Effects of Reduced IFR Arrival-Arrival Wake Vortex Separation Minima and Improved Runway Operations Sequencing on Flight Delay

by

Elizabeth Bly

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics and Astronautics at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

Two methods to improve runway throughput are evaluated in this thesis. The first, increasing runway capacity during periods of bad weather by reducing IFR arrival-arrival wake vortex separations. The second, increasing runway efficiency in all weather conditions using event sequencing algorithms. Two algorithms were studied: a Serve-the-Longest-Queue algorithm for flight sequencing coupled with a greedy heuristic algorithm for runway assignment and a mixed integer programming optimization algorithm for simultaneous flight sequencing and runway assignment. The MIT Extensible Air Network Simulation (MEANS) was used to simulate NAS operations to determine the potential benefits in terms of delay reduction for both methods. For the case where reduced IFR arrival-arrival wake vortex separations was studied, the Airport Runway Capacity Calculator (ARCC), developed in support of this work, was used to determine the increased capacity at eleven congested US airports. Results indicate that the total delay in the National Airspace System (NAS) could have been reduced by 31.8% over the month of January, 1999 (a reduction of 243,672 minutes) representing a benefit of 116 minutes per IFR hour. For the cases where the event sequencing algorithms were studied, the algorithms were only implemented at Newark Airport (EWR) and the resulting delay values were compared to the performance of a FIFO algorithm that is representative of existing operations. The flight delay for the Serve-the-Longest-Queue algorithm and the FIFO algorithm were similar, though relative performance depended on the airline schedule. The integer programming optimization algorithm out performed the other two algorithms significantly reducing the average delay at EWR by 65.6% and 67.0% and the average NAS delay by 24.3% and 24.7% relative to the FIFO and Serve-the-Longest-Queue algorithms respectively.

Thesis Supervisor: John-Paul B. Clarke
Title: Associate Professor
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Chapter 1

Introduction

1.1 Motivation

Airport capacity, defined as the maximum number of operations (arrivals and departures) that can be processed in a given time period, is a limiting factor in the performance of the National Airspace System (NAS) because airports are system choke points. In addition to limiting the total number of flights in the NAS, an airport’s capacity restricts arrival and departure rates, with capacity shortfalls inducing delay and schedule disruption that is propagated through the NAS. Airport capacity is limited by a number of factors, including: runway configuration and equipment, gate and tarmac space availability, and taxiway layout. For most major US airports, the airport capacity is most tightly constrained by the runway throughput. Hence the runway capacity is the driving factor in airport capacity. The runway capacity at an airport is a function of not only the physical layout of the runways and the runway equipage, but also of the mix of aircraft using the runway (fleet mix) and the flight rules in use, which are in turn a function of the local weather conditions - Instrumented Flight Rules (IFR) during periods of poor weather and Visual Flight Rules (VFR) during periods of fair weather.

Currently, many of the major US airports are scheduled to operate at or near their maximum capacity under VFR, and for short periods during the day, even exceed the available VFR capacity. For example, at New York LaGuardia (LGA), the scheduled
demand requires the airport to operate near its VFR capacity for approximately eight hours per day. At Atlanta's Hartsfield Airport (ATL), the scheduled demand exceeds the available VFR capacity for approximately two hours each day in eight separate arrival/departure banks [1]. If the periods where demand exceeds capacity remain short - which is often the case during fair weather operations - the resulting delay can often be absorbed without severe schedule disruption or significant increases in airport congestion. However, during prolonged periods when IFR are in effect, the available runway capacity, and hence the available airport capacity, drops. In some cases, such as San Francisco (SFO) and Lambert St. Louis (STL) runway capacity is reduced as much as forty percent [1]. As it is impossible to predict when airports will experience prolonged periods of IFR early enough for airlines to alter their schedules accordingly, the demand remains at the VFR level, resulting in longer periods where demand exceeds capacity. These longer periods of excess demand frequently result in longer arrival and departure queues as flights are forced to wait because the airport cannot accommodate them. Longer arrival and departure queues lead to longer flight delays, which the schedule may be unable to absorb and as a result, the delay is propagated through the NAS. For example, at Newark Liberty (EWR), the demand typically exceeds capacity for approximately three hours a day during fair weather operations. However, for days when the airport experiences degraded weather conditions, demand can exceed capacity for over seven and a half hours a day with a corresponding increase of severely delayed flights from six percent to eighteen percent [1].

