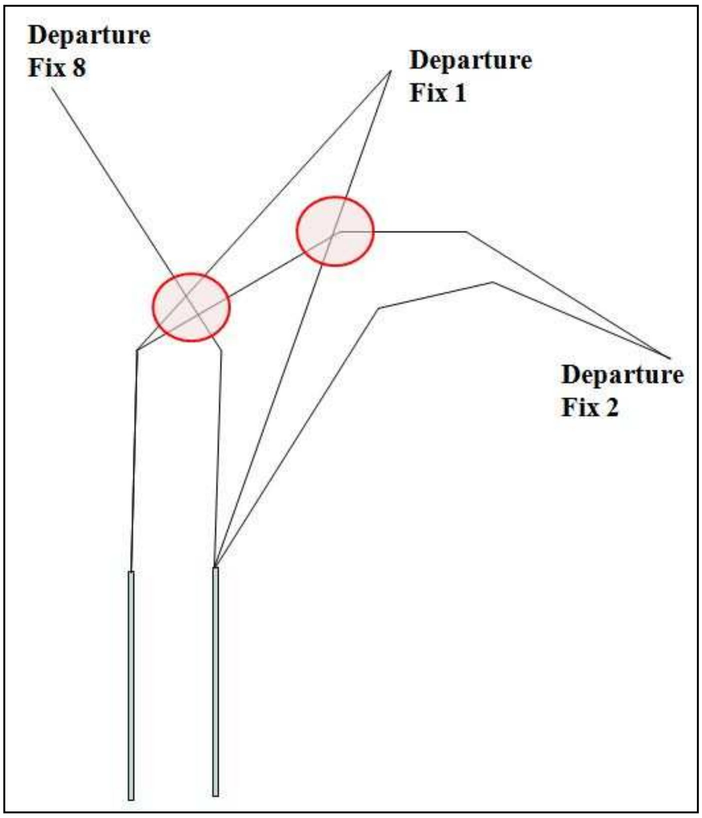


**Figure 3.1 Potential mid-air crossing situations for departures took off from different runways**

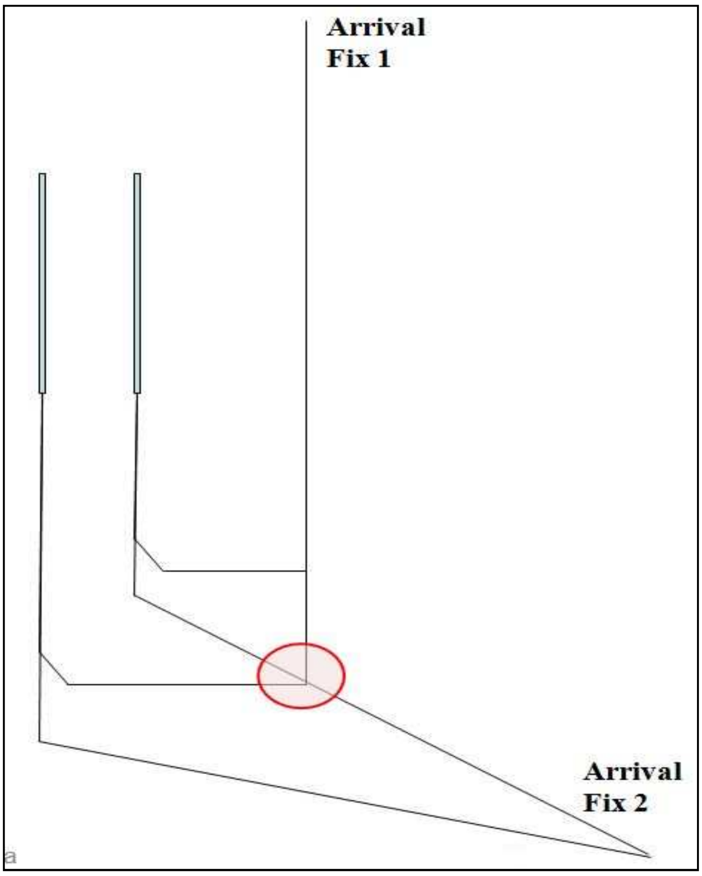


Figure 3.2 Potential mid-air crossing situations for arrivals landing on different runways

#### 3.1.1.2 Scheduling assignments

Each route may have a number of scheduling points. Each scheduling point represents the physical location of aircraft along the route; the locations and the sequential order of the points describe a route. In this study, the first scheduling point of an arrival route is the arrival fix (i.e. A1, A2, … An) where the aircraft enters the terminal airspace; and the last scheduling point is the landing threshold of the runway. For departure routes, the first scheduling point is the runway end where aircraft commences departure. The departure fix (i.e. D1, D2, … Dn) where an aircraft exits the terminal airspace is the final schedule point on a departure route.

Initial Estimated Time of Arrival ETA, is the time originally assigned by the flight schedule for each aircraft crossing its scheduling point. It is fixed by the original input data. The Scheduled Time of Arrival (STA) is a calculated time when aircraft cross its scheduling point.

For instance, the ETA of an arriving aircraft at runway implies the initial landing time assigned by the original flight schedule. The first flight in the schedule would arrive without any delay, but due to separation constraints and other factors, any following flights may face certain amount of delays. The STA of an arrival aircraft at runway is the scheduling time computed by the system. Usually only the first aircraft in the entire flight schedule will have its ETA equal to its STA because it is the first in the queue and has no need for any delay.

As for departures, the ETA at runway is the initial assigned departure time. Due to other arrivals and departures in front of it, the later in the departure line-up queue, the more likely it will have delays. Its STA on runway is the computed time for commencing departure.

#### 3.1.1.3 Sequencing decision variables

When aircraft are assigned to the same runway, they share at least one common scheduling point on their route, which is on the runway. When aircraft are assigned to the same route, they will share more common scheduling points. The sequencing decision variables determine the order with which two aircraft cross a common scheduling point on their assigned routes. This common scheduling point could be on runway, a departure fix, an arrival fix, or an intermediate scheduling point on a given route. Two routes may have multiple common sections. Separation requirement needs to be enforced at each scheduling point.

### 3.1.2 Given conditions

In this study, we considered three major conditions, the runway geometry, the direction of operation, which is either arrival or departure, and the traffic mix which implies particularly to arrival peak traffic and departure peak traffic. The details of the conditions are further expanded in the following chapters.

### 3.1.3 Optimization criteria

The operational capacity of an airport is not measured alone with airport throughput. It is in fact determined by a combination of the runway throughput and overall system delay, where the system delay is the sum of arrival delay and departure delay. An operational capacity of an airport is often defined as the maximum runway throughput under an acceptable level of system delay. Therefore, by minimizing overall system delay and maximizing airport throughput, we can effectively improve the airport operational capacity.

### 3.1.4 Constrains, i.e. complicated operation rules

In the real world, numerous constraints need to be considered when scheduling arrivals and departures for an airport. But safety is always the number one emphasis in the aviation world, thus the most important constraints are separation constraints.

Separation between any pair of aircraft has to maintain a minimum separation requirement. Usually the radar separation within a terminal airspace is 3NM. This implies any two successive aircraft passing through the same common scheduling point must fulfill the minimum time of separation at the scheduling point. Furthermore, there are runway separations between two arriving aircraft; between two departing aircraft; and between an arriving aircraft and a departing aircraft.

For instance, the minimum separation between two successive arrivals is 3 NM or wake turbulence separations if it is greater than 3 NM. The same separation standard also applies to two departures. The wake turbulence separation is defined by aircraft categories; usually the separation increases when the leading aircraft is heavier than the following aircraft.

When arrivals and departures use the same runway, the separation is slightly different. There are usually two situations, departure takeoffs before an arrival; or an arrival lands before a departure. In the first situation, the departure must commence departure before the arrival aircraft reaches 3NM from the runway threshold. In the second situation, once the aircraft has landed, it will take some time to slow down before it can turn off the runway; this time is defined here as runway occupancy time (ROT). ROT differs based on the category of the aircraft, i.e. a Heavy usually takes longer to slow down than a lighter aircraft, and it may take the runway exit farther down the runway. The departure cannot commence to depart until this arrival aircraft clears the runway.

Also included in this study is when arrival and departure use a pair of closely spaced parallel runways. Often in this case, one runway is explicitly used for arrivals and the other one is for departures only. Since arrival and departure are on two separated pieces of concrete, the ROT is insignificant. However, to protect the missed approach path for the arriving aircraft, the departure may still need to wait until the arriving aircraft passes its decision height, and sometime controllers may even wait until the arriving aircraft touchdown before clearing a departure. In either case, the time needed to separate a departure after an arrival on two parallel runways is usually less than the separation requirement if they are using the same runway. If the two runways are much farther apart, and operate independently, than there is no separation required between aircraft using different runways.

In this study, we also imposed the following operational rules:

- No passing rule - the system preserves the ordering of any pair of flights as in the initial flight schedule, and there is no overtaking at any point along the assigned route;
- First Come First Serve (FCFS);
- No early arrival or early departure in the system - STA of an aircraft cannot be earlier than its ETA;
- Each flight can only be assigned to one route at a time.

Apart from the above, the limitation of aircraft performance and airspace geometry must also be included. In real life operations, a controller may order an arriving aircraft to vector away from its flight path in order to ensure separation. Vectoring will increase the flight distance of the aircraft, but the geometric location of a fix and the runway set the minimum track distance of a route; and the aircraft speed determines the minimum flight time for a particular aircraft on an assigned route. Therefore, the transit time bound between any two points on a route has to obey the physical rules.

Application of windowing – in order to optimize the scheduling and assignment of a larger demand set, we adapted the use of a windowing technique to carve up the demand into a sequence of smaller demand sets. The windowing approach taken was to solve the first window, then we solved the second given the first window's solution. In general, the $k^{th}$ window is solved given the solution obtained for window k-1, k-2, … k-1. Previous window solutions effectively serve as additional constraints on future window solutions. This process is respected until all flights in the demand set have been scheduled and assigned. Note: overlap between successive demand windows was not considered (15).

It is important to recognize that not every operational constraints and metric could be accurately expressed mathematically. The reality is, a good optimal solution derived by an automatic system would provide helpful advisory in real life operations, but it may not always be the best solution.

### 3.1.5 Solution requirements

All aircraft in the ultimate solution need to have sufficient separation, to ensure that the solution is safe. A close proximity is when two or more aircraft are less than the minimum vertical or horizontal separation. Usually when aircraft tracks are parallel to one and other, it is easier to be controlled and maintain the required separation. When tracks of two or more aircraft cross each other, it causes the air traffic controller more attention in monitoring aircraft movements until they safely pass the crossing point. It is more difficult in the environment of a terminal area when many aircraft are changing speed and doing a climb or descent maneuver. Due to this consideration, one of the measurements for safety is if mid-air crossings are minimized. Other requirements for the solution include the processing time of producing a solution needs to be short enough. And, in order to make it more acceptable by air traffic controllers, the solution needs to be capable of coping with real traffic.  Most importantly, the goal of this study is to develop an effective solution.

## 3.2 Related Work and Relations

### 3.2.1 Arrival scheduling

Most of the related work has been focused on arrival scheduling problems.  C. Brinton from NASA Ames developed the Implicit Enumeration (IE) scheduling algorithm to optimize arrival aircraft sequence and schedules.  The algorithm adopted the foundation of the Traffic Management Advisor and operates in a dynamic feedback environment (17).  Abela et al. looked into two approaches for solving the problem of scheduling aircraft landing time in order to minimize costs, where costs are defined by the difference between aircraft landing times and the preferred landing time.  They developed a heuristic for the problem using a genetic algorithm (GA), and formulated the problem as a mixed integer program (MIP) to develop a branch and bound algorithm for its solution (18).  Lee and Davis from NASA Ames developed the Final Approach Spacing Tool (FAST) to incorporate the terminal area controller in early, iterative testing (9).  FAST is one of the few advanced automation tools that incorporated the controller’s job in its design.

### 3.2.2 Departure scheduling

There are few studies that considered scheduling problem for departures.  Anagnostakis et al. developed a framework and solution methodology for an automated decision-aiding system.  The objective of the work was to assist air traffic controllers in handling departure traffic and mitigate the adverse effects of ground congestion and delays (19).  Gupta et al. applied MILP for deterministically scheduling departure aircraft (4).  The study addressed the departure scheduling problem based on different queuing schemes for departures to access a runway.  The earliest takeoff times and an optional prioritization scheme for takeoff within a predefined time-window were also taken into consideration. Rathinam et al. applied dynamic programming method to solve departure scheduling problem (3).

### 3.2.3 Airspace movement

The studies mentioned above often focused on the scheduling problem on runway or on airport and omitted the complex operation in airspace. Gilbo developed a model which used dynamic time-dependent allocation of airport capacity and flows between arrival and departures coordinated with the operational constraints at runways and arrival and departure fixes as well as with dynamic traffic demands and weather. The model considered the runways and arrival and departure fixes jointly as a single system resource. The model took into account the interactions between runway capacity and capacities of fixes to optimize the traffic flow through the airport system (20). In 2004, Prevot et al. promoted an integrated air/ground system combining trajectory-orientation, data link communication, and airborne separation assistance as complementary components of a modernized airspace system (21). Zhang et al. presented an optimal sequencing model based on multi-approach routes, and developed a new efficient scheduling algorithm which utilized combinatorial optimization techniques to find the optimal aircraft arrival sequence and the optimal STAs for the aircraft at the runway threshold. The algorithm also enabled prioritization of aircraft according to their importance (22). Saraf and Slater proposed an optimal airport arrival scheduling algorithm in 2008. The algorithm worked within a hierarchical scheduling structure which consists of a scheduler at multiple points along the arrival route. They applied an Eulerian model-base optimization scheme to compute the optimal acceptance rates at all downstream metering points. The model provided maximum airport throughput while keeping sector counts within limits (23).

### 3.2.4 Integrated airport scheduling

Chen & Zhao used MILP models to provide optimal schedules for departures and arrivals at John-Kennedy airport (15). Bohme et al.(13), and Kim et al. also applied the MILP model to optimize runway assignment and reduction in aviation emissions (14). Provan applied dynamic MILP in strategic Runway configuration management (RCM) problem (24). These studies have proved the dynamic MILP method can effectively provide optimized solution for aircraft scheduling problem, especially when there is only one single stream of aircraft, i.e. single runway. We inserted the MILP solver to be part of the system we designed; details of MILP and the application in our system are further expanded in later sections.

### 3.2.5 Main differences from previous work

This study considered arrivals and departures parts in one system. Unlike many of previous work, this system applies different methods in optimizing runway assignment and scheduling for each runway. The natures of the two problems are different. The scheduling problem can be easily described linearly, but runway assignment is a discrete problem which have to consider many conditions and constraints in order to reach an operational optimal solution. As mentioned previously, we applied MILP method in scheduling; and applied knowledge and experiences of ATC operations to construct the intelligent system in optimize runway assignment which is most important for unevenly distributed air traffic. When defining the knowledge module, the controller acceptability was considered.

## 3.3 Exploring Optimization Methods

### 3.3.1 Knowledge base optimization (25)

As described by S. Hader, a typical knowledge base optimization problem usually consists of two modules, the knowledge base module and the optimization module.

#### 3.3.1.1 Knowledge base module - need a representation

There are two phases in this module. The first is to analyze the current system to identify the existing bottleneck and deficiency. Then transforming the knowledge to a different stage by specifying the parameters to change, the direction and magnitude of suitable changes to make the bottleneck and deficiencies disappear. Usually, the domain knowledge is represented as heuristics rules in form of IF < *condition* > THEN < *conclusion* >. Where the *condition* describes the situation in which this knowledge is applicable; and the *conclusion* describes changes to knowledge base elements (e.g. system designs, internal states) which have to be carried out if the rule becomes active (25).

#### 3.3.1.2 Optimization module

Various optimization techniques, optimization methods can be inserted in this module, like discrete search, generic algorithm (GA), fuzzy logic or others. In this thesis, the optimization system was presented that uses the knowledge-based approach in combination with intelligent optimization technique to optimize system modeled by appropriate analysis codes.

### 3.3.2 Overview of intelligent optimization methods

Several intelligent optimization methods were studied in order to determine the most efficient means of balancing runway utilization.

#### 3.3.2.1 Genetic Algorithms (GA) (5)

GA is one of Evolutionary Algorithms (EA) which generates solutions to optimization problems using techniques inspired by natural evolution (26). When observing evolution in nature, survivors of the environment are usually the fit individuals whose strong genes are carried on through generations by reproducing; while the unfit ones will die before generating offspring, and their characteristics will eventually cease to exist. The crossover and mutation of the survivors will produce the species that are most likely to be fitter than their parents and will have a better chance to survive in a given environment.

Over the years, GA has been applied on computational fluid mechanic in automotive design, engineering design, robotics, optimized telecommunications routing, trip, traffic and shipment routing, encryption and code breaking (26). To apply GA on the runway assignment problem, we set the minimum of overall airport delay or maximum utilization of runways as the measurements of the fitness of the system.

#### 3.3.2.2 Particle Swarm Optimization (PSO) (27)

When Kennedy and Eberhardt first developed the PSO method in mid 1990's, it was intended for simulating social behavior of a bird flock or fish school. It was then used to optimize problems by iteratively trying to improve a candidate solution with regard to a given measure of quality.

The following flowchart illustrates the basic PSO methodology:

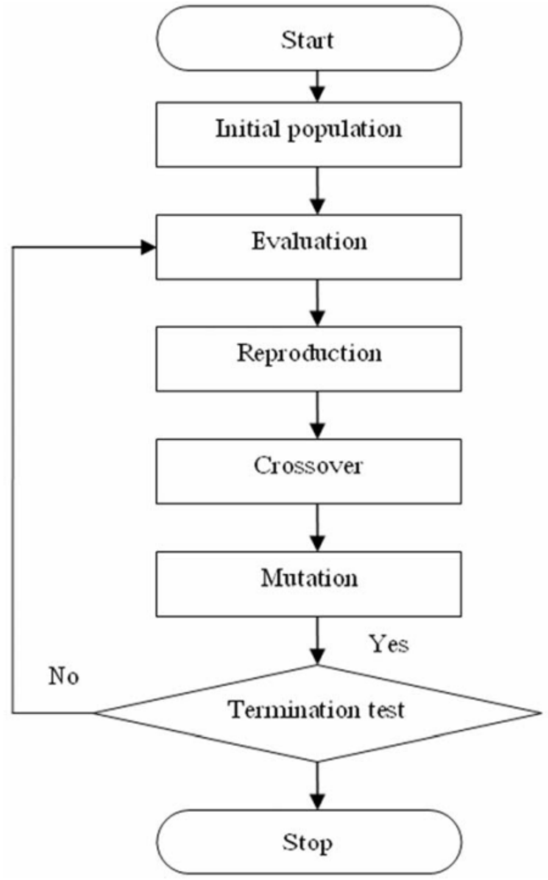


**Figure 3.3 A typical flow (Wei 2010)**

#### 3.3.2.3 Ant Colony Algorithms (27)

The algorithms are inspired by the behavior of natural ant colonies. The methodology of the algorithm starts with initializing pheromone of each ant, then evaluates the level of pheromone and select the path with a higher pheromone level. It is then update the local trail with the amount of pheromone, as well as the global trail with a shorter completed route. The evaluation, selection and updating processes are repeated until the shortest global route is found or the number of iteration reaches K, the predefined maximum number of iteration. The method has been applied on scheduling problem, telecommunication networks, vehicle routing problems, etc.

#### 3.3.2.4 Simulated Annealing (SA)

SA is another stochastic search method which is able to find a good approximation to the global optimum of a given function in a large search space (27). It is used to find an acceptable good solution in a fixed amount of time, rather than the best possible solution. At each step, the SA heuristic compares some neighboring states of the current states, and probabilistically decides between moving the system to another state or staying in the current state. One of the special characteristics in SA is the accepting of worse solution as it searches for the global optimal solution. The advantage of it is that the system would not be stuck with a local optimum (27).

After reviewing the advantages and settings for the above methods, fuzzy logic and other discrete optimization methods, generic algorithm is decided to be the optimization model in our knowledge-based system in order to obtain the optimized runway assignment. The set-up of this method of this system is detailed in the next chapter.

# Chapter 4 Overview of Solution Strategy and Problem Formulation

## 4.1 Solution Strategies

The closed-loop system is assembled by integrating two optimization modules: advanced dynamic scheduling system using a self-contained MILP (15) solver to coordinate both departure and arrival in order to compute a flight schedule for each runway; and a knowledge based intelligent optimization algorithm to balance runway utilization. Figure 4.1 illustrates the closed-loop system architecture.

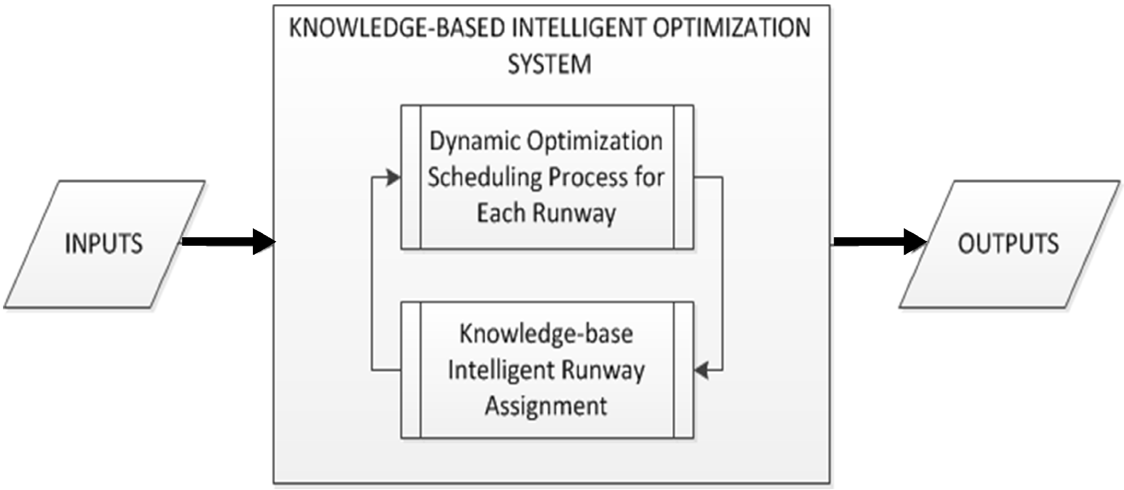


**Figure 4.1 System Design Flow chart**

### 4.1.1 Initial solution

The process of MILP solutions with fixed routes is applied to each runway. In this process, each individual arrival aircraft and departure aircraft is assigned to a default route.

For arrivals, these routes link the arrival fix where the aircraft enter the terminal airspace to a particular landing runway; and for departures, the routes link a particular departure runway to the departure fix where aircraft exit the terminal airspace. The default routes are the ones with shortest flight distances. This implies that the runway associated with the default route is the available runway closer to the arrival or departure fix. These routes are fixed in this process, and the MILP optimization produces optimal STAs at the multiple scheduling points.

In this study, the First-Come-First-Served (FCFS) algorithm is implemented in the process of initial solution. The FCFS means all flights are first sorted in ascending order based on their ETAs at the first scheduling point on their routes, and then each flight is further scheduled while satisfying separation and/or other constraints on a FCFS basis. This implies that the first flight in the entire set of the traffic flow would be permitted to travel on its assigned route without any delay. And each of the remaining flights is scheduled one by one following their position in the FCFS order.

The FCFS algorithm is applied to arrival traffic and departure traffic respectively. The sequence between arrival and departure is determined via the MILP optimization process. The FCFS algorithm strongly resembles what human controllers would do in the real world, but it may not produce the most optimal solution. All routes in this process are fixed, that implies runway assignment is fixed within this process. In other words, the process of finding the initial solution does not include performing the optimization in runway assignment. This is executed by the runway assignment module of the system.

### 4.1.2 Intelligent methods for runway assignment

The second module of the system applies a knowledge-base intelligent optimization method to enhance overall airport efficiency by finding a more suitable runway for each aircraft. The criteria of the evaluation of this runway assignment module are made based on minimizing overall airport delay and increasing airport throughput.

As stated previously, the most convenient runway to use, by default, would be the one nearest to the direction of traffic flow. For instance, most inbound traffic for ATL is either from northeast direction such as New York or Boston or from northwest direction such as west coast, and most outbound traffic is heading either northeast or northwest. Without balancing runway utilization, most traffic would prefer to land or takeoff using the pair of runways on the north side of the airport. It is because the flying distance is shorter than being re-routed to or from the runways on the south side of the airport. As shown in Figure 2.2, radar tracks for inbound traffic from the north are thicker than those from the south, and this traffic has already been balanced with many arrivals from the north being rerouted to the south side of the airport. For example, some arrivals originating from northeast had probably been re-routed farther southeast when they passed Charlotte to enter the terminal airspace from the southeast entrance. With the latest development of Performance Based Navigation (PBN) technology, flights could be packed more closely than before; it may open up future opportunities for more parallel arrival routes entering the terminal airspace from the north. Thus, aircraft would not have to be re-routed around the terminal airspace, but would join the final approach route to runways on the south side of the runway within the terminal airspace. However, that would require a more robust/efficient plan for runway assignment. Currently, many runway assignment studies only focus on optimization without considering the geometric condition of the flight routes, and the potential increases in controller workload.

This runway assignment module of the system first takes the default runway assignment, and calculates an estimated traffic demand on each runway, and then decides whether to re-assign the aircraft to another runway based on the overall airport delay, utilization of runways, and the accessibility of the runway. Due to the complicity of this decision making process, we applied a knowledge-based intelligent optimization method. The method not only simplifies the calculation but allows inserting our considerations to make the solution more appealing to operators in the real world, like air traffic controllers. The accessibility of the runway is determined by the geometric relationship of the runway with the departure fix or the arrival fix, the arrival route or departure route of the previous traffic using that alternative runway. Each time, the module takes a series of aircraft assigned previously to each runway within a time window, then selects randomly from a pool of aircraft based on the accessibility to the other runways, then process a crossover or mutation operation to form new series of aircraft for each runway. The Figure 4.2 and Figure 4.3 below depict the crossover and mutation operators on a series of aircraft assigned to two independent parallel runways.

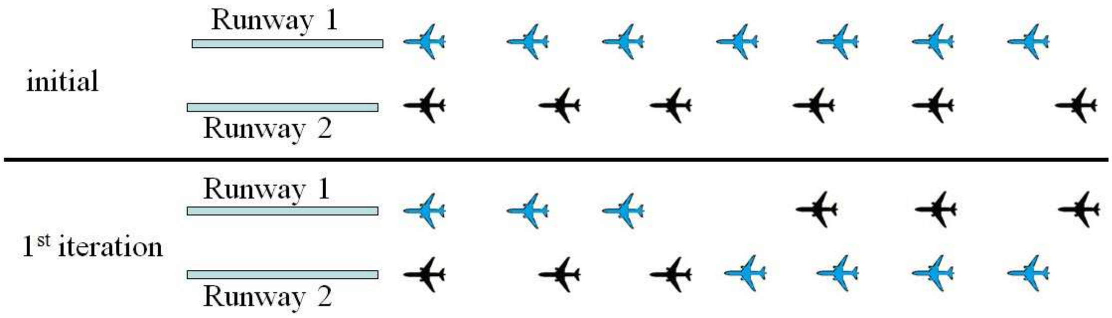


**Figure 4.2 The crossover operator**

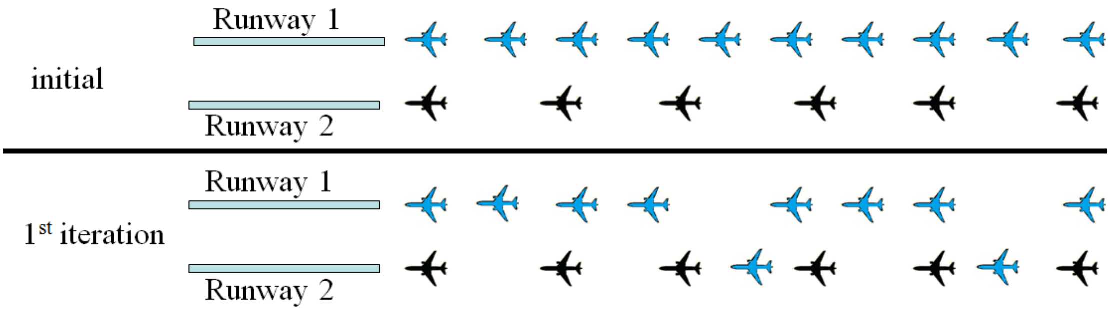


**Figure 4.3 The mutation operator**

Both crossover and mutation operators are implied whenever it is suitable. The new series of aircraft are then feed to the sequencing module to get the most optimal STAs. The iteration process continues until the ultimate best solution achieved or the restriction of calculation time is reached, whichever comes first. The pool of the aircraft being considered for further selection was chosen based on the knowledge of practical air traffic control operation to eliminate the amount of mid-air crossing. Figure 4.4 illustrates the process.

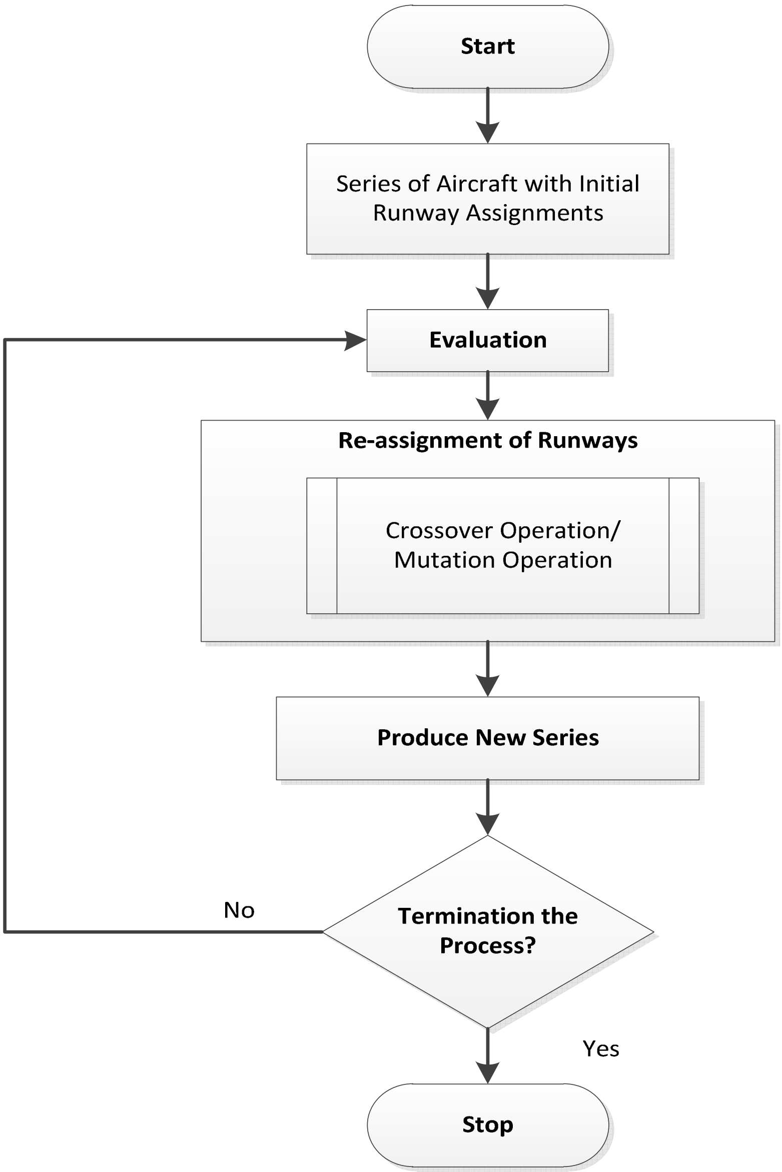


**Figure 4.4 The flowchart for runway assignment process**

## 4.2 Mathematical Formulation

In order to leverage open-source, self-contained Mixed Integer Linear Programming (MILP) solvers, the non-linear constraints developed in the previous section need to transform into a set of equivalent linear constraints. The following Mixed Integer Linear Programming (MILP) formations are adopted from Chen's Advanced MILP system with adjustment to the uniqueness of our system (15).

Definitions and Notations:

| | |
|---|---|
| $N_{arr}$ | Total number of arrival aircraft |
| $N_{dep}$ | Total number of departure aircraft |
| $X$ | Total number of arrival routes that are available to be assigned to based on the runway configuration |
| $Y$ | Total number of departure routes that are available to be assigned to based on the runway configuration |
| $P$ | Total number of scheduling points on an arrival route |
| $Q$ | Total number of scheduling points on a departure route |
| $K$ | Total number of common scheduling points between two routes |
| $i$ | Index for arriving aircraft, $\forall\, i \in N_{arr}$; sorted in ascending order of earliest un-impeded ETAs |
| $j$ | Index for departing aircraft, $\forall\, j \in N_{dep}$; sorted in ascending order of earliest un-impeded ETAs |
| $x$ | Index for arrival routes, $\forall\, x \in X$, each route uniquely connects an arrival fix to the point at landing threshold of a particular runway |
| $y$ | Index for departure routes, $\forall\, y \in Y$, each route uniquely connects the departure end of a particular runway to a departure fix (exit point of the TMA) |
| $p$ | Index for scheduling points on arrival routes, $\forall\, p \in P$ |
| $q$ | Index for scheduling points on departure route, $\forall\, q \in Q$ |
| $k$ | Index for common section, $\forall\, k \in K$ |

### 4.2.1 Mathematical expressions of decision variables

There are three categories of decision variables: route decision variables, continuous time decision variables, and sequencing decision variables.

#### 4.2.1.1 Route assignments which imply to runway assignment

Runway usage can be implicitly defined by using the route structure

$$\mathrm{r}_{\mathrm{i}}^{\mathrm{x}} = \begin{cases} 1, & \text{if arrival route x is assigned to an arrival aircraft i} \\ 0, & \text{otherwise} \end{cases}$$

where $1 \leq i \leq N_{arr}$ and $1 \leq x \leq X$. That means, when the computed solution shows $\mathrm{r}_{\mathrm{i}}^{\mathrm{x}} = 1$, the arrival aircraft $i$ is assigned to route $x$, otherwise, aircraft $i$ cannot take route $x$. Thus, if a constraint for runway usage is imposed to a flight, then the arrival route $x$ associates a particular arrival fix to a certain runway would be inaccessible for the fight, $\mathrm{r}_{\mathrm{i}}^{\mathrm{x}} = 0$.

$$\mathrm{r}_{\mathrm{j}}^{\mathrm{y}} = \begin{cases} 1, & \text{if departure route y is assigned to a departure aircraft j} \\ 0, & \text{otherwise} \end{cases}$$

where $1 \leq j \leq N_{dep}$ and $1 \leq y \leq Y.$ That mean, when the computed solution shows $\mathrm{r}_{\mathrm{j}}^{\mathrm{y}} = 1$, the departure aircraft $j$ is assigned to route $y$, otherwise, aircraft j cannot take route y. Thus, if a constraint for runway usage is imposed to a flight, then the departure route y associates to a certain runway to a particular departure fix would be inaccessible for the fight, $\mathrm{r}_{\mathrm{j}}^{\mathrm{y}} = 0$.

#### 4.2.1.2 Scheduling assignments

The following decision variable represents the continuous time of arrival at various scheduling points.

a. Points on an arrival route: $1 \leq p \leq P$,
   Where $p = 1$ when the arrival enters the TMA, and $p = P$ when the arrival cross the runway landing threshold.
b. Points on a departure route: $1 \leq q \leq Q$,

Where $q = 1$ when the departure aircraft takes off from the runway, and $q = Q$ when the departure exits the TMA.

Thus, $\hat{\mathrm{t}}_{\mathrm{ip}}$ is the initial planned ETA at scheduling point p for an arrival aircraft i

$\hat{\mathrm{t}}_{\mathrm{jq}}$ is the initial planned ETA at scheduling point q for a departure aircraft j

$\mathrm{t}_{\mathrm{ip}}$ is the computed STA at scheduling point p for an arrival aircraft i

$\mathrm{t}_{\mathrm{jq}}$ is the computed STA at scheduling point q for a departure aircraft j

#### 4.2.1.3 Sequencing decision variables

The sequencing decision variables determine the order with which two aircraft cross a common scheduling point on their assigned routes. This common scheduling point could be a runway, a departure fix, an arrival fix, or an intermediate scheduling point on a given route. Two routes may have multiple common sections. The sequence decision at each common section could be different. For instance, the sequence of aircraft A and aircraft B on their common section k could be different from their sequence on their next common section k+1. Thus, for a total number of K common sections for two flights those need to be sequenced, there could be K sequence decisions needed to be determined.

$$\lambda^{\mathrm{k}}_{\mathrm{i_1 i_2}} = \begin{cases} 1, & \text{if arrival } \mathrm{i_1} \text{is ahead of arrival } \mathrm{i_2} \text{on their kth common section} \\ 0, & \text{otherwise} \end{cases}$$

$$\lambda^{\mathrm{k}}_{\mathrm{j_1 j_2}} = \begin{cases} 1, & \text{if arrival } \mathrm{j_1} \text{is ahead of arrival } \mathrm{j_2} \text{on their kth common section} \\ 0, & \text{otherwise} \end{cases}$$

$$\lambda^{\mathrm{k}}_{\mathrm{ij}} = \begin{cases} 1, & if\ arrival\ i\ is\ ahead\ of\ departure\ j\ on\ their\ kth\ common\ section \\ 0, & otherwise \end{cases}$$

Where $1 \le i \le N_{arr}$ $1 \le i \le N_{dep}$ and $1 \le k \le K.$

It requires different separation standards between two arrival aircraft than two departure aircraft, or a pair of arrival and departure aircraft. The sequencing decision variables allow the implementation of different separation requirements.

### 4.2.2 Optimization criteria

The following are the objective functions according to the pertinent objectives:

Minimize Overall System Delay:

Equation 4-1

$$\operatorname*{Min}_{A,B,C} I \ = \sum_{i=1}^{N_{arr}} \omega_i\left(t_i^{runway} - \hat{t}_i^{runway}\right) + \ \sum_{j=1}^{N_{dep}} \omega_j\left(t_j^{runway} - \hat{t}_j^{runway}\right)$$

Maximize Throughput:

Equation 4-2

$$\operatorname*{Min}_{A,B,C} J = \ \left(t_N^{runway} - \ t_1^{runway}\right)$$

Such that,

| | |
|---|---|
| A | represents the continuous time decision variable |
| B | represents the route decision variables which imply to runway assignments |
| Z | represents the sequencing decision variables |
| $\omega_i$, $\omega_j$ | are the weighting coefficients for delay |
| $t_i^{runway}$ | is the final computed landing time STA for arrival aircraft i to land on a runway |
| $\hat{t}_i^{runway}$ | is the initial planed landing time ETA for arrival aircraft i to land on a runway |
| $t_j^{runway}$ | is the final computed departure time STA for departure aircraft j to takes off from a runway |
| $\hat{t}_j^{runway}$ | is the initial planned departure time ETA for departure aircraft j to take off from a runway |

Therefore,

| | |
|---|---|
| $\left(t_i^{runway} - \ \hat{t}_i^{runway}\right)$ | represents the delay for arrival aircraft i |
| $\left(t_j^{runway} - \ \hat{t}_j^{runway}\right)$ | represents the delay for departure aircraft j |
| $\left(t_N^{runway} - \ t_1^{runway}\right)$ | is regarding to the time from first runway departure/arrival till the last runway departure/arrival |

### 4.2.3 Mathematical expressions of constraints

#### 4.2.3.1 Single Route Constraints

Aircraft can only be assigned to one route in each iteration.

Unique arrival route for aircraft $i$, Equation 4-3

$$\sum_{x=1}^{X} r_i^x = 1$$

Unique departure route for aircraft $j$, Equation 4-4

$$\sum_{y=1}^{Y} r_j^y = 1$$

#### 4.2.3.2 Sequencing Constraints

$$\boldsymbol{\lambda_{\mathrm{i_1 i_2}}^{\mathrm{k}} - \frac{1}{M}\left(t_{i_2 p_2} - t_{i_1 p_1}\right) + M\left(2 - r_{i_1}^{x_1} - r_{i_2}^{x_2}\right) \geq 0} \qquad \text{Equation 4-5}$$

$$\boldsymbol{\lambda_{\mathrm{i_1 i_2}}^{\mathrm{k}} - \frac{1}{M}\left(t_{i_2 p_2} - t_{i_1 p_1}\right) - M\left(2 - r_{i_1}^{x_1} - r_{i_2}^{x_2}\right) \leq 1} \qquad \text{Equation 4-6}$$

$$\boldsymbol{\lambda_{\mathrm{j_1 j_2}}^{\mathrm{k}} - \frac{1}{M}\left(t_{j_2 q_2} - t_{j_1 q_1}\right) + M\left(2 - r_{j_1}^{y_1} - r_{j_2}^{y_2}\right) \geq 0} \qquad \text{Equation 4-7}$$

$$\boldsymbol{\lambda_{j_1 j_2}^{k} - \frac{1}{M}\left(t_{j_2 q_2} - t_{j_1 q_1}\right) - M\left(2 - r_{j_1}^{y_1} - r_{j_2}^{y_2}\right) \leq 1} \qquad \text{Equation 4-8}$$

$$\boldsymbol{\lambda_{ij}^{k} - \frac{1}{M}\left(t_{jq} - t_{ip}\right) + M\left(2 - r_i^x - r_j^y\right) \geq 0} \qquad \text{Equation 4-9}$$

$$\boldsymbol{\lambda_{ij}^{k} - \frac{1}{M}\left(t_{jq} - t_{ip}\right) - M\left(2 - r_i^x - r_j^y\right) \leq 1} \qquad \text{Equation 4-10}$$

$$\boldsymbol{t_{i_2 p_2}} - \boldsymbol{t_{i_2 p_2}} > 0 \qquad \text{Equation 4-11}$$

$$\boldsymbol{\lambda_{\mathrm{i_1 i_2}}^{\mathrm{k}} \geq \frac{1}{M}\left(t_{i_2 p_2} - t_{i_1 p_1}\right)} \qquad \text{Equation 4-12}$$

$$\boldsymbol{\lambda_{\mathrm{i_1 i_2}}^{\mathrm{k}} \leq \frac{1}{M}\left(t_{i_2 p_2} - t_{i_1 p_1}\right) + 1} \qquad \text{Equation 4-13}$$

### 4.2.3.3 Separation Requirements

$$(t_{i_2p_2} - t_{i_1p_1}) + M\left(3 - \lambda^k_{i_1i_2} - r^{x_1}_{i_1} - r^{x_2}_{i_2}\right) \geq \delta\left(\lambda^k_{i_1i_2}, c_{i_1}, c_{i_2}, p_1, p_2\right) \qquad \text{Equation 4-14}$$

$$-(t_{i_2p_2} - t_{i_1p_1}) + M\left(2 + \lambda^k_{i_1i_2} - r^{x_1}_{i_1} - r^{x_2}_{i_2}\right) \geq \delta\left(\lambda^k_{i_1i_2}, c_{i_1}, c_{i_2}, p_1, p_2\right) \qquad \text{Equation 4-15}$$

$$(t_{j_2q_2} - t_{j_1q_1}) + M\left(3 - \lambda^k_{j_1j_2} - r^{y_1}_{j_1} - r^{y_2}_{j_2}\right) \geq \delta\left(\lambda^k_{j_1j_2}, c_{j_1}, c_{j_2}, q_1, q_2\right) \qquad \text{Equation 4-16}$$

$$-(t_{j_2q_2} - t_{j_1q_1}) + M\left(2 - \lambda^k_{j_1j_2} - r^{y_1}_{j_1} - r^{y_2}_{j_2}\right) \geq \delta\left(\lambda^k_{j_1j_2}, c_{j_1}, c_{j_2}, q_1, q_2\right) \qquad \text{Equation 4-17}$$

$$(t_{jq} - t_{ip}) + M\left(3 - \lambda^k_{ij} - r^x_i - r^y_j\right) \geq \delta\left(\lambda^k_{ij}, c_i, c_j, p, q\right) \qquad \text{Equation 4-18}$$

$$-(t_{jq} - t_{ip}) + M\left(2 - \lambda^k_{ij} - r^x_i - r^y_j\right) \geq \delta\left(\lambda^k_{ij}, c_i, c_j, p, q\right) \qquad \text{Equation 4-19}$$

$$(t_{i_2p_2} - t_{i_1p_1}) \geq \delta\left(\lambda^k_{i_1i_2}, c_{i_1}, c_{i_2}, p_1, p_2\right) \qquad \text{Equation 4-20}$$

$$-(t_{i_2p_2} - t_{i_1p_1}) + M \geq \delta\left(\lambda^k_{i_1i_2}, c_{i_1}, c_{i_2}, p_1, p_2\right) \qquad \text{Equation 4-21}$$

### 4.2.3.4 Limitations due to Aircraft Performance

$$(t_{i(p+1)} - t_{ip}) + M\left(1 - \lambda^x_i\right) \geq \tau_{min}(c_i, p, p+1) \qquad \text{Equation 4-22}$$

$$(t_{i(p+1)} - t_{ip}) - M\left(1 - \lambda^x_i\right) \leq \tau_{max}(c_i, p, p+1) \qquad \text{Equation 4-23}$$

$$(t_{j(q+1)} - t_{jq}) + M\left(1 - \lambda^y_j\right) \geq \tau_{min}(c_j, q, q+1) \qquad \text{Equation 4-24}$$

$$(t_{j(q+1)} - t_{jq}) - M\left(1 - \lambda^y_j\right) \leq \tau_{max}(c_j, q, q+1) \qquad \text{Equation 4-25}$$

Where $\tau_{min}$ and $\tau_{max}$ are the feasible range of time when aircraft is feasible to travel from one scheduling point to the next. The time is defined by the distant between the two points, and the performance of that particular aircraft type, i.e. how fast it can go. Usually, to reduce the uncertainties, flight procedures restrict speed of aircraft within the terminal aircraft, i.e. under 250kt after entering TMA. In that case, performance of different aircraft would tend to be very similar. However, the distance could be changed due to vectoring. Within the terminal airspace, controllers often guide aircraft through radar vectoring; the result increases the flight distance in order to ensure the aircraft meet their separation standards.