The demand for NAS resources, specifically airport capacity is projected to increase over the next half decade at many of the major US airports. The projected average demand increase is on the order of twenty percent of the demand in 2000, though it varies wildly with Boston's Logan Airport (BOS) projected to see an increase of six percent, Los Angeles (LAX) projected to see an increase of twenty-five percent, and Orlando (MCO) projected to see an increase of forty-two percent. The projected demand increase will not only exceed the current capacity of many of these airports, especially those that already operate at or near their VFR capacity, it will also exceed in many cases the predicted future capacity when currently planned capac-
ity improvements are taken into account. Thus, the delays and schedule disruptions that occur when demand exceeds the available capacity will continue to increase. Additionally, many of the current planned capacity improvements will result in a greater increase in VFR capacity than in IFR capacity, increasing the disparity. For example, the currently planned capacity improvements at Philadelphia International (PHL) will increase VFR capacity by seventeen percent but only increase IFR capacity by eleven percent [1]. As the demand at many major US airports will continue to reach or exceed the VFR capacity, the planned capacity improvements will increase the disparity between capacity and demand during poor weather conditions, resulting in an increase of the severity of flight delay and schedule disruption under IFR.

Because currently planned airport capacity improvements will not keep pace with projected demand, other methods of improving airport throughput, or equivalently the realized airport capacity, need to be found. In this thesis we examine two methods of increasing runway throughput: reducing required aircraft separations, and improving the sequencing of events on the available runways. Reducing required aircraft separations, specifically IFR arrival-arrival wake vortex separations which contribute significantly to the disparity between VFR and IFR capacities, directly increases an airport’s available capacity. As a result, the gap between capacity and demand under IFR will be reduced as will flight delay and schedule disruption. Improved runway event sequencing increases the efficiency of capacity utilization, increasing the throughput and decreasing flight delays without directly increasing the airport’s available capacity. Two algorithms were studied: a Serve-the-Longest-Queue algorithm for flight sequencing coupled with a greedy heuristic algorithm for runway assignment and a mixed integer programming optimization algorithm for simultaneous flight sequencing and runway assignment.

1.2 Organization

An introduction to the methods that are currently employed to both increase runway capacity and improve the efficiency of capacity utilization is provided in Chapter two.
The advantages and drawbacks of each method and expected throughput improvements are discussed.

In Chapter three, the history behind IFR arrival-arrival wake vortex separation minima is presented along with a discussion of their effect on airport capacity. The motivation for reducing the current minima and the expected benefits garnered from the resultant capacity increase are presented. Additionally, the overall approach for analyzing the impact of reducing the IFR arrival-arrival wake vortex separation minima is presented. The presented approach includes a description of the study airports and the method used to determine the capacity increase stemming from the altered separation minima.

The motivation and approach for studying the impact of different event sequencing algorithms is presented in Chapter four. Two event sequencing methods are introduced: the Serve-the-K-Longest-Queues algorithm and event sequence optimization through mathematical programming. The presented approach includes the exact from of the Serve-the-K-Longest-Queues algorithm applicable to the selected study airport and the formulation for the mixed integer programming optimization algorithm.

In Chapter five, the Airport Runway Capacity Calculator (ARCC), a tool for determining the capacity of a given runway configuration as a function of the fleet mix, weather conditions and the aircraft separation rules, is introduced.

In Chapter six, the functionality and structure of the MIT Extensible Air Network Simulation (MEANS), which was used to analyze the benefits of both the reduced arrival-arrival wake vortex and the proposed event sequencing methods is described.

In Chapter seven the results of the analysis of the reduced wake vortex separations as well as the event sequencing techniques are presented. This includes a discussion of the benefits of reduced wake vortex separations based on runway configuration and level of airport congestion as well as a comparison of the performance of the two event sequencing techniques in terms of event sequence and flight delay.

A summary and discussion of directions for future work are provided in Chapter eight.
Chapter 2

Background

The Federal Aviation Administration (FAA) has long been concerned with improving throughput at the major US airports in an attempt to both keep pace with the ever rising demand for airport capacity and ameliorate flight delays and schedule disruptions caused by capacity shortfalls. There are two ways to increase throughput: increasing the available capacity and increasing the realized capacity. Available airport capacity can be increased either directly through the addition of new runways or indirectly though the introduction of new technology which enables alteration of operational procedures to allow decreased aircraft separation minima. The realized capacity, the capacity actually achieved at the airport for a given schedule, can be increased by improving the efficiency of capacity utilization through application of event sequencing and runway assignment algorithms.

Building a new runway at an airport has the greatest potential for increasing the available capacity. A new, completely independent runway at an airport increases the operational rates on the order of 33 arrivals and 33 departures per hour under VFR and 24 arrivals and 24 departures per hour under IFR. Even if the new runway cannot operate completely independently, significant benefit may still be reaped. For example, Phoenix Sky Harbor (PHX) recently introduced a third parallel runway with a centerline separation insufficient for independent operations but which still enables PHX to nearly double operations under IFR [1]. The benefit of a new runway may be further limited if the airport employs noise abatement procedures or the
standard wind and weather conditions at the airport are such that the new runway is either used infrequently or underutilized. While construction of a new runway has the greatest potential for increasing the available capacity and hence throughput, the time required for community approval, funding and construction may be prohibitive. For example, a proposal for constructing a set of new runways at Boston Logan’s Airport (BOS) has been stalled in the courts for over twenty-five years due to community activism [2].

Second to the construction of a new runway in terms of potential for increasing the available capacity at an airport is the introduction of new radar technology such as the Precision Runway Monitor (PRM) System [3]. PRM is a radar system used to monitor aircraft on final approach. The difference between PRM and conventional radar system is that PRM’s update rate is four to five times faster which improves the accuracy of positional information. The improved final approach positional information enables independent/simultaneous approaches to parallel runway systems with centerline separations as small as 750 feet. Without a PRM installation, IFR require parallel runways less than 4,300 feet apart to operate with dependent/staggered arrival streams and restricts those less than 1,400 feet apart to a single arrival stream. It has been shown via testing of PRM installations at Kennedy International (JFK), Minneapolis-St Paul International (MSP), PHL, STL and SFO that utilization of simultaneous parallel approaches when IFR are in effect can increase runway capacity on the order of fifteen to twenty percent. Even though PRM has been shown to reap significant benefit in terms of capacity improvements, it has limited applicability. Only twenty-five US airports are candidates for PRM systems, of which, only ten have sufficient demand to benefit from simultaneous parallel approaches.

Another technology which can increase the available capacity is the combination of Automatic Dependent Surveillance-Broadcast (ADS-B) and Cockpit Display of Traffic Information (CDTI) [4]. ADS-B/CDTI delivers positional, speed and identification information concerning nearby aircraft directly to pilots on the Traffic Alert and Collision Avoidance System (TCAS) display and like PRM, allows for closer arrival separations on final approach. Providing the information directly to the pilots
visually, rather than relaying it verbally through controllers, increases the speed of aircraft identification and decreases the probability of misidentification. This allows Visual separations to be applied to a broader ranger of scenarios, including a portion of marginal Instrumented Meteorological Conditions (IMC), all while decreasing controller workload. Unfortunately, the ADS-B/CDTI technology under development would only provide an increase in capacity if accompanied by changes to operational procedures. Additionally, even after ADS-B/CDTI technology has been deployed and the operational procedures updated, the full benefit will not be realized until all aircraft have been equipped, which could take years, depending on the equipage requirements.