The time when an arrival aircraft crosses the runway landing threshold is identical to the time crosses its last scheduling point on the route. Thus,

$$t_i^{runway} \equiv t_P^x$$

Equation 4-26

$$\hat{t}_i^{runway} \equiv \hat{t}_P^x$$

Equation 4-27

The time when a departure aircraft takes off from the runway is same as it crosses its first scheduling point on the route. Thus,

$$t_j^{runway} \equiv t_1^y$$

Equation 4-28

$$\hat{t}_j^{runway} \equiv \hat{t}_1^y$$

Equation 4-29

We assume there is no early arrival or early departure.

$$t_{ip} \geq \hat{t}_{ip}$$

Equation 4-30

$$t_{jq} \geq \hat{t}_{jq}$$

Equation 4-31

The system adopts a sequential dynamic scheduling system in computing schedule landing and takeoff on an individual runway. Figure 4.5 illustrates the scheduling window in a sequential scheduling system. The planning horizon is referring to the time interval in process, which starts at a certain look-ahead time from now (at the origin) and extends indefinitely to the right into the future. Unlike a static scheduling strategy carrying the scheduling process through the entire traffic sample window at once, the entire planning horizon is dived into a series of small scheduling windows in a dynamic scheduling system. Each scheduling window has the same length of time, and is sequentially aligned throughout the planning horizon. A static algorithm is applied to each of the scheduling windows. Thus, the computation time for each scheduling window could be significantly reduced due to the size of the window. It will potential allow the system to accept traffic data in real time. The downside is, additional constraints would have to consider the interaction of scheduled outcomes in adjacent windows.

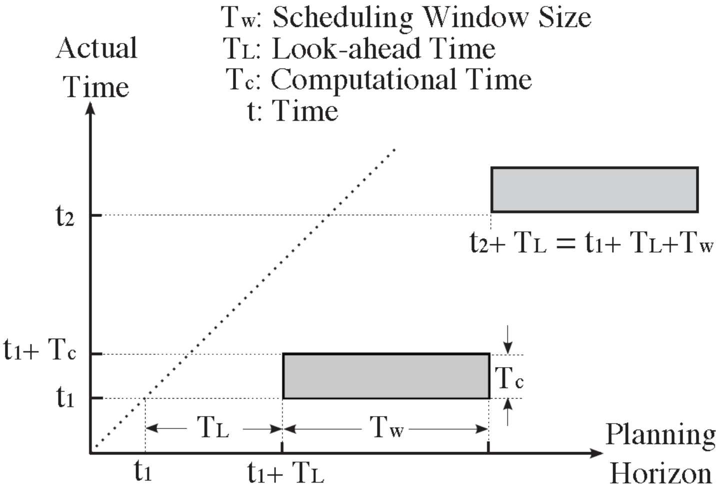


**Figure 4.5 The timeline of scheduling window (Chen, 2012)**

Since it takes time for an aircraft to fly from one scheduling point to another, it is possible that a single aircraft may fall into two sequential scheduling windows. In this case, as FCFS approach, we lock the STAs of the aircraft, and carry it over to the next scheduling window. Figure 4.6 shows the run-time sequence diagram for dynamic scheduling.

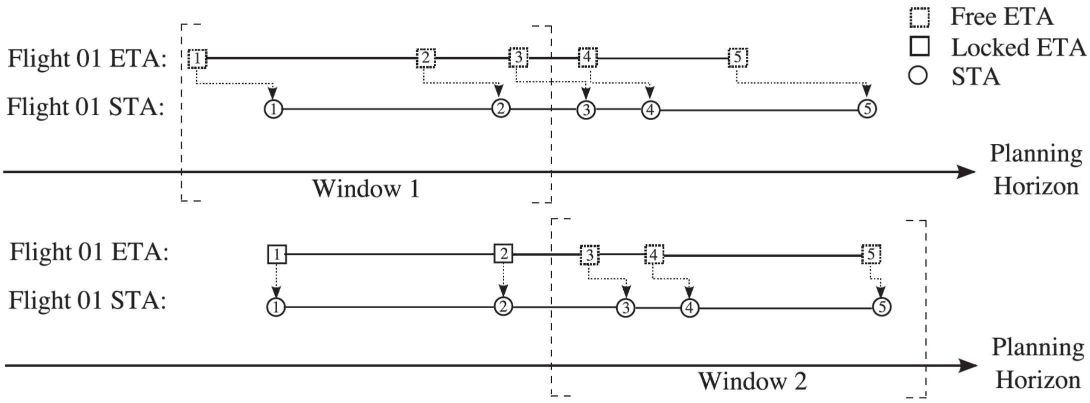


**Figure 4.6 Dynamic Scheduling over Multiple Scheduling Windows (Chen, 2012)**

# Chapter 5 Numerical Simulation

## 5.1 Simulation Model Development

The simulation program was written in Java and the academic version of “Gurobi Optimizer” from Gurobi Optimization was employed as the solver for MILP algorithms. The version of “Gurobi Optimizer” used for the simulations is 5.0.

In order to provide an optimal scheduling solution for a specific airport, it needs input data that includes the original traffic schedule which provides Estimated Time of Arrival (ETA) for each flight at all its scheduling points. The data is then entered into the system to determine the optimal runway assignment and optimal schedule. The following figure illustrates the flow of data.

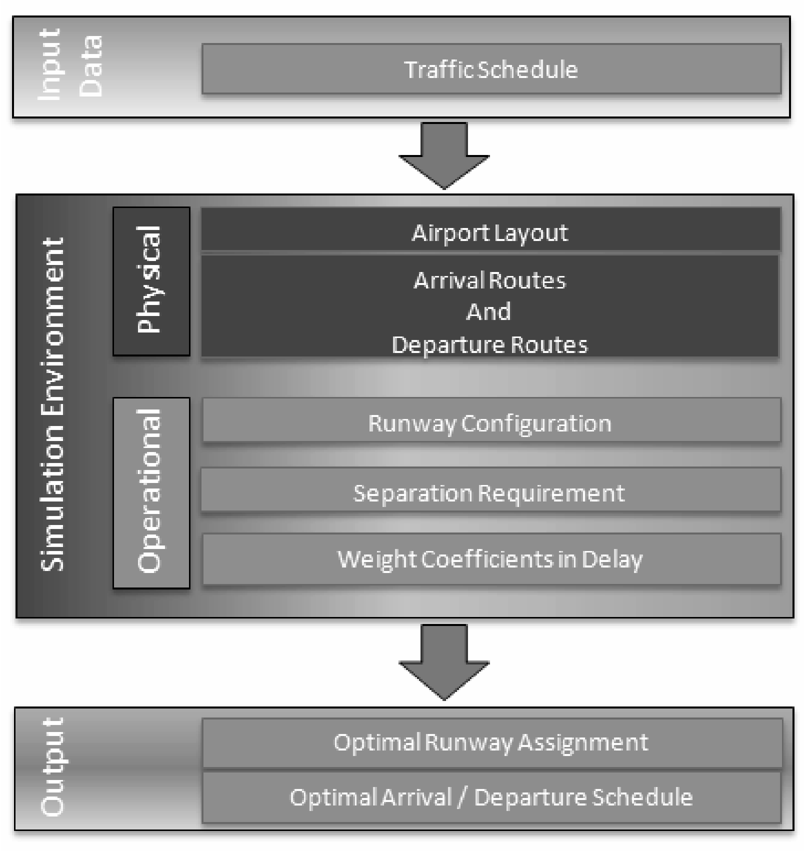


**Figure 5.1 Data flow in the system**

The simulation environment of the system can be divided into physical environment, and operational environment.

Physical environment is the physical conditions of the airport and its surrounding airspace:

- Airport layout which in fact implies the runway layout;
- Arrival routes, routes defined from arrival fixes to the approach end of the runway;
- Departure routes, routes defined from departure end of the runway to departure fixes.

Operational environment consist of the operational rules and constraints,

- Runway configuration indicates which departure runway, arrival runway, and the runway dependency on each other;

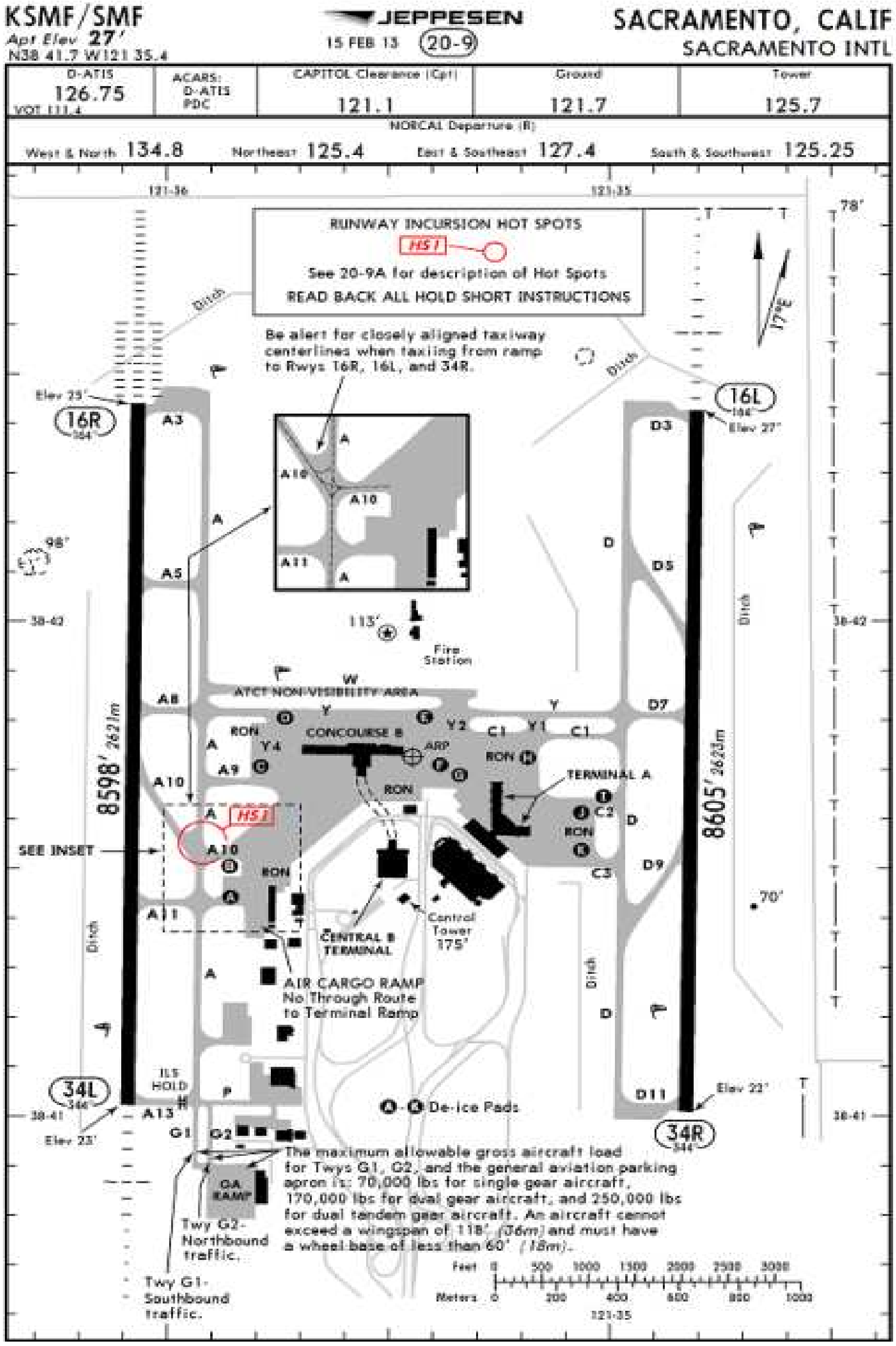
- Separation requirement includes all airborne separations and runway separations;
- Weight coefficients in delay prioritize aircraft based on operational considerations;
- An Operational window is also needed to be set up, which is the time-window used in the simulation.

## 5.2 Airport Models and Traffic Samples

The functionality of the system has been verified by performing 8 different test scenarios. The traffic data used in all scenarios were based on real traffic data from four airports, the Sacramento International Airport (KSMF), the Tacoma International Airport (KSEA), the Orlando International Airport (KMCO) and the Phoenix Sky Harbor International Airport (KPHX). All four airports have been listed in the top 30 busiest airports in the US, and all four airports have at least two parallel runways. Section 5.2.1 details the airport models for all four airports, which include runway layout and, arrival and departure routes under different runway configurations. It is followed by Section 5.3 , which explains the detailed traffic data used in the simulation.

### 5.2.1 Airport models:

#### 5.2.1.1 Sacramento International Airport, KSMF



RUNWAY INCURSION HOT SPOTS
HS1
See 20-9A for description of Hot Spots
READ BACK ALL HOLD SHORT INSTRUCTIONS

Be alert for closely aligned taxiway centerlines when taxiing from ramp to Rwys 16R, 16L, and 34R.

A-K De-ice Pads

The maximum allowable gross aircraft load for Twys G1, G2, and the general aviation parking apron is: 70,000 lbs for single gear aircraft, 170,000 lbs for dual gear aircraft, and 250,000 lbs for dual tandem gear aircraft. An aircraft cannot exceed a wingspan of 118' (36m) and must have a wheel base of less than 60' (18m).

Figure 5.2 Airport Layout of Sacramento Airport (KSMF) (Source: JeppView)

KSMF has a pair of parallel runways and it is assumed that both runways operates as dual-use runways, and can be operated simultaneously.

The traffic scenario in the simulation is when KSMF operates under its North Flow runway configuration.  The following figure illustrates the arrival and departure paths of the airport during its North flow operation based on the Four Corner Post terminal airspace configuration.

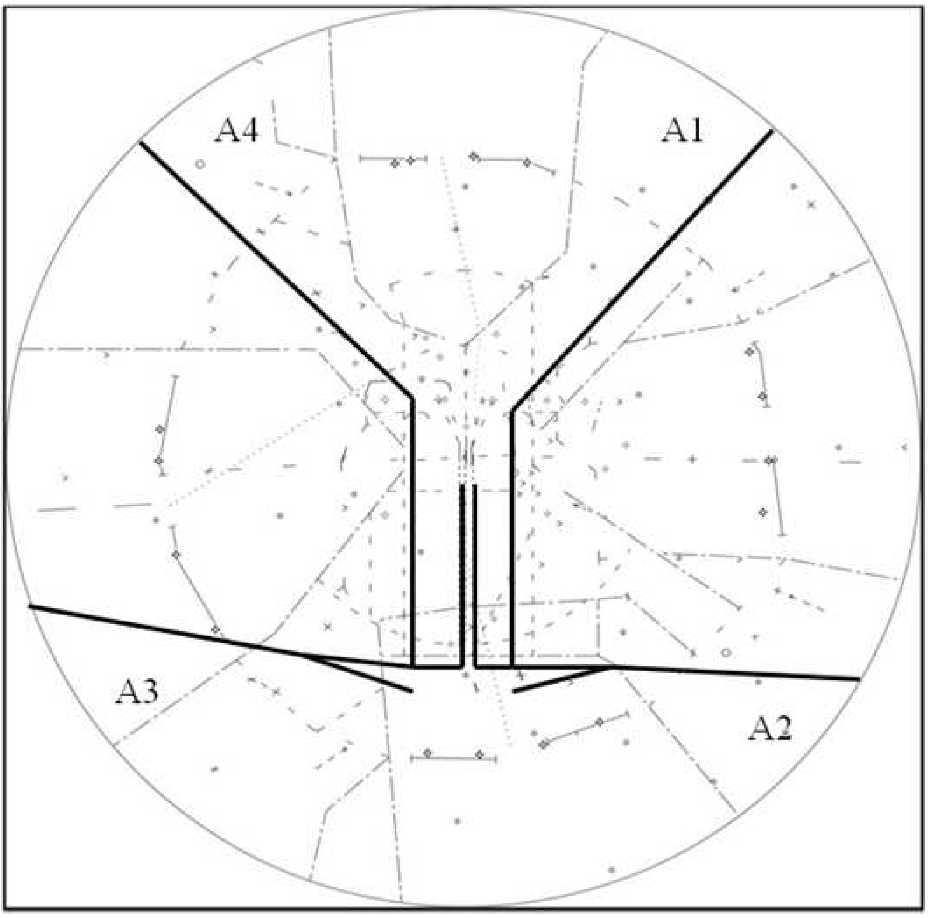


**Figure 5.3 Runway configuration of KSMF - North Flow Arrival**

### 5.2.1.2 Orlando International Airport, KMCO

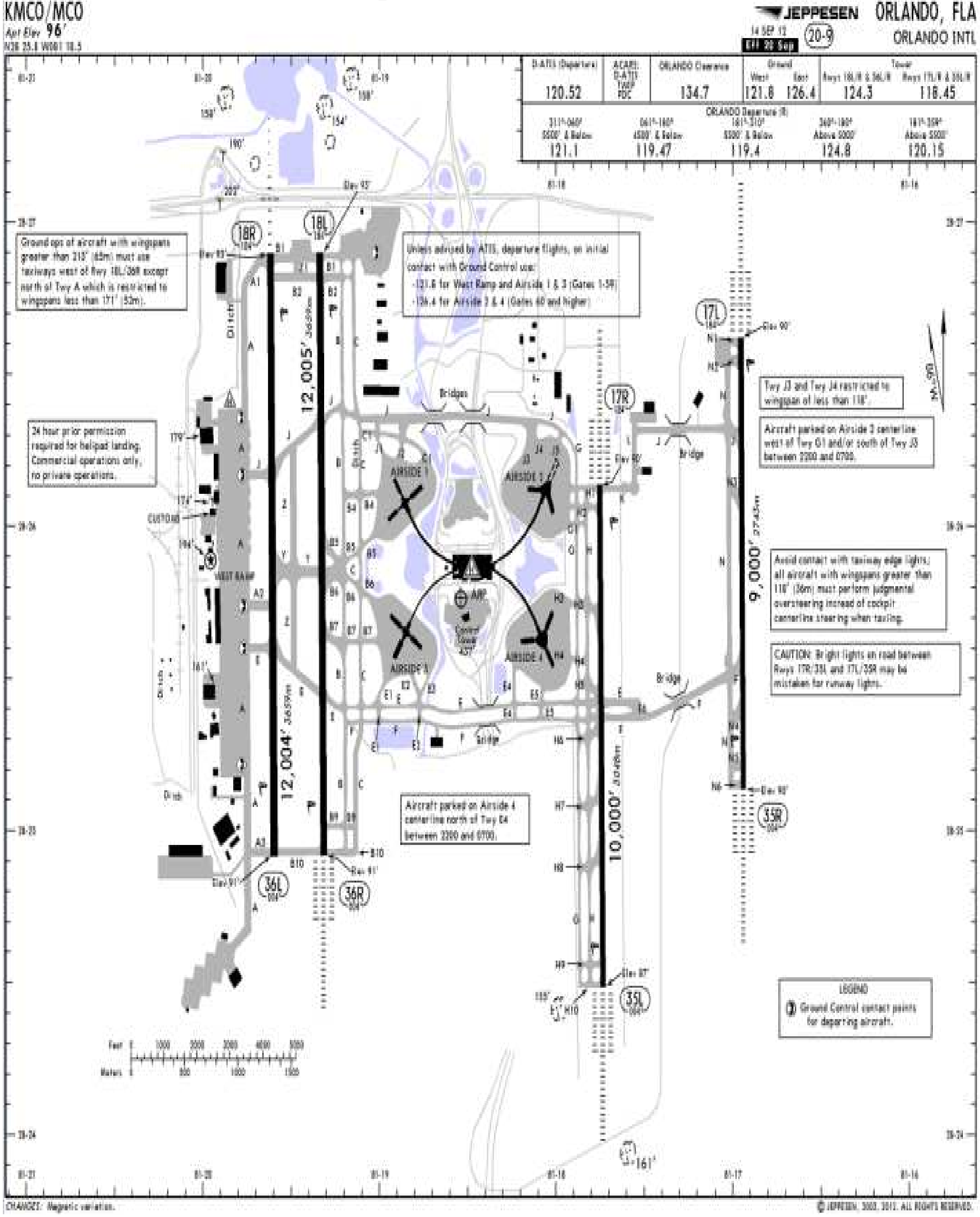


Figure 5.4 Airport Layout of Orlando International Airport (KMCO) (Source: JeppView)

KMCO has four parallel runways. The pair of runways on the West (18R/36L and 18L/36R) is closely spaced parallel runways, where one runway is used for departure and the other one is used for arrival. It is assumed that the East most runway (17L/35R) is closed for operation, and the runway East of the terminal (17R/35L) operates as a dual-use runway, and can be operated simultaneously with the pair of runways on the West side of the terminal.