One method of improving the realized capacity is to provide terminal area air traffic controllers with decision supports tools to aid in determining flight runway assignments and the event sequence. These decision support tools improve capacity utilization by employing either optimization techniques or heuristics which improve upon standard controller decision processes. One such decision support tool, Final Approach Spacing Tool (FAST), is a component of the National Aeronautics and Space Administration’s (NASA) Center Terminal Area Approach Control (TRACON) Automation System (CTAS) [5]. There are two versions of FAST, pFAST and aFAST, standing for passive and active FAST respectively. pFAST finds for a given set of arrival aircraft and TRACON arrival streams the runway assignments and a landing sequence that balances the demand on runway resources. aFAST has all the functionality of pFAST and additionally provides controllers with speed and heading advisories which enables controllers to implement the desired event sequence while minimizing the inter-arrival separations during final approach. pFAST has been used at Dallas-Fort Worth (DFW) and has been shown to increase the arrival throughput during an arrival push and reduce the controller workload. FAST’s major draw back is its failure to consider departures when determining runway assignments and the event sequence. As a result, FAST provides a sub-optimal event sequence when departures are present and will only benefit airports which utilize arrival bank structures and only during arrival pushes.
Another available decision support tool and a proposed component of CTAS is Expedite Departure Path (EDP) [6]. EDP uses the same algorithm as FAST to determine runway assignments and a departure sequence which balances runway loading. Additionally, EDP provides controllers with a set of tactical control advisories which take the aircraft from take-off to the assigned departure fix. While EDP is still under development, it is predicted to increase runway throughput on the same order as FAST. However, just as with the FAST tools, EDP provides a sub-optimal event sequence when arrivals are present due to the tool’s failure to consider arrivals when determining the event sequence. As a result, EDP will only benefit airports which utilize departure bank structures and only during departure pushes.

The methods to increase available and realized airport capacity that have been presented by no means constitute an exhaustive list; however, they are representative of the two fundamental sources of increased throughput. Of the techniques presented only one has the potential to produce large increases in throughput without being limited in terms of airport applicability - building additional runways. While utilizing technology that improves the quality of information has the potential to increase an airport’s available capacity, without corresponding alterations in controller procedures and rules the potential is nullified. While utilizing decision support tools to generate an event sequence has the potential to increase an airport’s realized capacity, unless the algorithm takes into account both arrivals and departures the resultant event sequence will fail to maximize the realized capacity under standard operating conditions.
Chapter 3

Reducing IFR Arrival-Arrival
Wake Vortex Separation Minima

3.1 Overview

A number of factors contribute to the capacity decrease that airports experience when they transition from VFR to IFR, including: changing inter-runway dependencies, utilization of different runway configurations and larger inter-aircraft separation minima. Inter-runway dependencies differ from VFR to IFR, in particular for parallel runway system, which contributes to the reduction in capacity. For example, under VFR, parallel runways with centerlines separations greater than 700 feet are able to operate independently, but those with smaller centerline separations are restricted to a single arrival stream. Under IFR, parallel runways with centerline separations less than 1,400 feet, twice the VFR limit, are restricted to a single arrival stream; and, parallel runways are only able to operate independently if the centerline separation is greater than 4,300 feet. As a result, parallel runways with centerline separations between 700 and 1,400 feet automatically lose half of the available arrival capacity when weather conditions degrade from Visual Meteorological Conditions (VMC) to IMC which requires a shift from VFR to IFR, even without factoring in the impact of the increased inter-aircraft separation minima. In addition to altered inter-runway dependencies, many airports lose the use of some runways, and hence some of the
available capacity, because those runways do not meet the minimum equipage requirements for IFR operations. Airports also, suffer a drop in available capacity due to the increased separation minima imposed by the FAA. The arrival-arrival wake vortex separation minimum, which restricts the separation between subsequent arrivals on the same runway, is one such separation minima. This particular separation minimum is the main source of lost arrival capacity for those airports utilizing the same or similar runway configuration under both VFR and IFR, such as LGA, which would otherwise not be impacted by changes in flight rules.

3.2 History

The FAA first imposed the IFR arrival-arrival wake vortex separation minima after the introduction of the Boeing 747 in 1969 when it became apparent that the wake vortex turbulence behind the heavier Boeing 747 posed a significant threat to smaller aircraft following in trail [7]. Wake vortices are rotating air masses that form at the wing tips and trail behind the aircraft. These rotating air masses are normally invisible, and hence are difficult to detect and all but impossible to avoid. The strength of the vortices is directly proportional to the lift being generated and thereby, to the weight of the aircraft, with heavier aircraft generating stronger wake vortices [8]. Wake vortices can impinge on trailing aircraft and disrupt the airflow over their wings causing severe roll and pitch disruption. Trailing aircraft are particularly sensitive to these disturbances when they are operating at lower velocities, for example during landing operations. Because lighter aircraft generate less lift, it takes less force to disrupt the generated lift and hence wake vortices can pose a serious threat for these smaller aircraft.

The current arrival-arrival wake vortex separation requirements (Table 3.1), thought significant, are less than the original separations imposed in 1969, which were upward of ten nautical miles in some cases. The reduction to the current minima was made after some initial analysis in 1970 of the strength of the generated wake vortices [7]. However, no significant research has been done to demonstrate that the
current arrival-arrival wake vortex separation minima correspond to an operational safety limit; rather, the current separations have been accepted because they have been demonstrated to be safe in practice. The separations have remained fixed even though there has been significant improvements made in surveillance technology in the last thirty years. Improvements which have increased the accuracy in positional information and thus enable smaller inter-aircraft separations [9]. The wake vortex separation minima shown in Table 3.1 are defined based on an aircraft’s Maximum Gross Take-Off Weight (MGTOW): aircraft with MGTOWs greater than 255,000 lbs are classified as Heavies, aircraft with MGTOWs between 41,000 lbs and 255,000 are Larges and all lighter aircraft are classified as Smalls. A separate weight class was created for the Boeing 757 when it entered service in the mid 1980s [10].

### Table 3.1: Current IFR Arrival-Arrival Wake Vortex Separation Minima

<table>
<thead>
<tr>
<th>Leading Aircraft</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(NM) H B757 L S</td>
</tr>
<tr>
<td>H</td>
<td>4 5 6</td>
</tr>
<tr>
<td>B757</td>
<td>4 4 4 4</td>
</tr>
<tr>
<td>L</td>
<td>2.5 2.5 2.5 4</td>
</tr>
<tr>
<td>S</td>
<td>2.5 2.5 2.5 2.5</td>
</tr>
</tbody>
</table>

3.3 Reducing Separation Minima

Under VFR, the FAA does not provide same runway arrival-arrival separation minima; rather, pilots are allowed to self separate based on visual contact. As a result, typical arrival-arrival separations under VFR are less than the imposed arrival-arrival wake vortex separation minima under IFR. Table 3.2 depicts the average observed VMC arrival-arrival separations as measured by Weiss [11]. The average observed separations are clearly smaller than the minima imposed under IFR (Table 3.1). As the measured separations are only average values, there exists historical proof that under VFR arrivals can operate at and below the average observed separations without experiencing fatal wake vortex impacts. Hence, Weiss’s average observed arrival-arrival
Table 3.2: Average Observed VMC Arrival-Arrival Separations

<table>
<thead>
<tr>
<th>Leading Aircraft</th>
<th>Trailing Aircraft (NM)</th>
<th>H</th>
<th>B757</th>
<th>L</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2.7</td>
<td>-</td>
<td>3.6</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>B757</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>1.9</td>
<td>-</td>
<td>1.9</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>1.9</td>
<td>-</td>
<td>1.9</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>

Separations can be taken as a conservative separation threshold for dangerous wake vortex impingements.

Ideally, the IFR arrival-arrival wake vortex separation minima could be reduced to the point that full VFR capacity is recovered. However, full VFR capacity recovery is not possible because of the other factors contributing to the capacity discrepancies. Though full VFR capacity cannot be recovered, even small magnitude reductions in the arrival-arrival wake vortex separation minima can result in increased runway throughput and a non-linear reduction of delay at airports where there is sufficient demand. This results from the compounding of the effect of the reduced separation minima over time. Assume for a moment a pure arrival schedule composed of aircraft all of the same weight class, for example all Large aircraft. If the arrival-arrival wake vortex separation minima were reduced from 2.5 NM to 2.4 NM, a reduction of only 0.1 NM, then a single runway can accommodate an extra arrival after every twenty-fifth arrival, an extra arrival every twenty-eight minutes. Table 3.3 shows the increased throughput results for the other weight classes with the same 0.1 NM reduction in separation.