The traffic scenario in the simulation is when KMCO operates under its South Flow runway configuration. The following figure illustrates the arrival and departure paths of the airport during its South flow operation based on the Four Corner Post terminal airspace configuration.

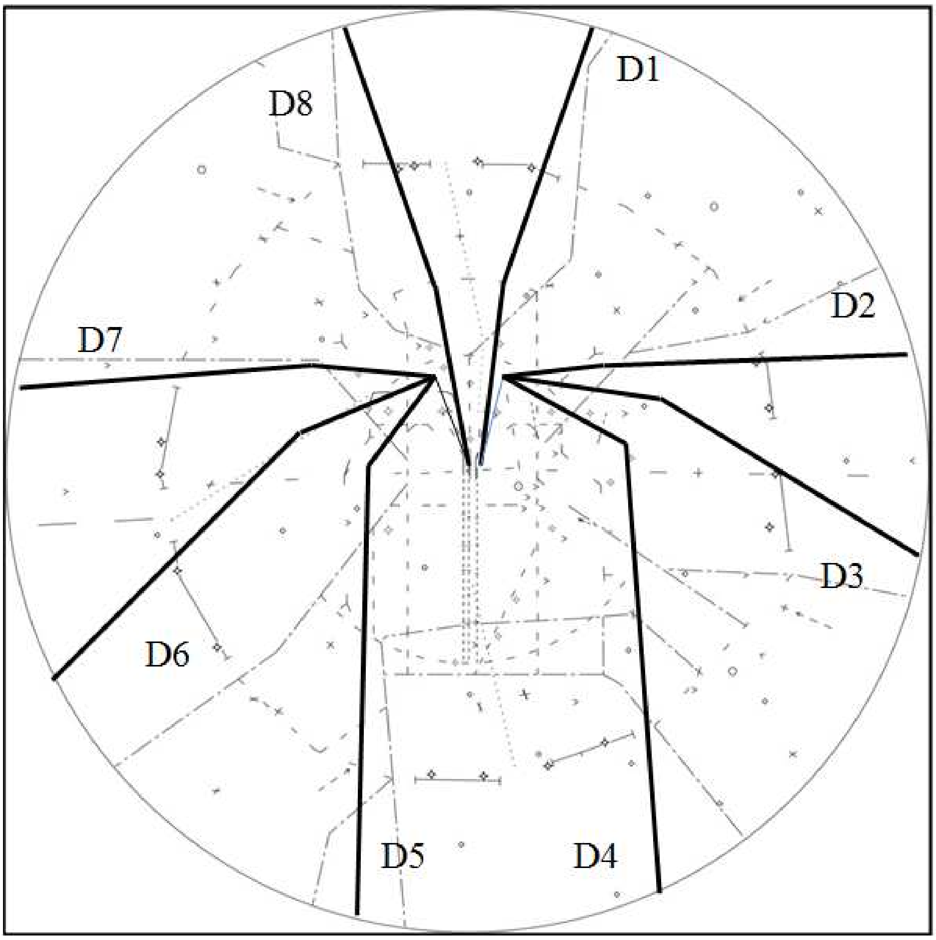


**Figure 5.5 Runway configuration of KMOC - North Flow Departure**

### 5.2.1.3 Tacoma International Airport, KSEA

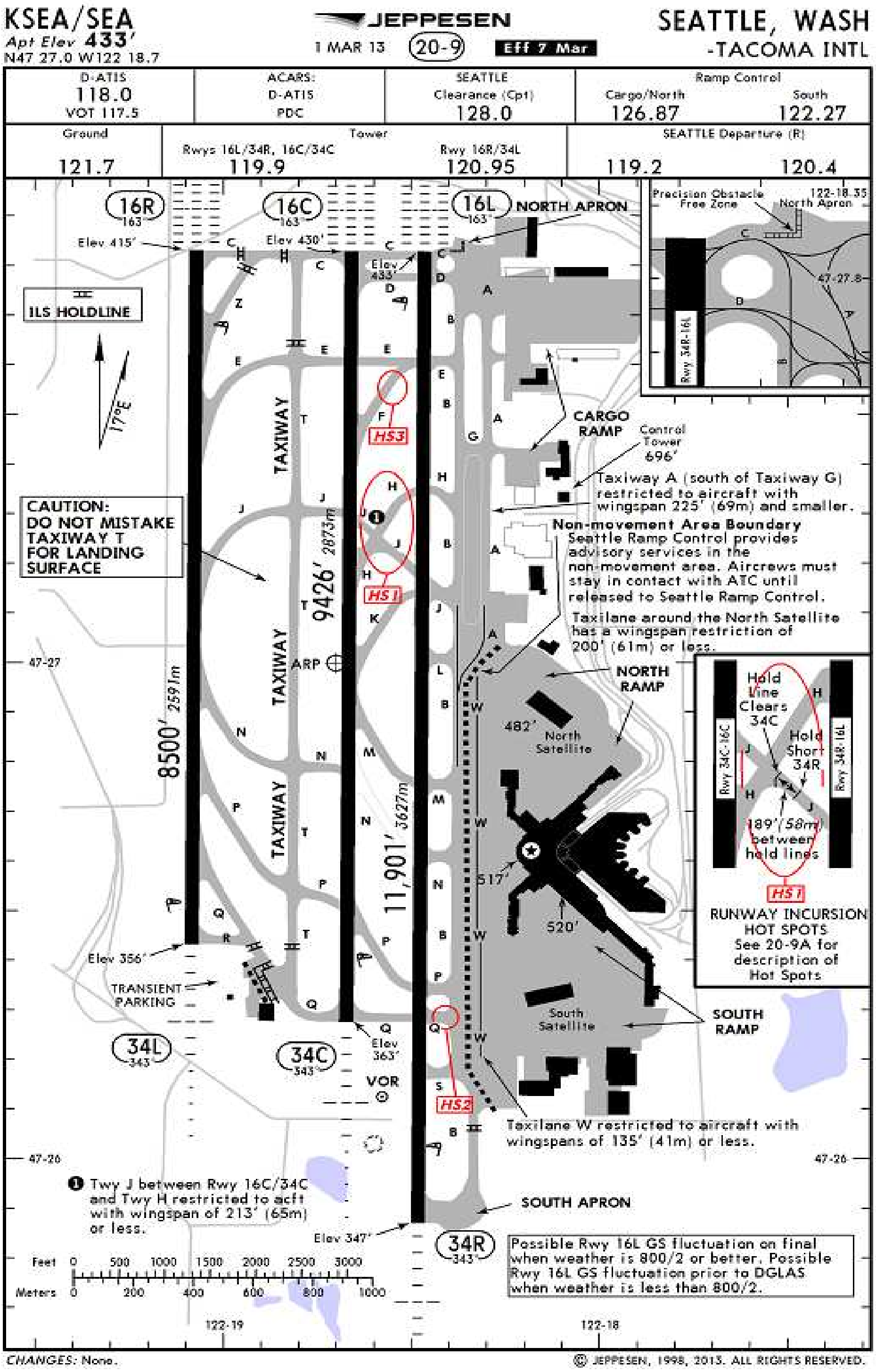


**Figure 5.6 Airport Layout of Tacoma International Airport (KSEA) (Source: JeppView)**

KSEA has three parallel runways. The pair of runways on the East (16C/34C and 16L/34R) is closely spaced parallel runways, where one runway is used for departure and the other one is used for arrival. It is assumed that the runway on the west (16R/34L) operates as a dual-use runway, and can be operated simultaneously with the other two runways.

The traffic scenario in the simulation is when KSEA operates under its South Flow runway configuration. The following figure illustrates the arrival and departure paths of the airport during its South flow operation, which are developed based on the Four Corner Post terminal airspace configuration.

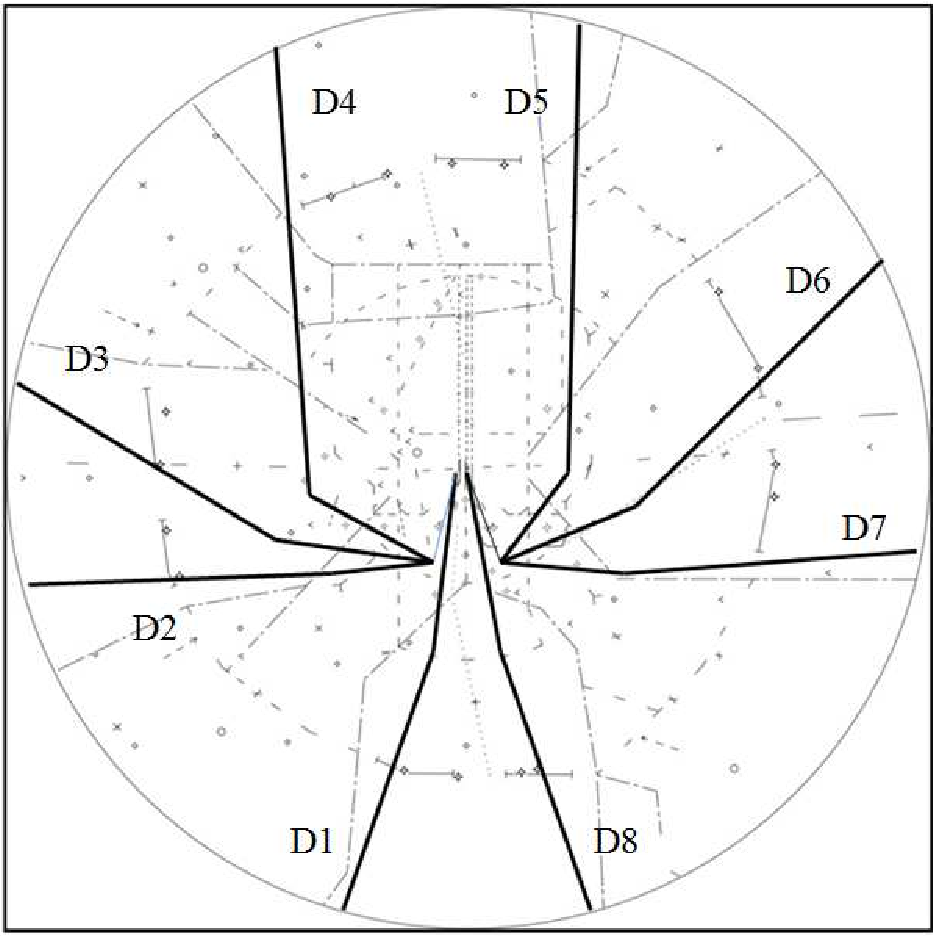
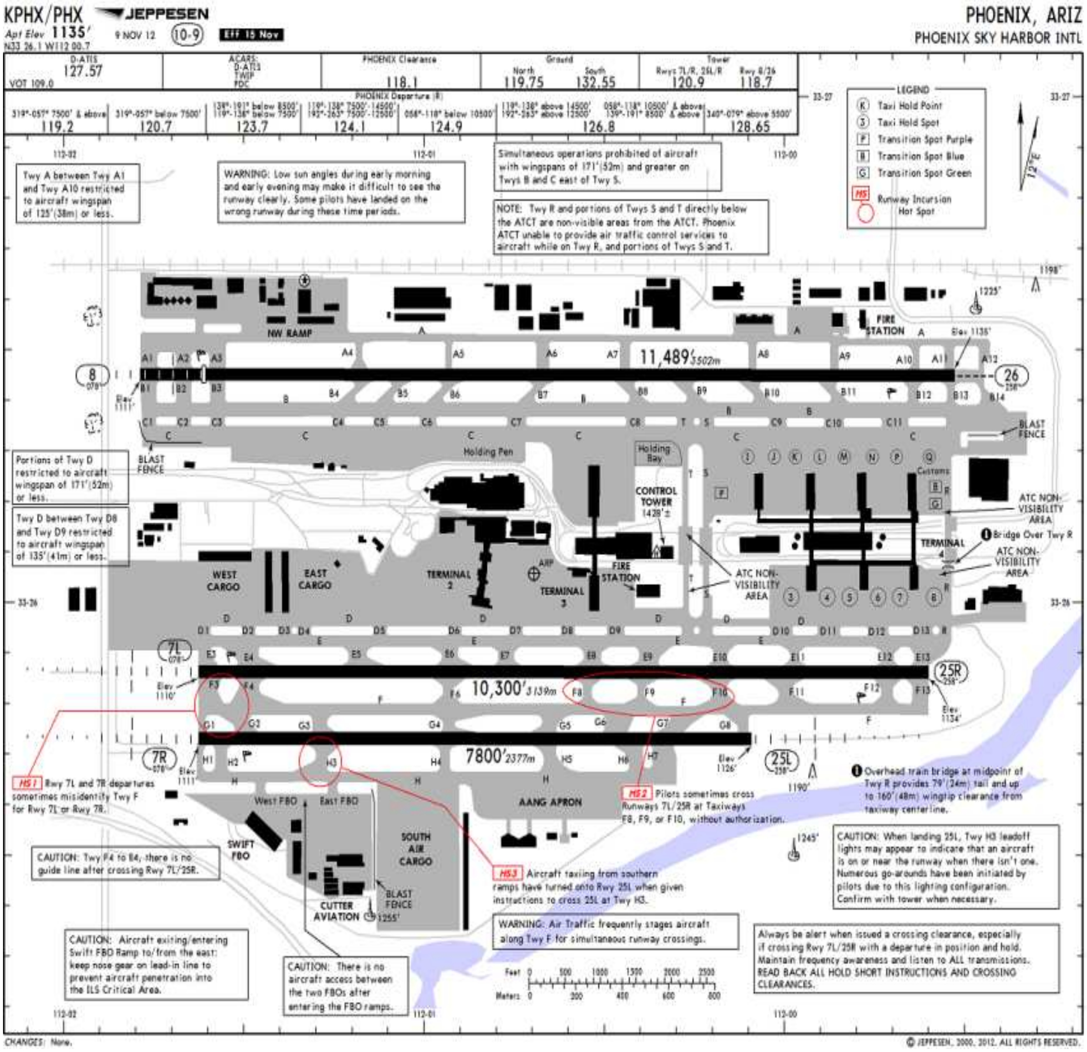


Figure 5.7 Runway Configuration of KSEA – South Flow Departure

### 5.2.1.4 Phoenix Sky Harbor International Airport, KPHX



Twy A between Twy A1 and Twy A10 restricted to aircraft wingspan of 125'(38m) or less.

WARNING: Low sun angles during early morning and early evening may make it difficult to see the runway clearly. Some pilots have landed on the wrong runway during these time periods.

Simultaneous operations prohibited of aircraft with wingspans of 171'(52m) and greater on Twys B and C east of Twy S.

NOTE: Twy R and portions of Twys S and T directly below the ATCT are non-visible areas from the ATCT. Phoenix ATCT unable to provide air traffic control services to aircraft while on Twy R, and portions of Twys S and T.

Portions of Twy D restricted to aircraft wingspan of 171'(52m) or less.

Twy D between Twy D8 and Twy D9 restricted to aircraft wingspan of 135'(41m) or less.

HS1 Rwy 7L and 7R departures sometimes misidentify Twy F for Rwy 7L or Rwy 7R.

HS2 Pilots sometimes cross Runways 7L/25R at Taxiways F8, F9, or F10, without authorization.

HS3 Aircraft taxiing from southern ramps have turned onto Rwy 25L when given instructions to cross 25L at Twy H3.

Overhead train bridge at midpoint of Twy R provides 79'(24m) tail and up to 160'(48m) wingtip clearance from taxiway centerline.

CAUTION: Twy F4 to E4, there is no guide line after crossing Rwy 7L/25R.

CAUTION: When landing 25L, Twy H3 leadoff lights may appear to indicate that an aircraft is on or near the runway when there isn't one. Numerous go-arounds have been initiated by pilots due to this lighting configuration. Confirm with tower when necessary.

WARNING: Air Traffic frequently stages aircraft along Twy F for simultaneous runway crossings.

CAUTION: Aircraft exiting/entering Swift FBO Ramp to/from the east: keep nose gear on lead-in line to prevent aircraft penetration into the ILS Critical Area.

CAUTION: There is no aircraft access between the two FBOs after entering the FBO ramps.

Always be alert when issued a crossing clearance, especially if crossing Rwy 7L/25R with a departure in position and hold. Maintain frequency awareness and listen to ALL transmissions. READ BACK ALL HOLD SHORT INSTRUCTIONS AND CROSSING CLEARANCES.

CHANGES: None.

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**Figure 5.8 Airport Layout of Phoenix International Airport (KPHX) (Source: JeppView)**

KPHX has three parallel runways. The pair of runways on the South side of the airport (07L/25R and 07R/25L) is closely spaced parallel runways, where one runway is used for departure and the other one is used for arrival. It is assumed that the runway on the North side of the airport (08/26) operates as a dual-use runway, and can be operated simultaneously with the other two runways.

The following figures illustrate the arrival and departure paths of the airport with the East runway configuration and West runway configuration. The procedures are developed based on the Four Corner Post terminal airspace configuration.