Table 3.3: Reduced Separation Throughput Benefit

<table>
<thead>
<tr>
<th>Weight Class</th>
<th>No. Arrivals Until Free Arrival</th>
<th>Time until Free Arrival(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-Heavy</td>
<td>40</td>
<td>62.4</td>
</tr>
<tr>
<td>B757-B757</td>
<td>40</td>
<td>72.0</td>
</tr>
<tr>
<td>Large-Large</td>
<td>25</td>
<td>27.7</td>
</tr>
<tr>
<td>Small-Small</td>
<td>25</td>
<td>40.0</td>
</tr>
</tbody>
</table>
For some weight classes, the increase in throughput may not seem significant, however the effects in terms of delay reduction can be. In order to illustrate the effects or reducing the arrival-arrival wake vortex separation minima in terms of delay reduction, again assume a set of Large arrivals scheduled via a poisson process with a rate of one hundred arrivals per hour, a rate significantly larger than the maximum available capacity for a single runway system. The scheduled arrival times as well as the minimum landing times after the arrival-arrival wake vortex separations have been imposed for both the original 2.5 NM separation and the reduced 2.4 NM separation are shown in Figure 3-1. For the ten flights shown, the 0.1 NM separation reduction results in a delay reduction of nearly one hundred seconds. The last flight alone reaps a benefit of twenty two seconds, significantly greater than the three seconds gained directly from the separation reduction. The later the flight in the day, the larger the potential delay reduction because the effects are compounded throughout the day and later flights reap the benefit of previous flights. If the schedule contains gaps which can absorb some of the accumulated delay, later flights will not realized the full delay reduction from the previous flights. Figure 3-2 depicts a schedule that contains gaps.

Figure 3-1: Reduced Separation Example With No Absorption Gaps: (L) Standard Separations, (R) Reduced Separations

27
large enough to absorb some of the accumulated delay - after the first and fifth flight in the 2.5 NM cases and also after the forth flight in the 2.4 NM case. Note that in the 2.4 NM case the fifth flight does not receive the full benefit of the delay reduction from the previous flights. Similarly, flights six through ten do not reap the benefit of the previous flights. Even if later flights do not reap the benefit from the previous flight’s delay reduction due to the presence of gaps in the schedule, the reduced separations widen the available schedule gaps. The gap widening increases the space available to accommodate the departure traffic, decreasing the departure delay and increasing the runway throughput. It is important to note that reducing the arrival-arrival wake vortex separation requirements will only result in delay reductions for schedules that have multiple arrivals in a row.

Figure 3-2: Reduced Separation Example With Absorption Gaps: (L) Standard Separations, (R) Reduced Separations

3.4 Approach

In order to evaluate the impact of reduced IFR arrival-arrival wake vortex separation minima on NAS operations in terms of flight delay, seven sets of reduced separation
minima were studied. The seven sets of separation minima were applied to operations at each of eleven candidate airports. The altered capacity curves for each set of separation minima were found using the Airport Runway Capacity Calculator (ARCC) for the most frequently used runway configurations and the average fleet mix at each candidate airport. The altered capacity curves were then used in MEANS to simulate NAS operations during the entire month of January 1999. The results of each MEANS simulation run was then compared in terms of total flight delay, flight delay by airport and flight delay by day of the month.

3.4.1 Reduced Separation Minima

The first step in selecting a set of reduced separation minima is to identify a lower bound on the separations of interest. Because the average observed VMC arrival-arrival separations measured by Weiss have proven safe in operation, they are ideal for this purpose. By examining the observed average VMC arrival-arrival separations, with extrapolated separations for both leading and trailing Boeing 757s (Table 3.4), and the current separations minima, reproduced in Table 3.5, it becomes apparent that there are only four different separation value pairs: 6 NM and 4.5 NM for the Heavy-Small sequence, 5 NM and 3.6 NM for the Heavy-B757, and Heavy-Large sequences, 4 NM and 2.7 NM for the Heavy-Heavy, leading B757 and Large-Small sequences, and 2.5 NM and 1.9 NM for all other sequences. For ease of distinction these different separation value pairs are hereafter termed as separation pairs A, B, C and D respectively and are denoted by different gray scale valuations in Table 3.4 and Table 3.5.