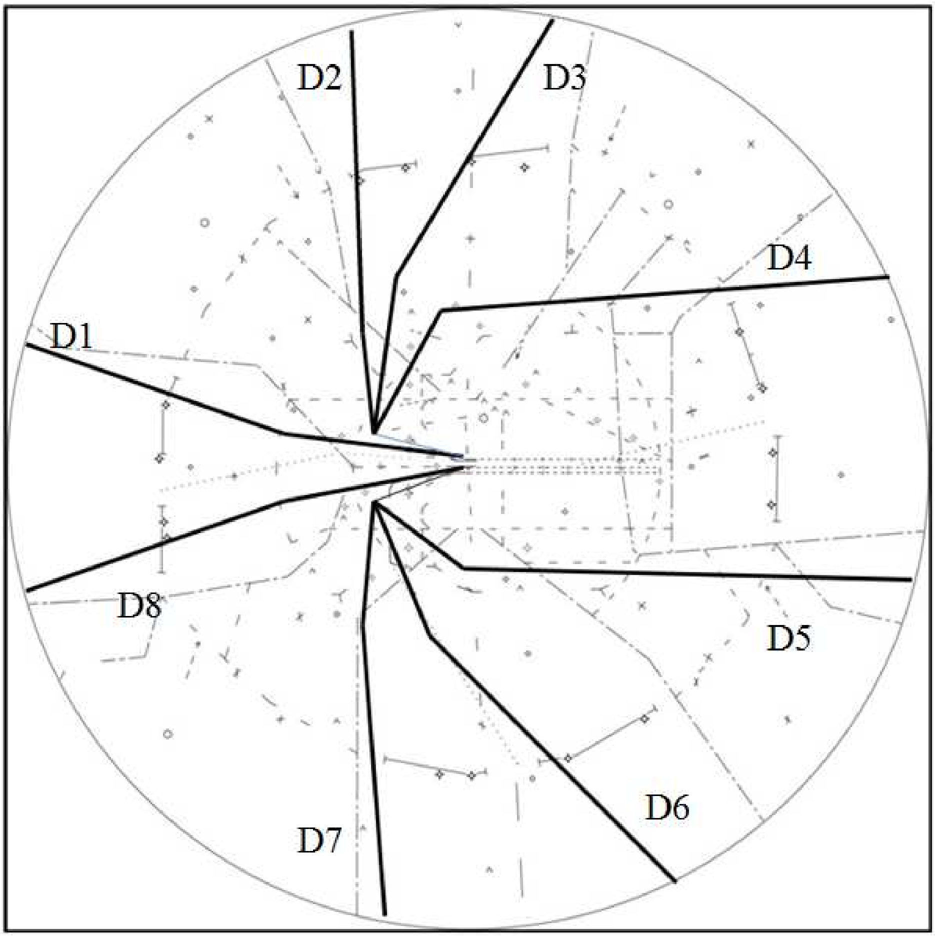


Figure 5.9 Runway Configuration of KPHX – West Flow Departure

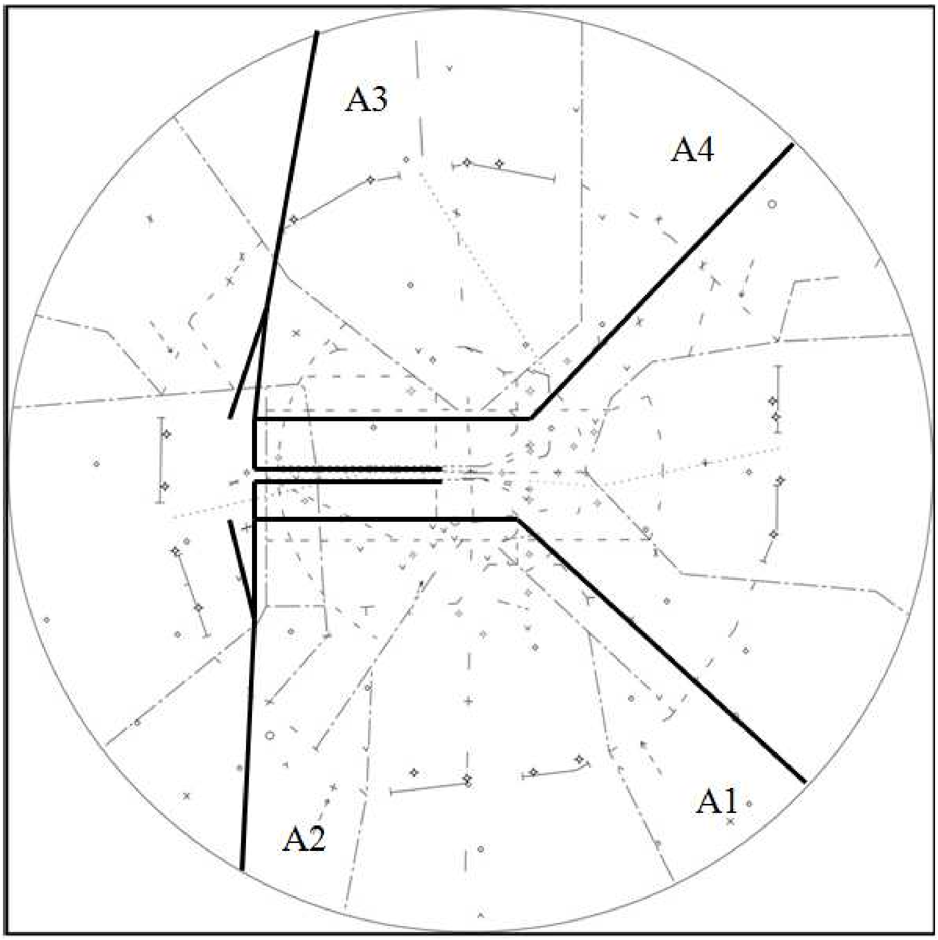


Figure 5.10 Runway Configuration of KPHX – East Flow Arrival

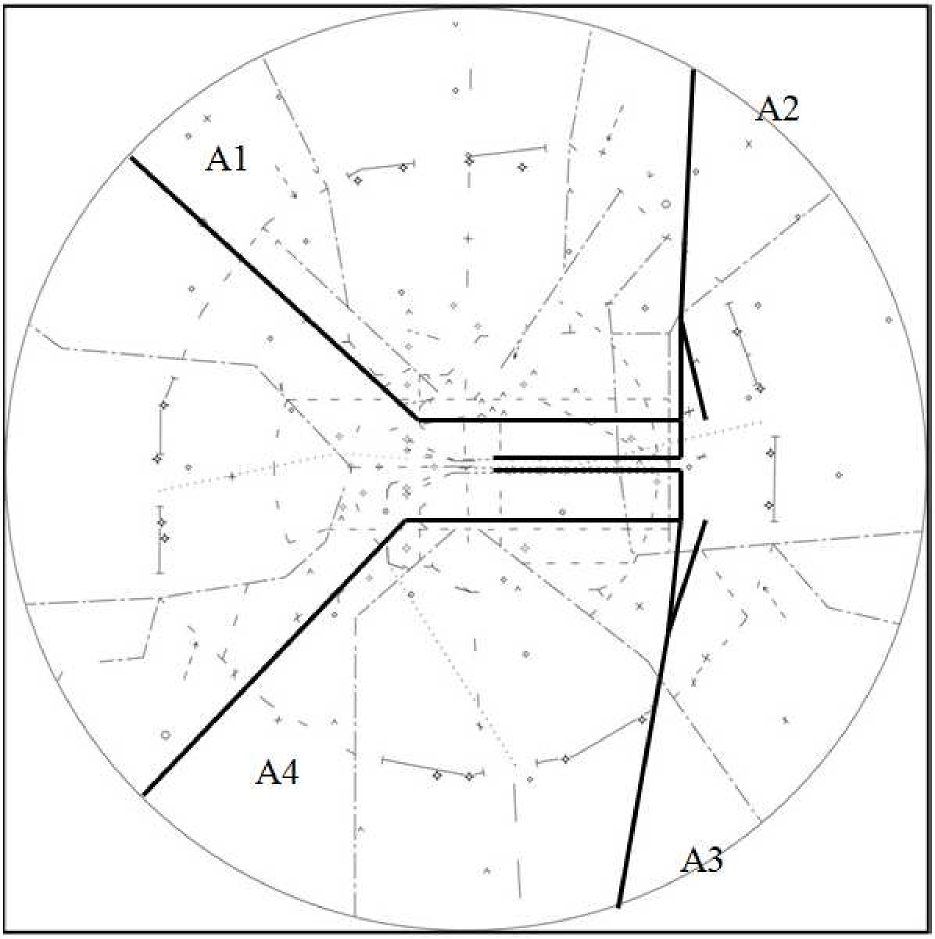


**Figure 5.11 Runway Configuration of KPHX – West Flow Arrival**

### 5.2.2 Runway operation

In order to simplify the computation, it is assumed that all runways are capable for takeoff and landing of a heavy aircraft. Furthermore, all runways, except those indicated as the closely spaced parallel runways can conduct independent simultaneous operations.

## 5.3 Scheduling Window

Each scheduling window size is set to be 60 minutes. This should give controllers enough time to plan ahead and still maintain the dynamic of the solution reacting to real-time traffic feed.

## 5.4 Traffic data – traffic mixes

Normally at every major commercial airport, traffic can be categorized in at least two of the four traffic mixes. They are Arrival Peak, Departure Peak, Hub, and Steady-State. Strategies used to find the optimal solutions for each traffic mix are slightly different. This study focused on traffic mixes during Departure Peak and Arrival Peak only. The traffic samples we used for this study are three hours traffic windows.

### 5.4.1 Departure peak operation

The following figure illustrates a typical traffic mix during Departure Peak (Figure 5.12). It is most like those found at airports facilitated as home base for one or more major airlines. This departure pattern usually happens early in the morning when all aircraft leave the base airport to start their journey of the day. At this time, there may be a few arrivals, but most traffic would be departures.

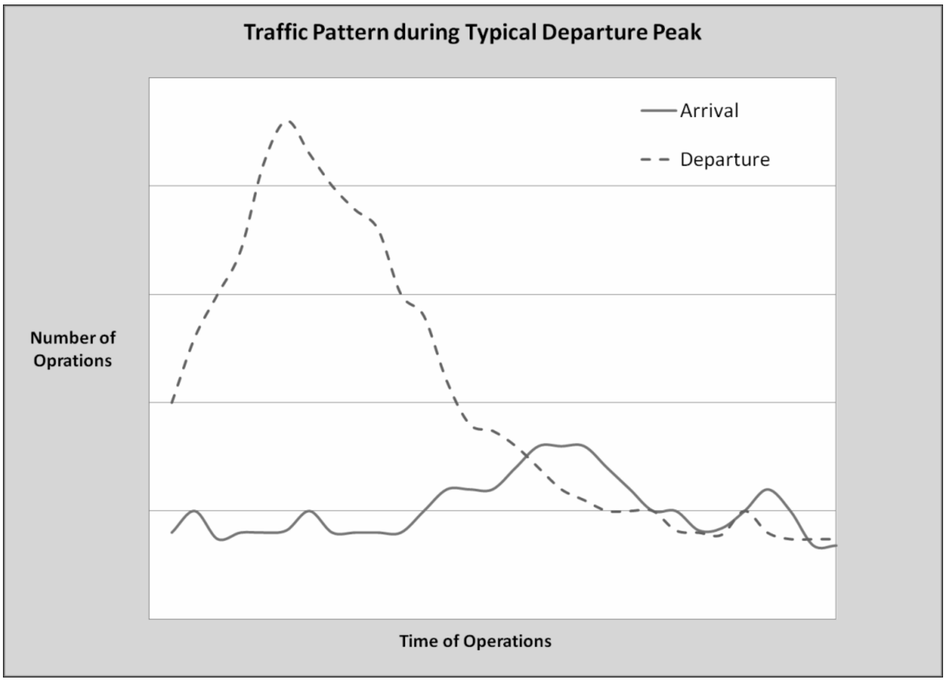
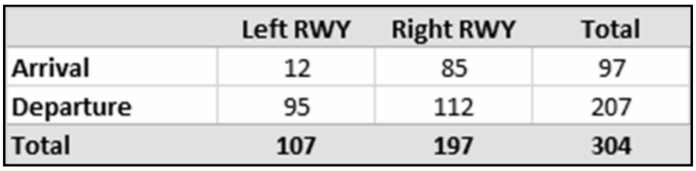


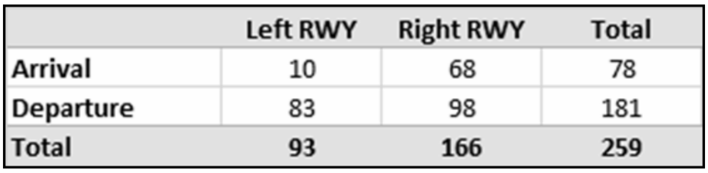
**Figure 5.12 Typical Departure Peak Traffic mix**

To evaluate the system performance for Departure Peak, four traffic samples were used. Two of them were derived from real traffic data at KMCO with runway configuration during the North flow operation (Table 5.1,Table 5.2). One was from KSEA during South flow operation (Table 5.3). And the other one was from KPHX during a West flow operation (Table 5.4).



| | Left RWY | Right RWY | Total |
|---|---|---|---|
| Arrival | 12 | 85 | 97 |
| Departure | 95 | 112 | 207 |
| **Total** | **107** | **197** | **304** |

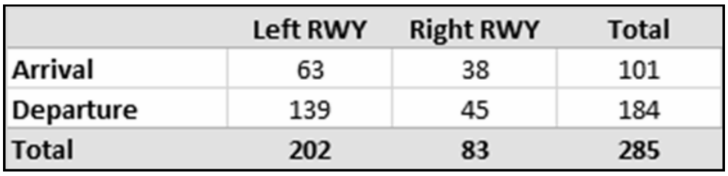
**Table 5.1 Departure Peak at KMCO with North Flow Operation – Traffic Demand 1**



| | Left RWY | Right RWY | Total |
|---|---|---|---|
| Arrival | 10 | 68 | 78 |
| Departure | 83 | 98 | 181 |
| **Total** | **93** | **166** | **259** |

**Table 5.2 Departure Peak at KMCO with North Flow Operation – Traffic Demand 2**

KMCO is located on the East Coast; most departure traffic leaves in the Northwest direction and the four parallel runways are orientated north-south (Figure 5.4). In our simulation, we assumed the east most runway, 17L/36R was closed due to construction. Thus, during North flow operation, the pair of closely spaced runways on the west side of the airport, runway 36L/36R, would handle most of the departure traffic.



| | Left RWY | Right RWY | Total |
|---|---|---|---|
| Arrival | 63 | 38 | 101 |
| Departure | 139 | 45 | 184 |
| **Total** | **202** | **83** | **285** |

**Table 5.3 Departure Peak at KSEA with South Flow Operation**

KSEA is located on the west coast, most departure traffic heads East. The three parallel runways are orientated north-south ( Figure 5.6). Thus, during south flow operation, the pair of closely spaced runways on the East side of the airport, runway 16L/16C, would handle most of the traffic.

|  | Left RWY | Right RWY | Total |
|---|---|---|---|
| Arrival | 21 | 54 | 75 |
| Departure | 14 | 68 | 82 |
| **Total** | **35** | **122** | **157** |

**Table 5.4 Departure Peak at KPHX with West Flow Operation**

KPHX is located in the South; most departure traffic head toward the north. The three parallel runways are orientated east-west (Figure 5.8). Thus, during West flow operation, the single runway on the North, runway 26, would handle most of departure traffic.

### 5.4.2 Arrival peak operation

The following figure illustrates a typical traffic mix during arrival peak (Figure 5.13). It may also be found at airport facilitated as home base for one or more major airlines. This arrival pattern usually happens at night when all aircraft need to come back to the base airport. At this time, there may still have a few departures, but most traffic would be arrivals.

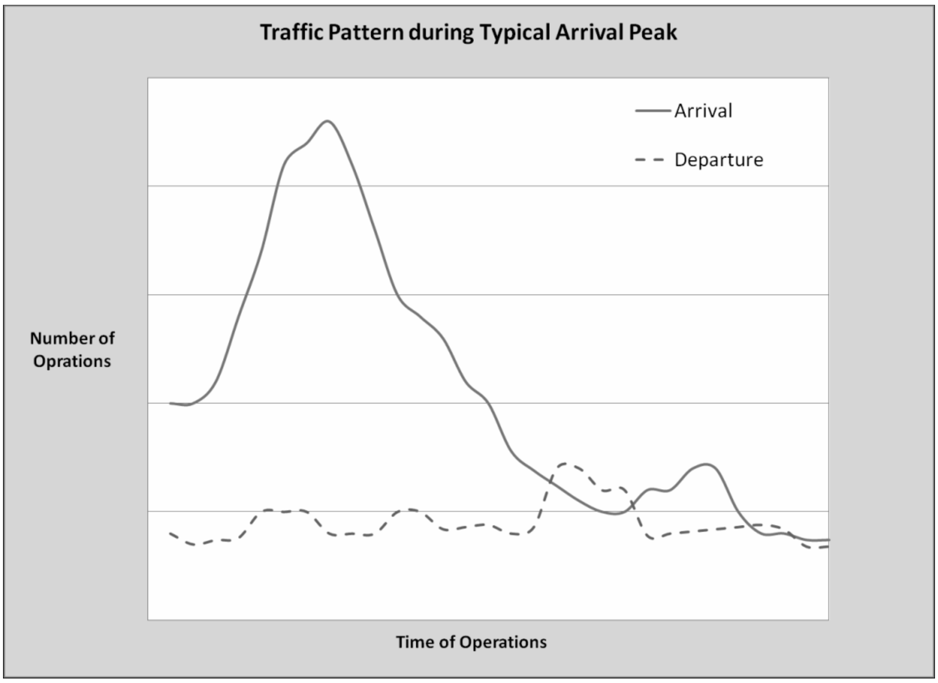
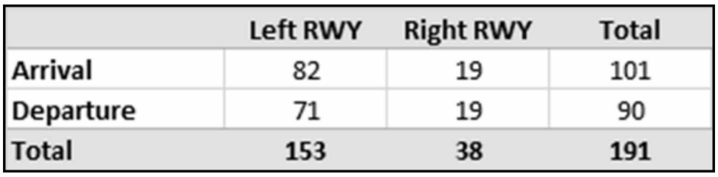


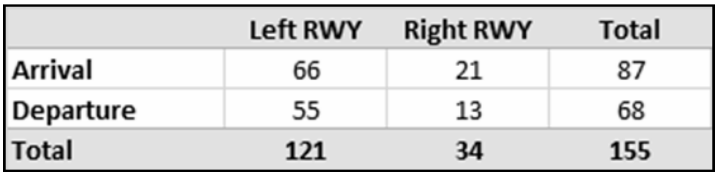
**Figure 5.13 Typical Arrival Peak Traffic mix**

To evaluate the system performance for arrival peak, four traffic samples were used. Two of them were derived from real traffic data at KPHX with runway configuration during the East flow operation (Table 5.5, Table 5.6). One was from KPHX during West flow operation (Table 5.7). And the other one was from KSMF during a North flow operation (Table 5.8).



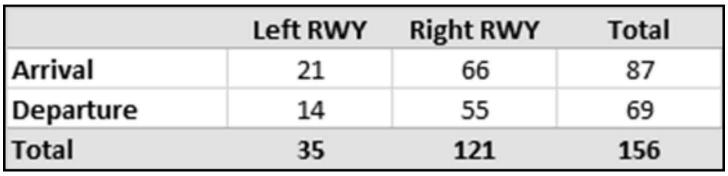
| | Left RWY | Right RWY | Total |
|---|---|---|---|
| Arrival | 82 | 19 | 101 |
| Departure | 71 | 19 | 90 |
| **Total** | **153** | **38** | **191** |

Table 5.5 Arrival Peak at KPHX with East Flow Operation – Traffic Demand 1



| | Left RWY | Right RWY | Total |
|---|---|---|---|
| Arrival | 66 | 21 | 87 |
| Departure | 55 | 13 | 68 |
| **Total** | **121** | **34** | **155** |

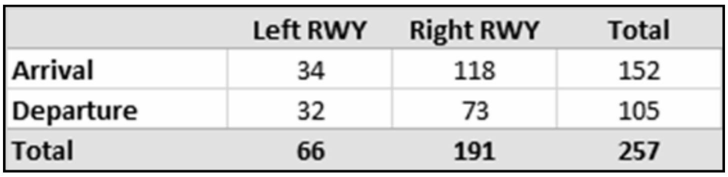
Table 5.6 Arrival Peak at KPHX with East Flow Operation – Traffic Demand 2



| | Left RWY | Right RWY | Total |
|---|---|---|---|
| Arrival | 21 | 66 | 87 |
| Departure | 14 | 55 | 69 |
| **Total** | **35** | **121** | **156** |

Table 5.7 Arrival Peak at KPHX with West Flow Operation

KPHX is located in the south, most arrival traffic comes from North. The three parallel runways are orientated east-west (Figure 5.8). Thus, during east flow operation, the single runway on the North, runway 08, would handle most of arrival traffic. And the situation reversed during West flow operation.



| | Left RWY | Right RWY | Total |
|---|---|---|---|
| Arrival | 34 | 118 | 152 |
| Departure | 32 | 73 | 105 |
| **Total** | **66** | **191** | **257** |

Table 5.8 Arrival Peak at KSMF with North Flow Operation

KSMF is located on the West coast; most arrival traffic comes from East. The two parallel runways are orientated north-south (Figure 5.2). Thus, during North flow operation, the single runway on the North, runway 34R, would handle most of arrival traffic.

### 5.4.3 Typical hub operation

The following figure illustrates a typical traffic mix during Arrival Peak (Figure 5.14). This type of traffic mix is commonly found at airports used as hubs for one or more major airlines. Most traffic at hub airports are transit flights. Passengers will fly in and then connected to another flight to continue their trip to the destination airport. The typical hub traffic usually has a short period of arrival push. Then immediately after arrival, passengers will connect to a departure flight; the traffic demand creates a short period of departure push. The pattern is repeated a few times throughout the day. For example, Atlanta International airport is the major hub for Delta Airlines, the traffic mix at ATL shows this type of traffic mix.

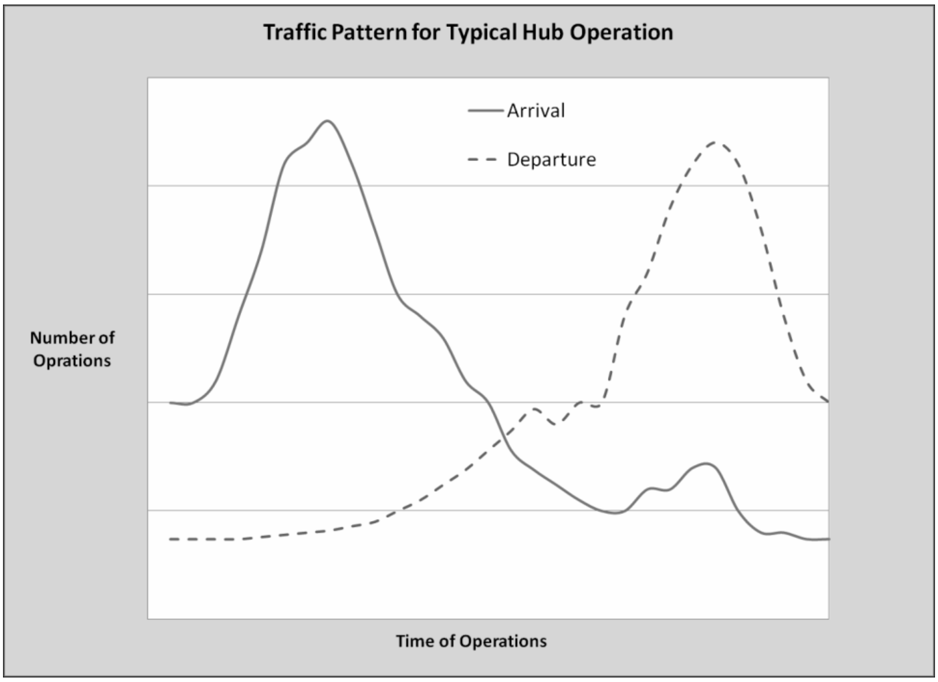


**Figure 5.14 Typical Hub Traffic mix**

### 5.4.4 Steady-state operation

The following figure illustrates a typical traffic mix during arrival peak (Figure 5.15). This type of traffic mix could be found at any airports, but it is more commonly found at home base airports. But unlike Departure Peak or Arrival Peak, Steady-State traffic mix is mostly during the mid-day when neither arrival nor departure reaches extreme high level of intensity. The traffic at the airport during this time is more or less evenly distributed by both departures and arrivals.

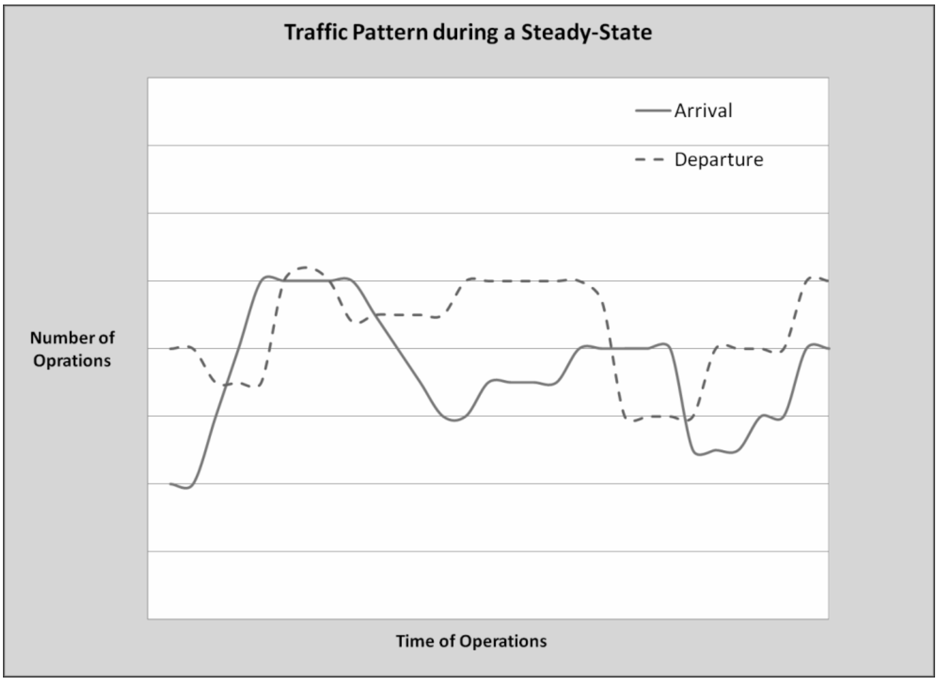


**Figure 5.15 Typical Steady-state Traffic mix**

## 5.5 Separation Standards

To simplify the simulation, only three aircraft types were used in the traffic data, Heavy, Boeing 757, and Large. This section tallies the separation standards used in the numerical simulation.

### 5.5.1 Airborne separation

In real world operation, a safe separation between any two aircraft must obey ICAO (or local state, i.e. FAA) separation standards, such as longitudinal and vertical separation under procedural control, or radar control. Outside a terminal airspace, the standard separation is normally 5 NM, and within a terminal airspace, the radar separation is reduced to 3 NM. But successive aircraft on final and takeoff shall also maintain the minimum wake turbulence separation. The wake turbulence separation standard varies with the wake turbulence category of the leading aircraft and the following aircraft. For the convenience of computation, it is assumed that the same separation standard applies to successive departures and successive arrivals.

| **Leading/Following** | **Heavy** | **B757** | **Large** |
|---|---|---|---|
| **Heavy** | 90 | 110 | 110 |
| **B757** | 90 | 90 | 90 |
| **Large** | 80 | 80 | 80 |

**Table 5.9 Arrival Separations (in seconds)**

| **Leading/Following** | **Heavy** | **B757** | **Large** |
|---|---|---|---|
| **Heavy** | 60 | 120 | 120 |
| **B757** | 60 | 60 | 120 |
| **Large** | 60 | 60 | 60 |

**Table 5.10 Departure Separations (in seconds)**

### 5.5.2 Runway separation

For safety concern, only one aircraft is allowed to be on a runway at a time. That means, for arrivals on the same runway, the leading aircraft has to turn off the runway before the successive aircraft crosses the runway landing threshold; and for departures on the same runway, the earliest time for a successive aircraft to commence departure is after the previous departure aircraft is airborne. The arrival separations and the departure separations tallied in the previous section shall allow enough time for the leading aircraft cleared off the runway. This study also incorporates the coordination of arrival and departure aircraft, thus we would have to consider the separation between arrival aircraft and departure aircraft.

Our simulation scenarios have two basic situations.

The first case is a dual use runway, where a single runway is used for both arrivals and departures, which mean a departure followed by an arrival. The departure has to be airborne before the arrival crosses the runway landing threshold; if an arrival is followed by a departure, then the departure aircraft cannot commence departure until the landing aircraft turn off the runway. The separation is defined based on runway occupancy time, a Heavy usually takes a slightly longer time to slow down after touchdown and turn off the runway; and a Heavy usually needs to accelerate for a longer distance and takes more time before airborne.

| **Leading/Following** | **Heavy** | **B757** | **Large** |
|---|---|---|---|
| **Heavy** | 55 | 55 | 55 |
| **B757** | 40 | 40 | 40 |
| **Large** | 40 | 40 | 40 |

**Table 5.11 Separation for a Departure after an Arrival on Dual-Use Runway (in seconds)**

| **Leading/Following** | **Heavy** | **B757** | **Large** |
|---|---|---|---|
| **Heavy** | 90 | 110 | 110 |
| **B757** | 90 | 90 | 90 |
| **Large** | 80 | 80 | 80 |

**Table 5.12 Separation for a Departure before an Arrival on Dual-Use Runway (in seconds)**

The second situation is for a pair of closely spaced parallel runways, where the two runways are probably separated by less than 2,100 feet, and one runway is solely used for arrivals, and the other one is used for departures only. Then, the departure aircraft may commence departure once the arrival aircraft touches down; or it has to commence departure before the arrival crosses the runway landing threshold.

| **Leading/Following** | **Heavy** | **B757** | **Large** |
|---|---|---|---|
| **Heavy** | 10 | 10 | 10 |
| **B757** | 10 | 10 | 10 |
| **Large** | 10 | 10 | 10 |

**Table 5.13 Separation for a Departure after an Arrival on Closely Spaced Parallel Runways (in seconds)**

The separation is the same for a departure aircraft takeoff before an arrival aircraft.

| Leading/Following | Heavy | B757 | Large |
|---|---|---|---|
| **Heavy** | 10 | 10 | 10 |
| **B757** | 10 | 10 | 10 |
| **Large** | 10 | 10 | 10 |

**Table 5.14 Separation for a Departure before an Arrival on Closely Spaced Parallel Runways (in seconds)**

### 5.5.3 Constraints

As explained in the previous chapters, there are many constraints for the problem. In this study, we considered the most important ones in order to maintain certain level of reality of the operational environment but still possible to achieve our objectives. The constraints included one-route constraint, which imposed every aircraft, can only be assigned to one route at a time. All aircraft have to maintain minimum separation. That means separation between any pair of successive aircraft in the air has to be not less than the separation requirement listed in the Section 5.5.1, or Section 5.5.2 if at least one of aircraft is on the runway. Neither early arrival nor early departure is allowed in the model. This is also implied that there is no overtaking during the process. All aircraft have to follow the order of FCFS. In the process of optimizing runway assignment, we also imposed conflict-free constraint. A conflict-free operation will create a safer operational environment, and reduce controller workload. Thus, it will make this approach more appealing to controllers.

The time constraint for the entire process was set to be 120 seconds. The final result was the best solution found within this time limit.

## 5.6 Performance Index

As indicated previously, the performance index gives a general expression in minimizing the weighted overall system delay, Equation 4-1

$$\operatorname*{Min}_{A,B,C} I = \sum_{i=1}^{N_{arr}} \omega_i\left(t_i^{runway} - \hat{t}_i^{runway}\right) + \sum_{j=1}^{N_{dep}} \omega_j\left(t_j^{runway} - \hat{t}_j^{runway}\right)$$

Equation 4-2

$$\underset{A,B,C}{\text{Min}}\, J = \left(t_N^{runway} - t_1^{runway}\right)$$

Such that

| | |
|---|---|
| A | represents the continuous time decision variable |
| B | represents the route decision variables which imply to runway assignments |
| Z | represents the sequencing decision variables |
| $\omega_i$, $\omega_j$ | are the weighting coefficients for delay |
| $t_i^{runway}$ | is the final computed landing time STA for arrival aircraft i to land on a runway |
| $\hat{t}_i^{runway}$ | is the initial planed landing time ETA for arrival aircraft i to land on a runway |
| $t_j^{runway}$ | is the final computed departure time STA for departure aircraft j to takes off from a runway |
| $\hat{t}_j^{runway}$ | is the initial planned departure time ETA for departure aircraft j to take off from a runway |

Therefore,

| | |
|---|---|
| $\left(t_i^{runway} - \hat{t}_i^{runway}\right)$ | represents the delay for arrival aircraft i |
| $\left(t_j^{runway} - \hat{t}_j^{runway}\right)$ | represents the delay for departure aircraft j |
| $\left(t_N^{runway} - t_1^{runway}\right)$ | is regarding to the time from first runway departure/arrival till the last runway departure/arrival |

Normally, due to safety and economic concerns, arriving aircraft usually have higher priority over departing aircraft. But it would be different from airport to airport, so when developing the system for simulation, the same weighting is applied equally on both departure delay and arrival delay.

# 5.7 Simulation Results

## 5.7.1 During a departure peak operation

### 5.7.1.1 Departure peak at KMCO with North flow operation – traffic demand 1

The Number of Operation chart shows hourly operation rates, which includes both departures and arrivals using the runway. It compares the default operation with the operation schedule provided by the optimization system. The bars on each chart represent the number of operations on each runway (or in some cases, a pair of closely spaced parallel runway). In almost all test scenarios, the scheduled operations show a more balance utilization of both runways. Furthermore, the overall airport throughput during the peak hour increased with the optimal schedule.

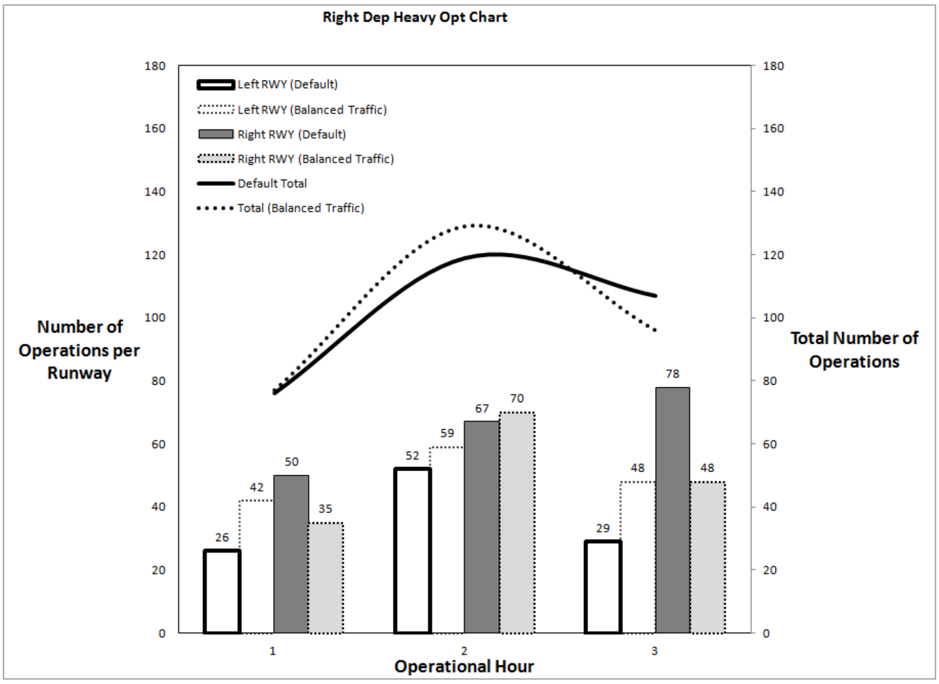


**Figure 5.16 Number of Operation – KMCO North Flow Operation 1**

The Total Delay chart shows hourly overall delay, which includes both departures delay and arrivals delay. It compares the default operation with the scheduled operation provided by the optimization system. The bars on each chart represent the delay on each runway (or in some cases, a pair of closely spaced parallel runway). In all test scenarios, the scheduled operations constantly show decreased overall delay.

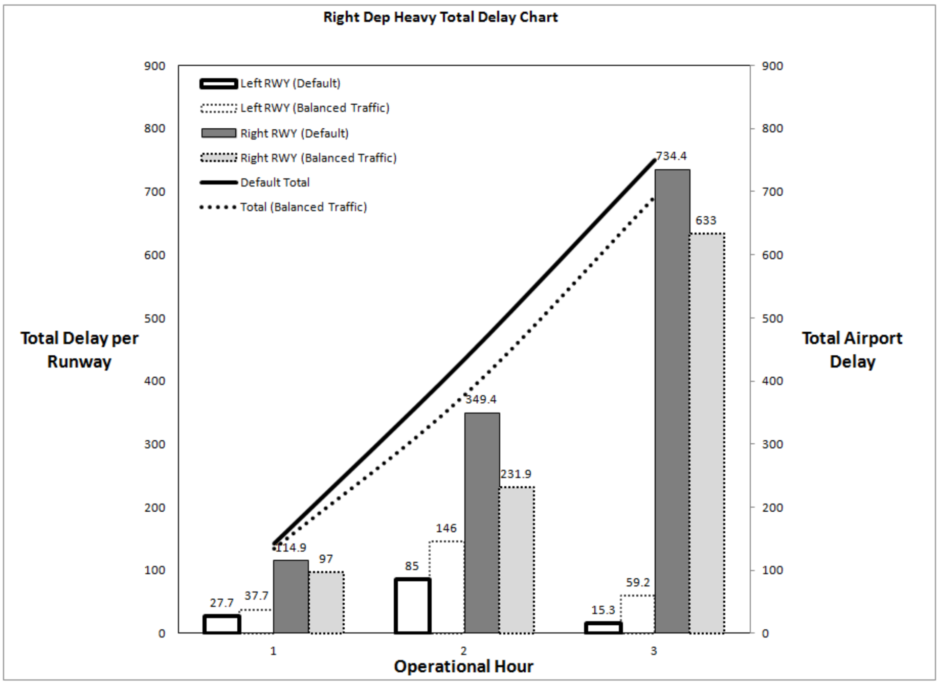


**Figure 5.17 Total Delay – KMCO North Flow Operation 1**

The Average Delay per Aircraft chart shows similar information as the Total Delay chart. But it is the delay experienced by a single aircraft.