Seven sets of reduced arrival-arrival wake vortex separation minima were studied (Table 3.6). These sets of reduced separations were found by subtracting a percentage of the difference between the current separation minima and the average observed separations with a 0% reduction corresponding to the current separation minima and a 100% reduction corresponds to the average observed VMC separations. Selecting sets of reduced separation minima in this manner ensures that the relative separations between different weight class pairs remain constants so that the separation minima
Table 3.4: Lower Bound for Reduced IFR Arrival-Arrival Wake Vortex Separation Minima

<table>
<thead>
<tr>
<th></th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading</td>
<td>(NM)</td>
</tr>
<tr>
<td>Aircraft</td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>2.7</td>
</tr>
<tr>
<td>B757</td>
<td>2.7</td>
</tr>
<tr>
<td>L</td>
<td>1.9</td>
</tr>
<tr>
<td>S</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 3.5: Current IFR Arrival-Arrival Wake Vortex Separation Minima

<table>
<thead>
<tr>
<th></th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading</td>
<td>(NM)</td>
</tr>
<tr>
<td>Aircraft</td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>4</td>
</tr>
<tr>
<td>B757</td>
<td>4</td>
</tr>
<tr>
<td>L</td>
<td>2.5</td>
</tr>
<tr>
<td>S</td>
<td>2.5</td>
</tr>
</tbody>
</table>

continue to reflect the relative strength of the wake vortices. In Table 3.6 the percentage value in column one corresponds to the percentage difference by which the separation minima were reduced and the column headers refer to the separation pairs discussed above. It is important to note that though the 100% reduction corresponds to the VMC average observed separations it does not correspond to a full recovery of VFR capacity even if the runway configuration remains unchanged because all other IFR separation requirements and inter-runway dependencies remain unaltered.

Table 3.6: Reduced IFR Arrival-Arrival Wake Vortex Separation Minima

<table>
<thead>
<tr>
<th>Separation Pair</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>5.85</td>
<td>4.86</td>
<td>3.87</td>
<td>2.44</td>
</tr>
<tr>
<td>20%</td>
<td>5.70</td>
<td>4.72</td>
<td>3.74</td>
<td>2.38</td>
</tr>
<tr>
<td>40%</td>
<td>5.40</td>
<td>4.44</td>
<td>3.48</td>
<td>2.26</td>
</tr>
<tr>
<td>60%</td>
<td>5.10</td>
<td>4.16</td>
<td>3.22</td>
<td>2.14</td>
</tr>
<tr>
<td>80%</td>
<td>4.80</td>
<td>3.88</td>
<td>2.96</td>
<td>2.02</td>
</tr>
<tr>
<td>100%</td>
<td>4.50</td>
<td>3.60</td>
<td>2.70</td>
<td>1.90</td>
</tr>
</tbody>
</table>
3.4.2 Airports of Interest

For an airport to benefit from the capacity increase garnered by reducing the IFR arrival-arrival wake vortex separation minima, the airport must be scheduled such that the demand exceeds the available capacity during normal IFR operations. By examining delay statistics for thirty-one of the busiest airports in the US both in terms of delays per one thousand operations and total amount of delay, candidate airports can be identified. Taking the ten most delayed airports in each of the two categories, as determined from analysis of OPSNET data for 2000, results in twelve candidate airports: Atlanta Hartsfield International (ATL), Boston Logan International (BOS), Chicago O’Hare International (ORD), Dallas-Fort Worth International (DFW), Houston Bush Intercontinental (IAH), Los Angeles International (LAX), Newark Liberty International (EWR), New York Kennedy International (JFK), New York LaGuardia (LGA), Phoenix Sky Harbor International (PHX), Philadelphia International (PHL) and San Francisco International (SFO). DFW was eliminated from the candidate pool because operations at DFW are limited by the taxi-way capacity as apposed to runway throughput restrictions, and altering the IFR arrival-arrival wake vortex separation minima has no impact on taxi-way capacity [1].