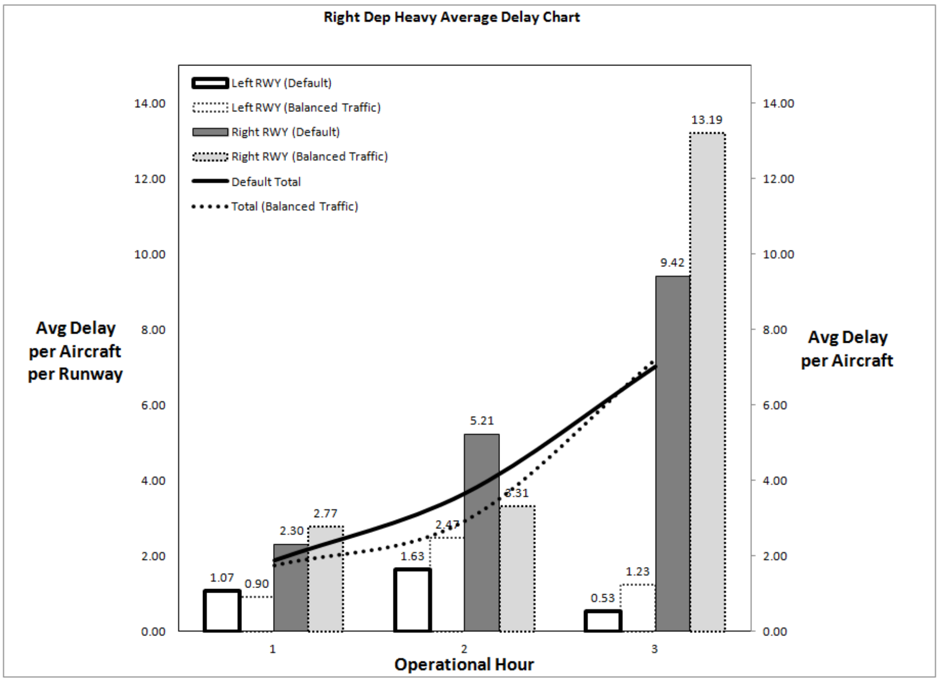


Figure 5.18 Average Delay per Aircraft – KMCO North Flow Operation 1

### 5.7.1.2 Departure peak at KMCO with North flow operation – traffic demand 2

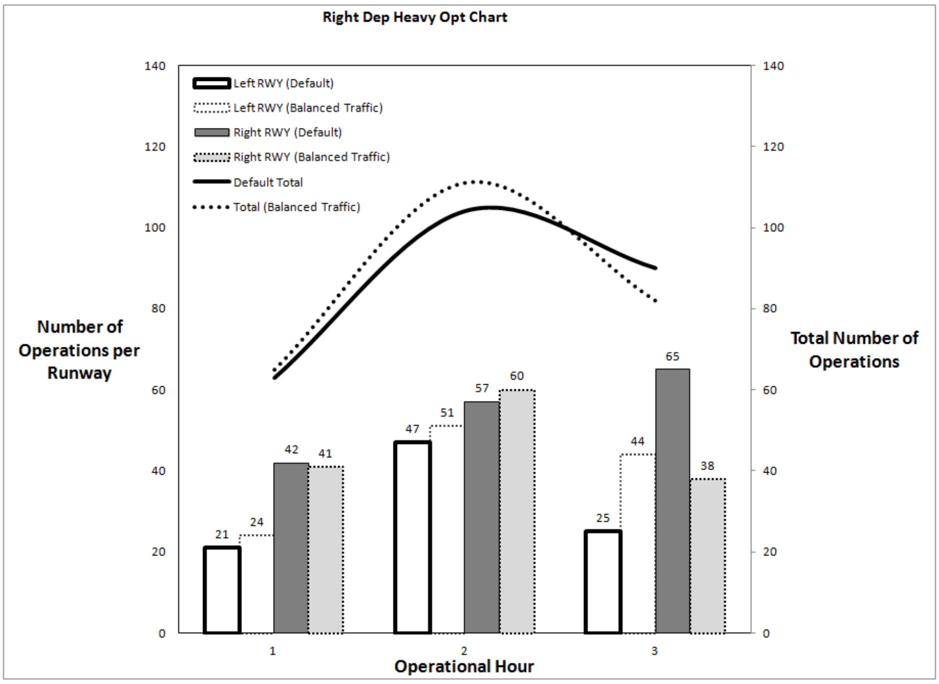


Figure 5.19 Number of Operation – KMCO North Flow Operation 2

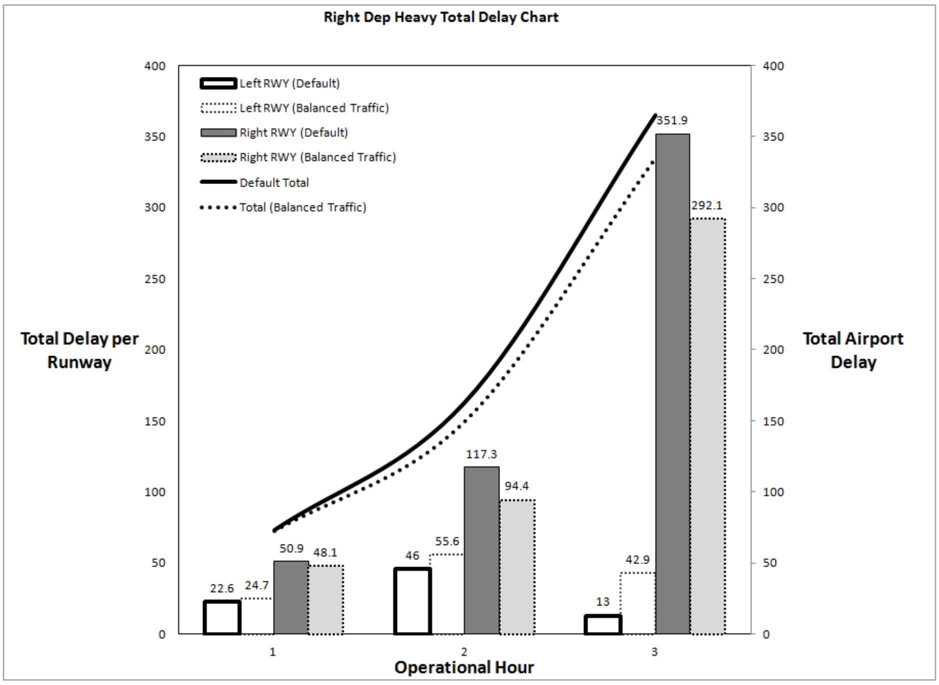


Figure 5.20 Total Delay – KMCO North Flow Operation 2

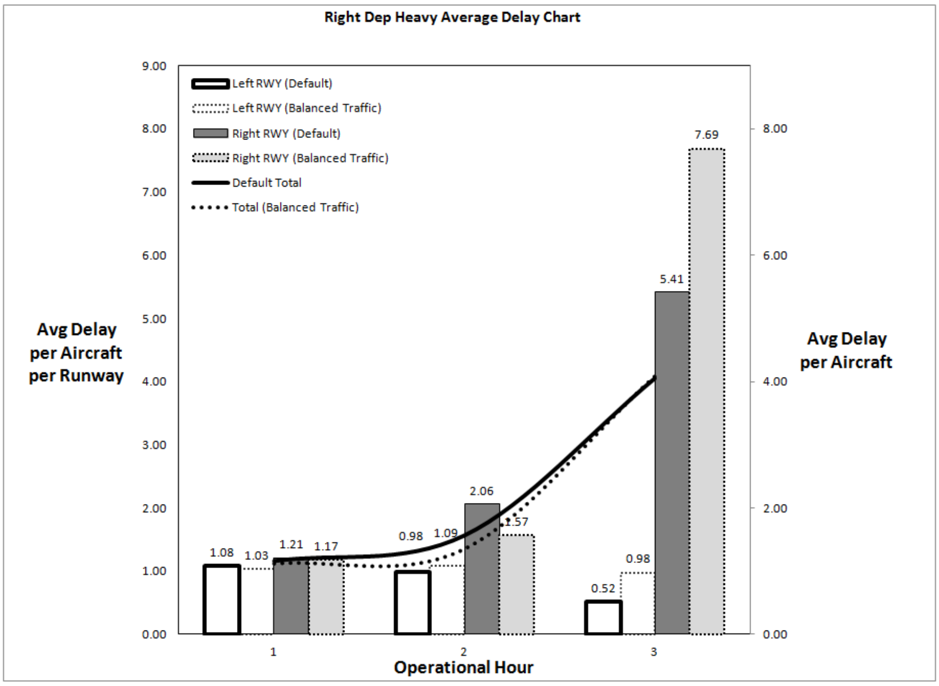


Figure 5.21 Average Delay per Aircraft – KMCO North Flow Operation 2

### 5.7.1.3 Departure peak at KSEA with South flow operation

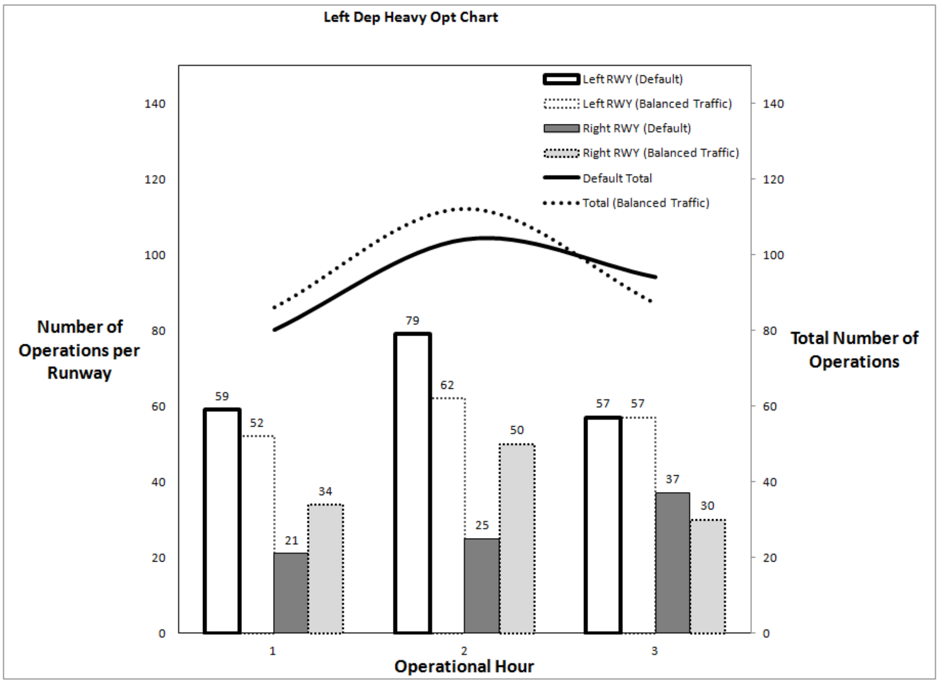


Figure 5.22 Number of Operation – KSEA South Flow

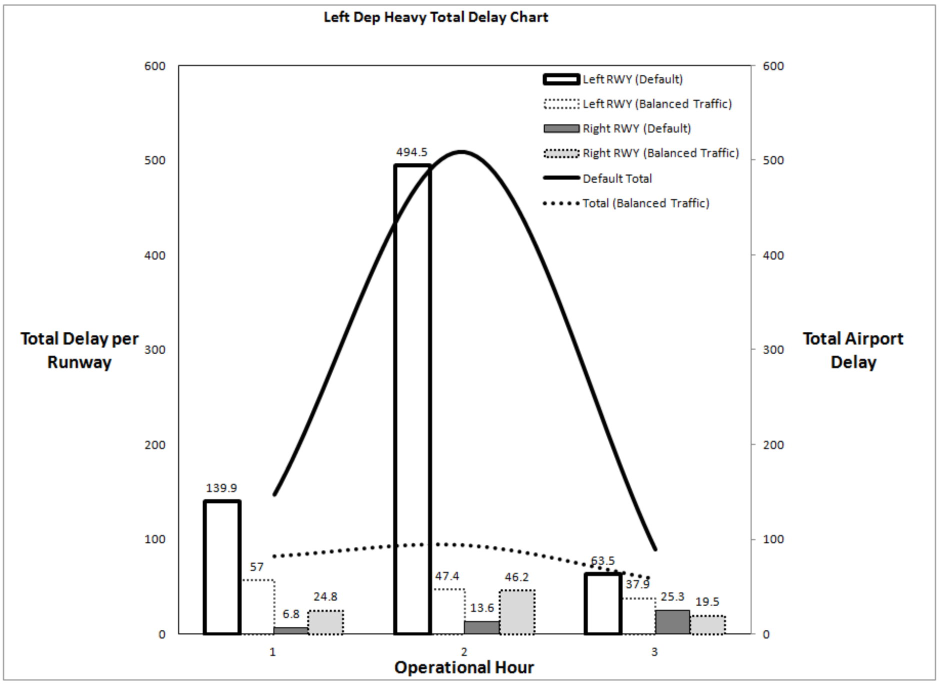


Figure 5.23 Total Delay – KSEA South Flow

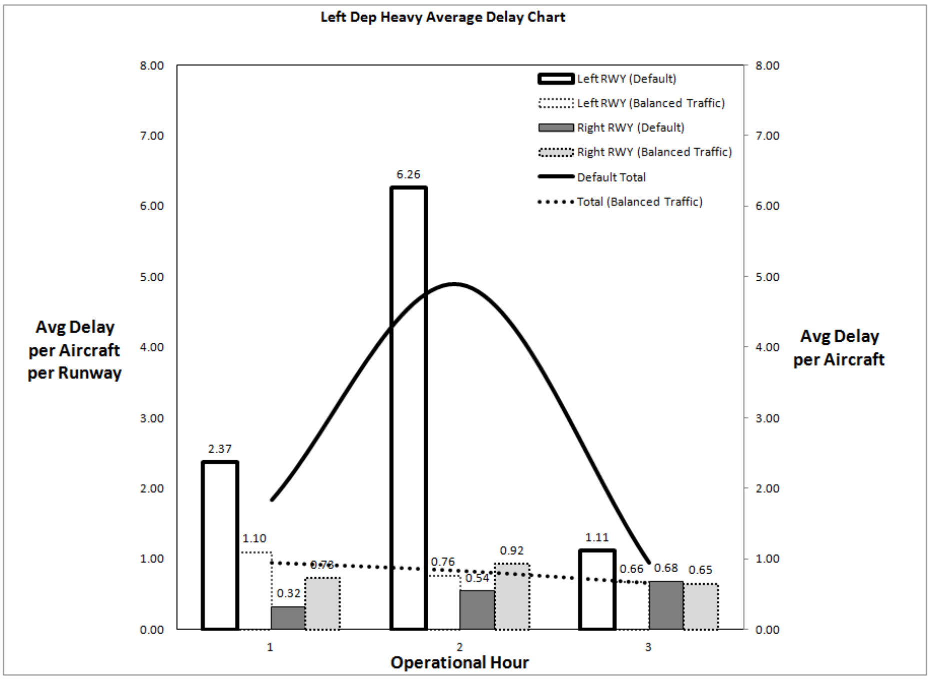


Figure 5.24 Average Delay per Aircraft – KSEA South Flow

### 5.7.1.4 Departure peak at KPHX with West flow operation

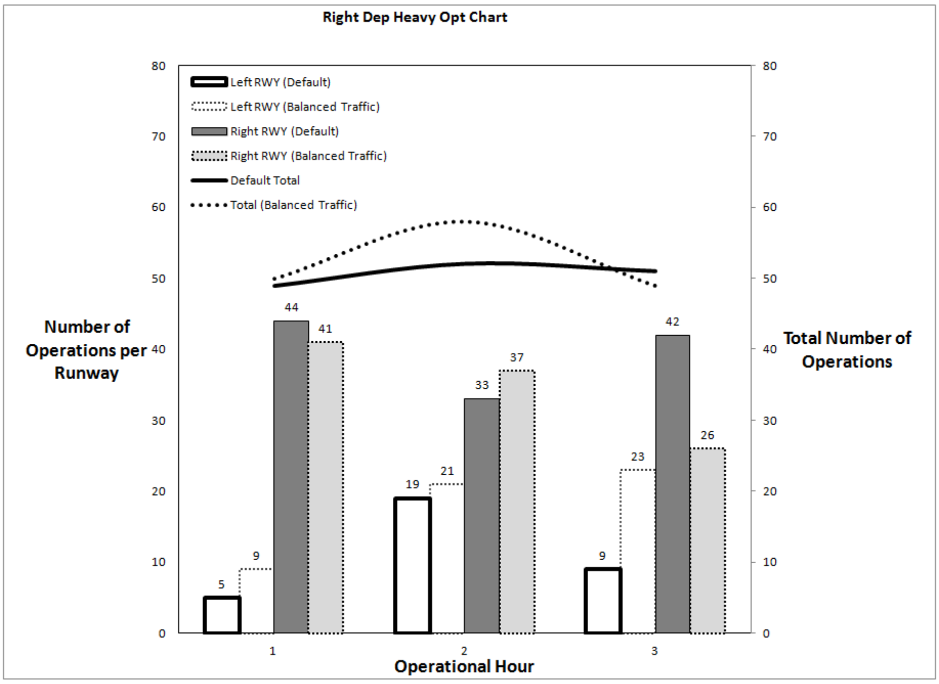


Figure 5.25 Number of Operation – KPHX West Flow Operation

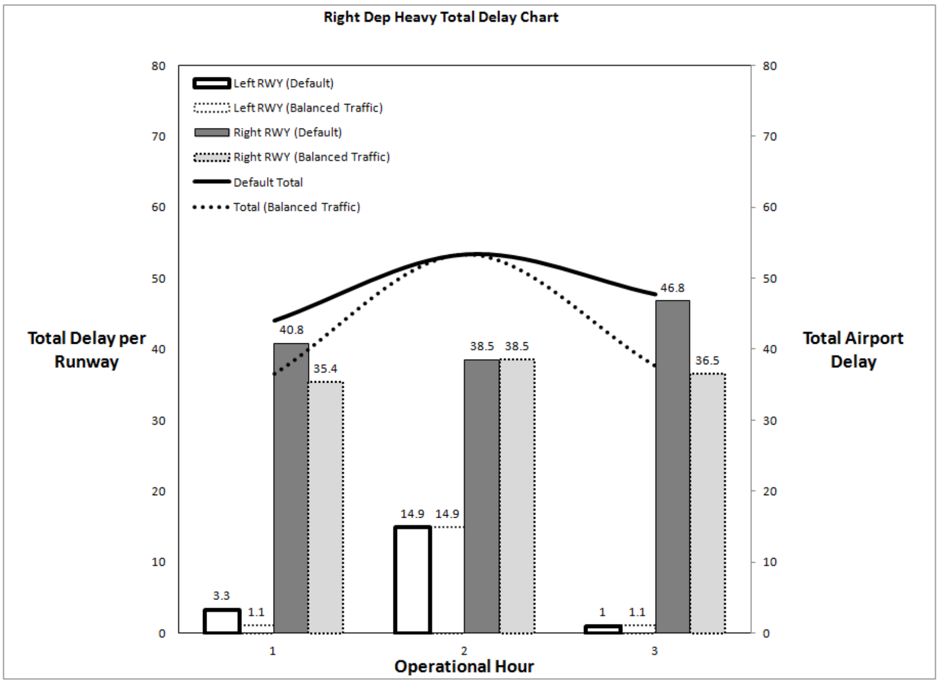


Figure 5.26 Total Delay – KPHX West Flow Operation

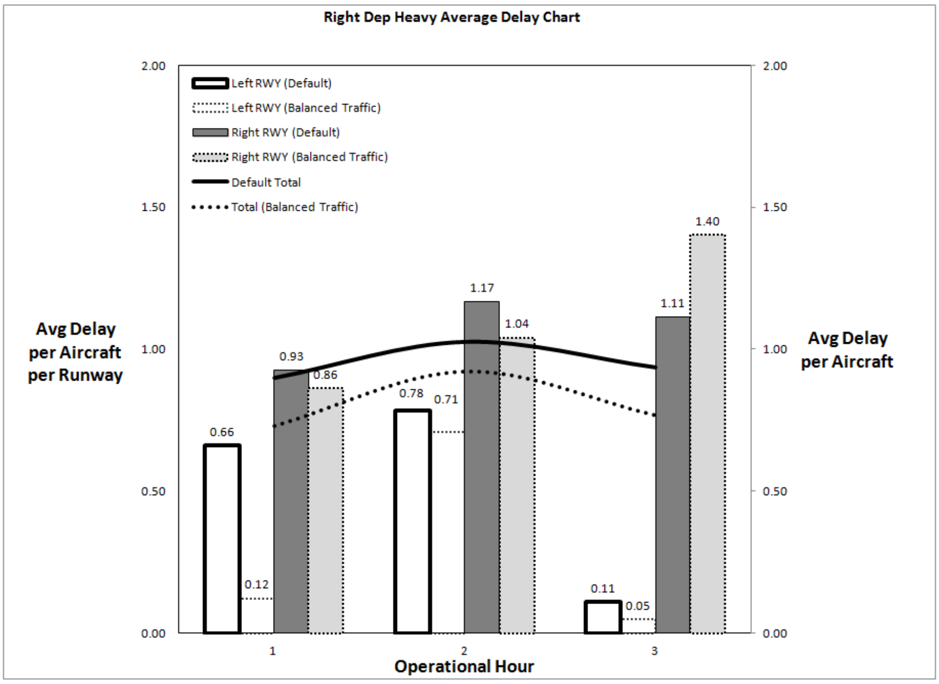


Figure 5.27 Average Delay per Aircraft – KPHX West Flow Operation

## 5.7.2 During an arrival peak operation

### 5.7.2.1 Arrival peak at KPHX with East flow operation – traffic demand 1

The Number of Operation chart shows hourly operation rates, which includes both departures and arrivals using the runway. It compares the default operation with the operation schedule provided by the optimization system. The bars on each chart represent the number of operations on each runway (or in some cases, a pair of closely spaced parallel runway). In almost all test scenarios, the scheduled operations show a more balance utilization of both runways. Furthermore, the overall airport throughput during the peak hour increased with the optimal schedule.

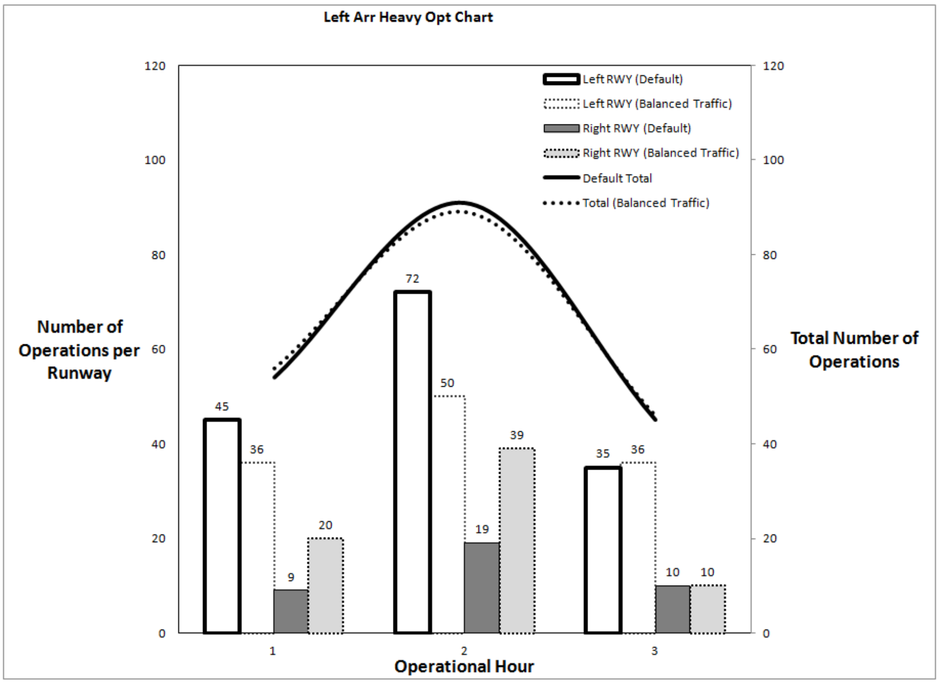


Figure 5.28 Number of Operation – KPHX East Flow with traffic demand 1

The Total Delay chart shows hourly overall delay, which includes both departures delay and arrivals delay. It compares the default operation with the scheduled operation provided by the optimization system. The bars on each chart represent the delay on each runway (or in some cases, a pair of closely spaced parallel runway). In all test scenarios, the scheduled operations constantly show decreased in overall delay.

The Average Delay per Aircraft chart shows similar information as the Total Delay chart. But it is the delay experienced by a single aircraft.

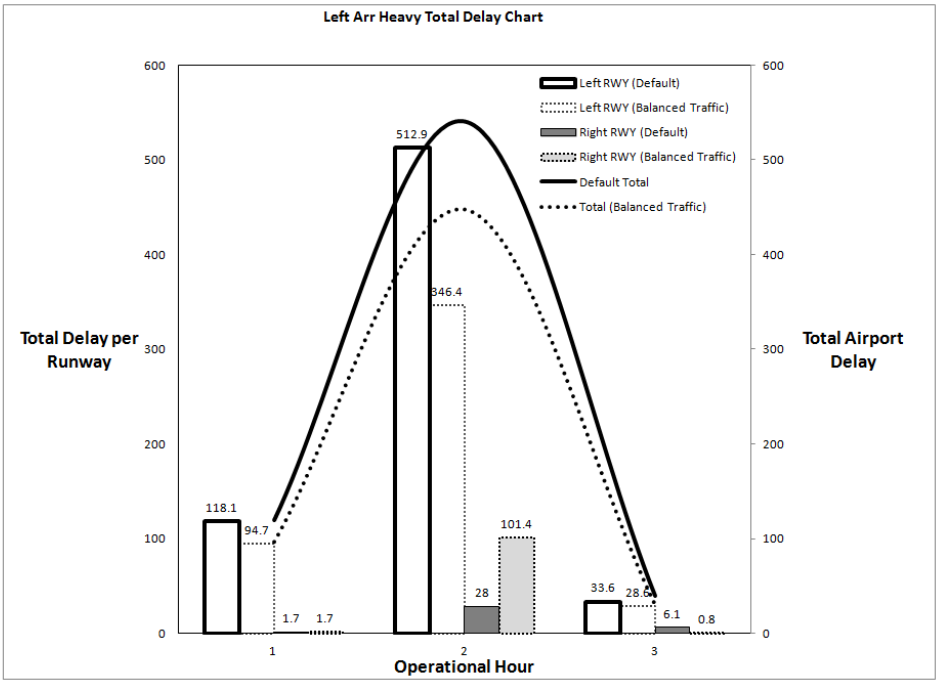


Figure 5.29 Total Delay – KPHX East Flow with traffic demand 1

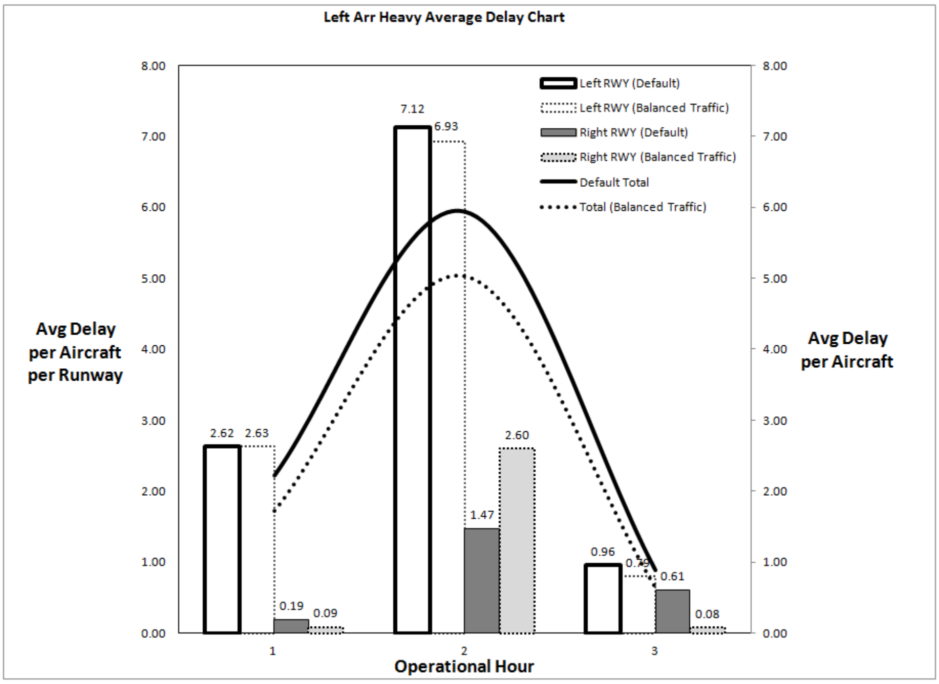


Figure 5.30 Average Delay per Aircraft – KPHX East Flow with traffic demand 1

### 5.7.2.2 Arrival peak at KPHX with East flow operation – traffic demand 2

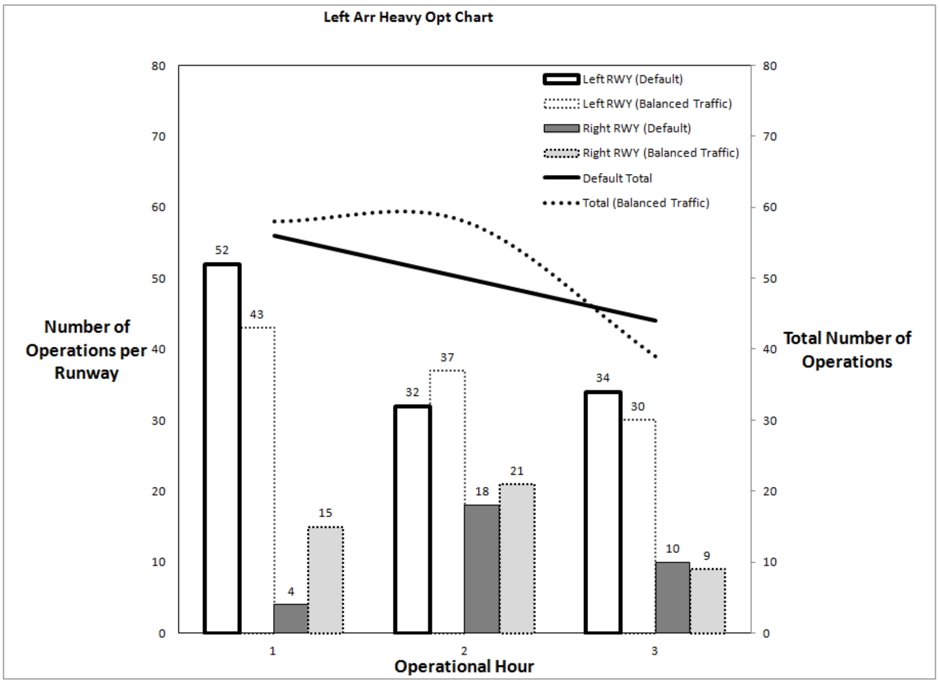


Figure 5.31 Number of Operation – KPHX East Flow with traffic demand 2

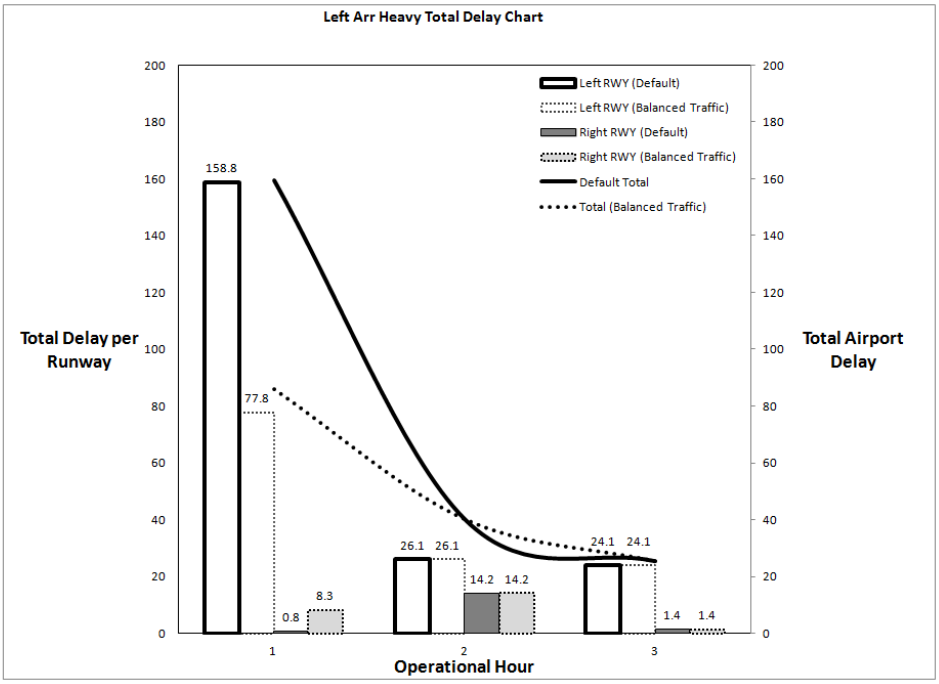


Figure 5.32 Total Delay – KPHX East Flow with traffic demand 2

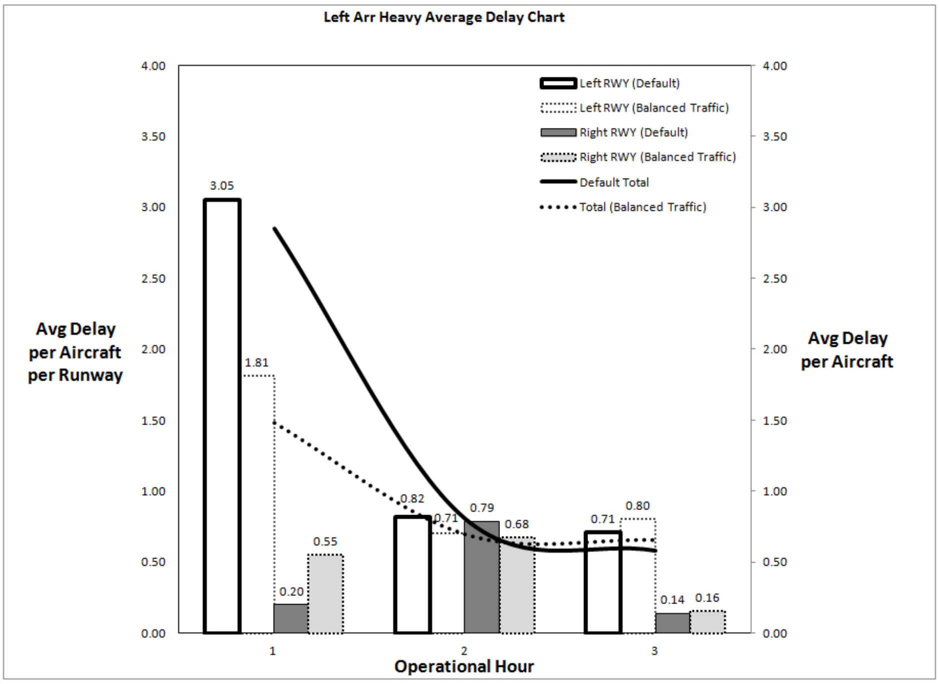


Figure 5.33 Average Delay per Aircraft – KPHX East Flow with traffic demand 2

### 5.7.2.3 Arrival peak at KPHX with West flow operation

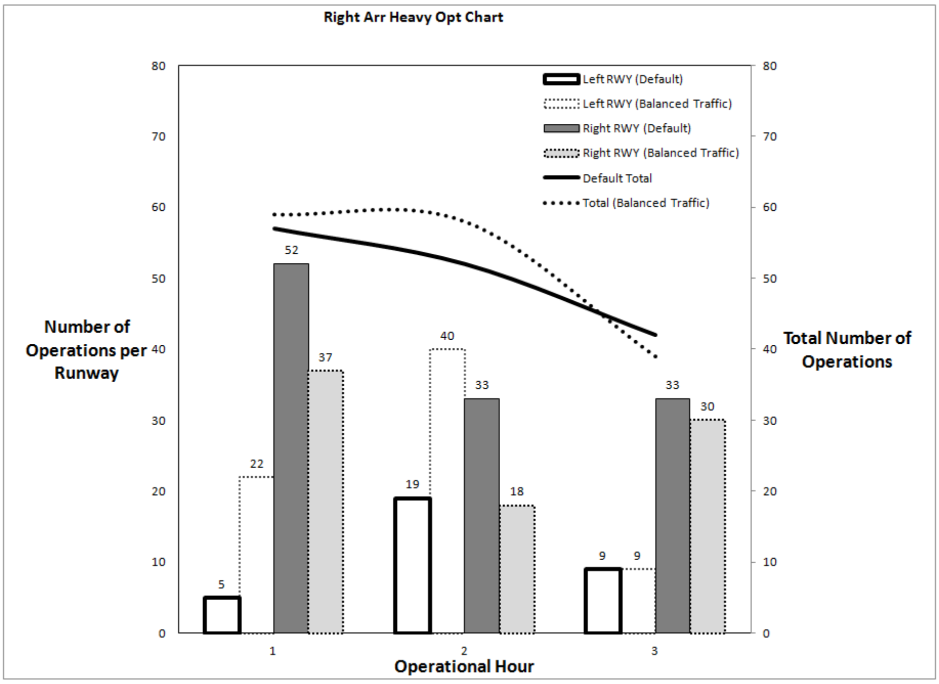


Figure 5.34 Number of Operation – KPHX West Flow

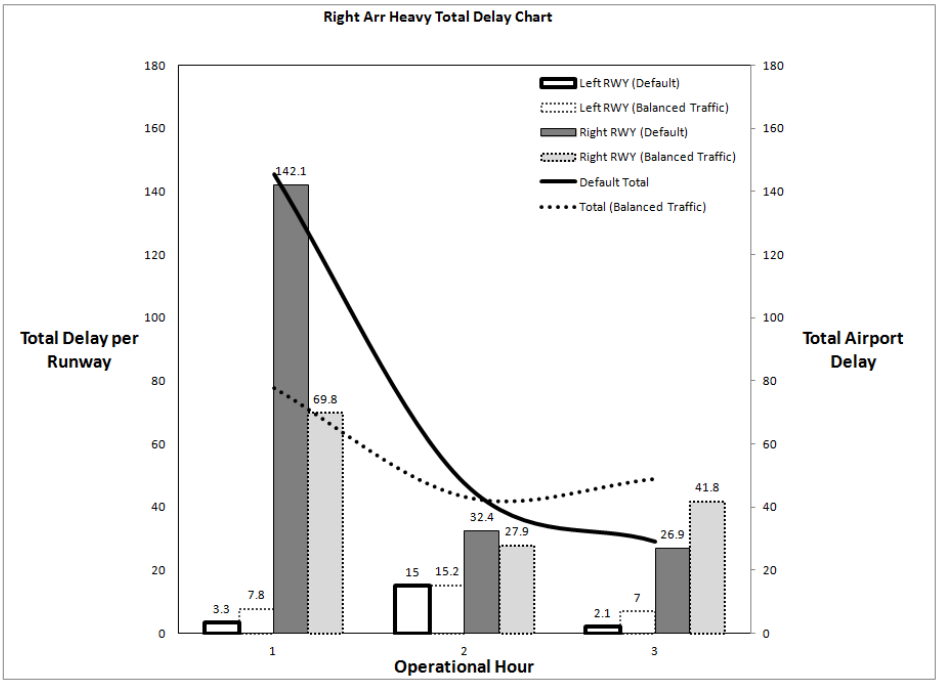


Figure 5.35 Total Delay – KPHX West Flow

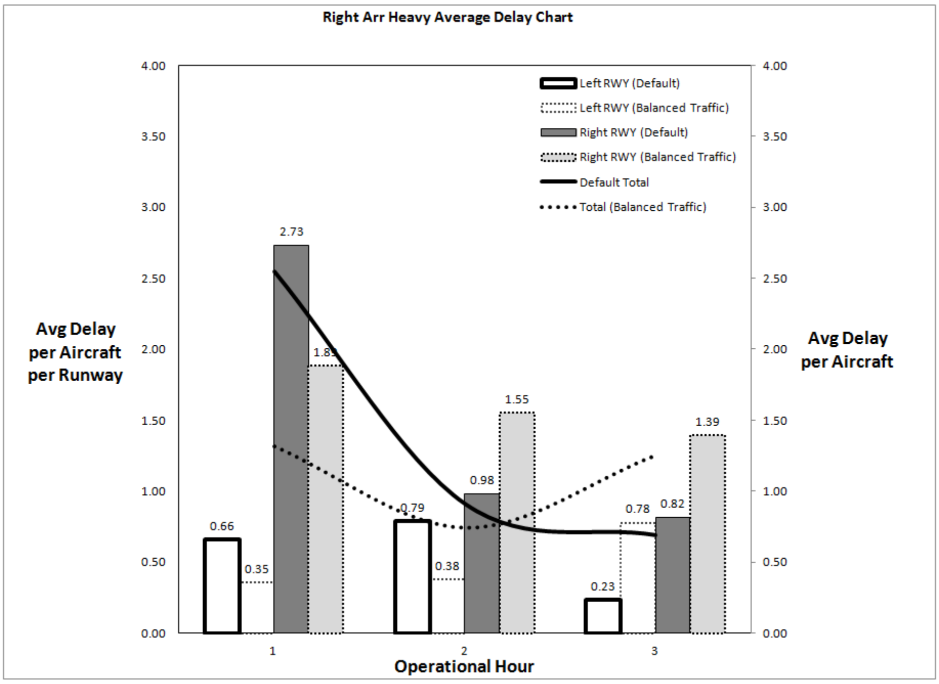


Figure 5.36 Average Delay per Aircraft – KPHX West Flow

### 5.7.2.4 Arrival peak at KSMF with North flow operation

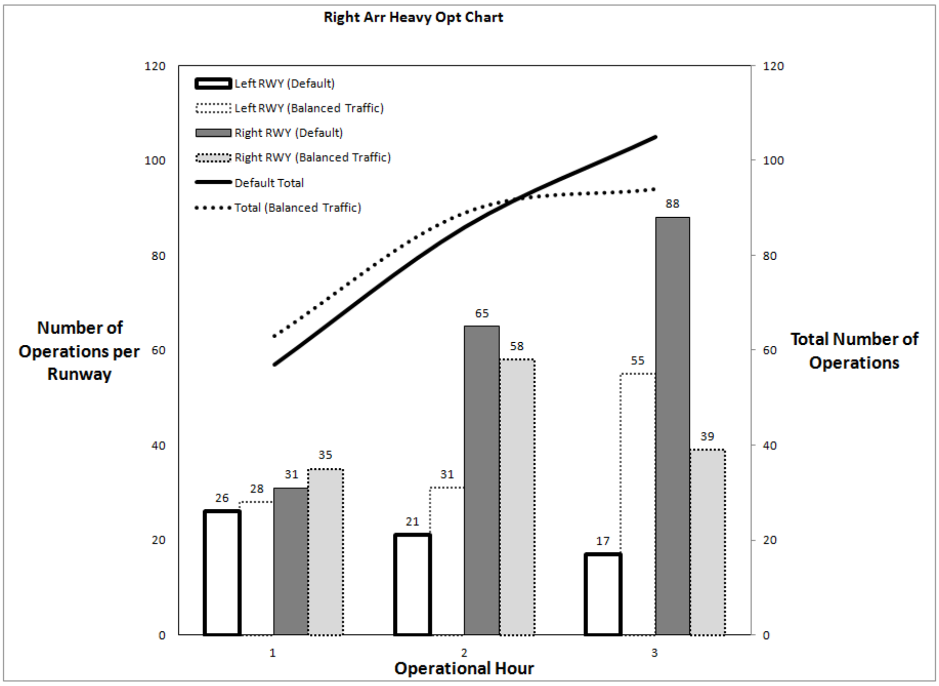


Figure 5.37 Number of Operation – KSMF North Flow

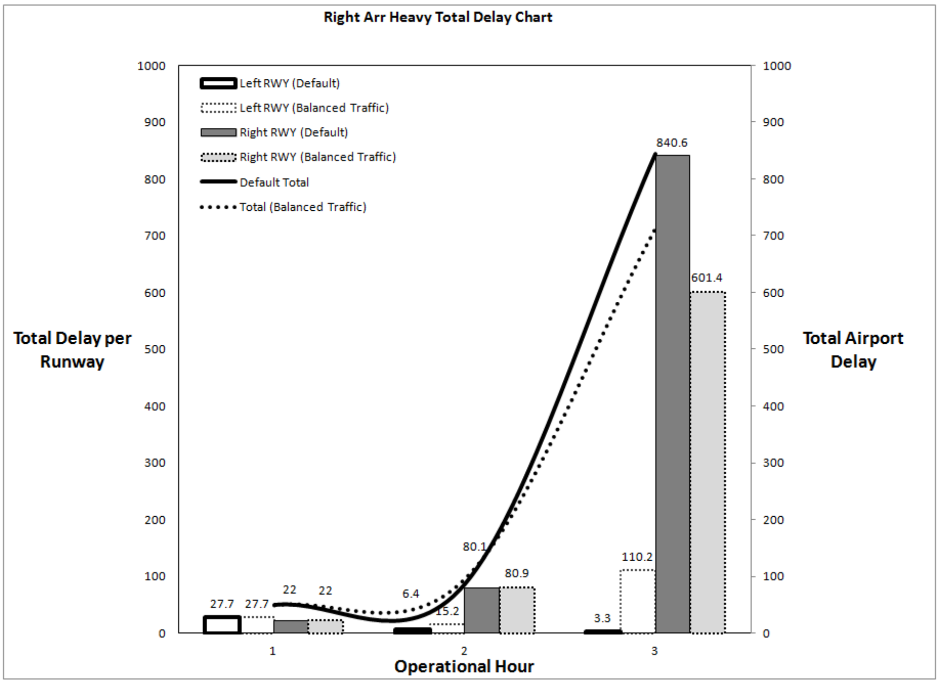


Figure 5.38 Total Delay – KSMF North Flow

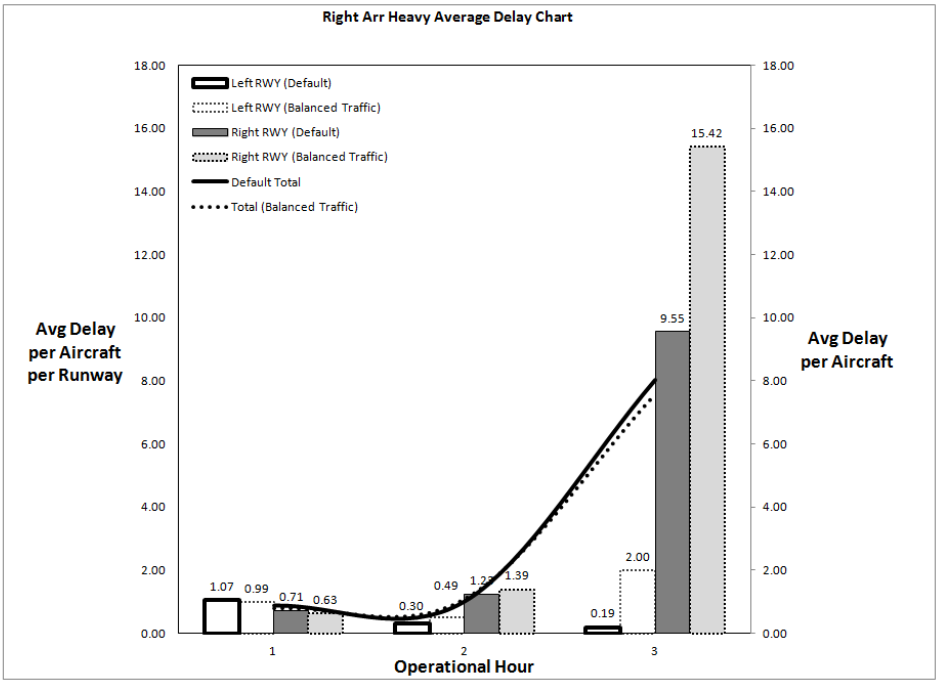


Figure 5.39 Average Delay per Aircraft – KSMF North Flow

All simulation results show benefit in airport throughput rate and overall average delay.

# Chapter 6 Conclusions

The effort in this dissertation demonstrated a closed-loop intelligent optimization system in managing terminal air traffic. The strategy of this approach is not only to compute the optimal arrival and departure schedule for each flight, but also to provide an optimal plan for runway assignment. The objective of this effort is to minimize the overall system delay and improve airport throughput during the peak hour operation. The importance of optimizing airport operation has been addressed in this thesis, especially regarding runway balancing for unevenly distributed traffic flow; along with the explanations of the challenges facing in terminal traffic management.

The solution was unfolded in the rest of the thesis. The approach is to use intelligent optimization system for runway assignment; the advanced MILP solver is embedded in the system to compute an optimal schedule for traffic stream of the available runway at the airport. It forms a closed-loop system with two layers, where the population of the trail solutions in the intelligent optimization system – the outer loop, was created based on expert knowledge of terminal airspace operation. Unlike many scheduling solutions, which allow aircraft to choose runways freely based on efficiency, this knowledge base system limited the arrival routes and departure routes in order to minimize mid-air crossing. As explained earlier in this thesis, mid-air crossings potentially increase conflicts. So, it automatically raises controllers' alert whenever an aircraft crosses over to land on a runway on the other side of airport, or takeoffs and heads to a direction farther away from the departure runway.

The effectiveness of the system has been verified by performing numerical simulations for eight different traffic scenarios.  The default flight plans in each scenario were established based on the real traffic mix at four of the 30 busiest airports in the US, KSMF, KMCO, KSEA, and KPHX.  All of these simulations demonstrated improvement in airport efficiency when applying the described system.  Results indicated optimizing runway assignment would further minimize system delay and maximize overall airport throughput.

# Chapter 7 Recommendations for Future Research

Hitherto, it was proved this intelligent optimization system should be able to improve efficiency and increase airport throughput. The system is not yet complete to cover all scenarios. A few of our considerations are runway system with cross-wind runways; reflecting on gate location in runway assignment; prioritizing flights within planning horizon; including constraints setting by the NAS traffic flow management system (TFMS); contemplating the multiplex airports system; and last but not least, the environmental factors.

Nevertheless, as discussed previously, cross-wind runway system are not as effective as parallel runway system, many major airports still have cross-wind runways, such as DFW, ORD, PHL, JFK. Due to the limitation of land or environmental constraints, the situation would not be changed in the near future. Cross-wind runway increases the restrictions on how to use the runway. The dependency of the runways will also have to be taken into consideration with the locations of cross point with other runways. Furthermore, availability of arrival routes and departure routes need to be carefully examined when there are cross-wind runways involved. Thus, we are interested in future study to test the capability of this system in managing traffic with cross-wind runways.

In our study, we assumed all runways are available for departures and arrivals. However, it may not be true in all airports. The aerodrome design of an airport may limit the accessibility of certain runways from or to a particular ramp area. And at other times, the taxiing traffic may cause extensively ground congestion, such that it may be advised not to use a particular runway. In addition, due to economic concerns, airlines would prefer to use a runway closer to its ramp. Future study in optimizing runway assignment with consideration of ground movement should be included, i.e. different gate allocation/airline apron allocation often has preferred runway assignment (28).

Another suggestion is to consider the planning horizon for each flight. That means flights reaching its maximum delay time would be put in the queue first. For example, during an Arrival Peak, a constant stream of landing aircraft occupies the runway. Since the number of departures is much less than arrivals, even if the departures have been held on ground with larger delay, it contributes very little in the overall system delay. However, in real world, controllers would usually hold off one or two arrivals to create enough gap in the arrival stream to allow the departure which has been waiting for a long time to takeoff first. NAS TFMS may also impose extra delay on departures heading to certain airport or via some regions due to weather. Thus, instead of FCFS for all departure aircraft, consideration of this additional delay into computing departure schedule would be useful during extreme weather condition.

So far, this system has only been tested with the single airport model. The reason is most of the major terminal airspaces only serve one airport with high volume of traffic flow. There are some airports within the airspace serving general aviation or military traffic, but the traffic demand is very low compared with the major commercial airport in the area. For example, ATL serves more than 3,000 flights daily, but there is not another airports in ATL TRACON that reaches 1,000 flights a day. However, there is New York TRACON with three major airports, JFK, EWA, and LGA; Potomac TRACON has IAD, BWI, and DCA. It brings up the interest in future study of this system in a multiplex airport system (29).

In the recent decade, emphasis on environmental factors have been increasing; according to the International air transport Association (IATA) reducing flight time by even one minute globally would save 4.8 million tones of CO2 a year (2). We would suggest the future studies include the environmental consideration when optimizing runway assignment, such as noise abatement, emission reduction, etc.  Noise and emission impacts by air traffic are involved with some complicated calculations, it would be almost impossible to depend solely on human judgments. An automated system is good at this kind of computation in a short period of time.

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