3.4.3 Runway Configuration

In order to gage the effect of the reduced separations on the available IFR capacity, for each of the candidate airports a set of runway configurations must be identified. It is possible that throughout the day, an airport may use many different runway configurations even though the weather conditions do not change. As a result the available capacity may change while the meteorological conditions remain constant. Ideally, all possible runway configurations would be modeled and the impact of the reduced IFR arrival-arrival wake vortex separations on the available capacity tracked as a function of the changing runway configurations. However, as information concerning the historically utilized runway configurations is unavailable, the most frequently used runway configurations under VFR and IFR as identified by the FAA were assumed
to be representative of standard operations (Table 3.7).

<table>
<thead>
<tr>
<th>Airport</th>
<th>VFR Configuration</th>
<th>IFR Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arrivals</td>
<td>Departures</td>
</tr>
<tr>
<td>ATL</td>
<td>8L, 9R</td>
<td>8R, 9L</td>
</tr>
<tr>
<td>BOS</td>
<td>4L, 4R</td>
<td>4L, 4R, 9</td>
</tr>
<tr>
<td>ORD</td>
<td>4R, 9L, 9R</td>
<td>4L, 4R, 32L</td>
</tr>
<tr>
<td>IAH</td>
<td>26L, 27R</td>
<td>8R, 14L</td>
</tr>
<tr>
<td>LAX</td>
<td>6L, 7R</td>
<td>6R, 7L</td>
</tr>
<tr>
<td>EWR</td>
<td>11, 22L</td>
<td>22R, 29</td>
</tr>
<tr>
<td>JFK</td>
<td>13L, 22L</td>
<td>32L</td>
</tr>
<tr>
<td>LGA</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>PHX</td>
<td>8L, 8R</td>
<td>8L, 8R</td>
</tr>
<tr>
<td>PHL</td>
<td>27L, 27R, 28</td>
<td>27L, 34</td>
</tr>
<tr>
<td>SFO</td>
<td>28L, 28R</td>
<td>1L, 1R</td>
</tr>
</tbody>
</table>

### 3.4.4 Fleet Mix

In addition to the runway configuration, a fleet mix in terms of the four FAA weight classes is needed to accurately model the impact of the reduced separations on the available IFR capacity. For each candidate airport, an average fleet mix was calculated in one of two ways: through a combination of OAG data and the fleet mixes from the Airport Capacity/Demand Profiles from 1998 [12] or a combination of OAG data and total operational counts from the Air Traffic Activity Data System (ATADS). The calculated fleet mix for each candidate airport is shown in Table 3.9.

If using a combination of OAG data and the fleet mixes from the Airport Capacity/Demand Profiles the process is rather simple. The Airport Capacity/Demand Profiles provides information on the annual aircraft mix for a number of domestic and international airports. The counts are divided into six separate categories (Table 3.8). Counts from the first two categories contain Heavy aircraft. The third category covers both a subset of Heavy aircraft and Boeing 757s. The forth category accounts for Large aircraft and it is assumed that all aircraft accounted for in the final two categories are Smalls. In order to convert these counts into a usable fleet mix, the
relative number of B757s needs to be extracted from the third category, which can be done using OAG data. The OAG data contains the planned equipment types for all scheduled flights in the US and from this data the ratio of the Heavy aircraft accounted for in category three to Boeing 757s can be extracted. This method of determining the fleet mix was used for all candidate airports for which the *Airport Capacity/Demand Profiles* has complete entries, which is all studied airports except BOS, IAH, ORD and PHX.

Table 3.8: *Airport Capacity/Demand Profiles* Categories

<table>
<thead>
<tr>
<th>No.</th>
<th>Category</th>
<th>Weight Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>747/777/A340/A330</td>
<td>Heavy, Heavy, Heavy, Heavy</td>
</tr>
<tr>
<td>2</td>
<td>DC10/MD11/L1011</td>
<td>Heavy, Heavy, Heavy</td>
</tr>
<tr>
<td>3</td>
<td>757/767/A300/A310</td>
<td>B757, Heavy, Heavy, Heavy</td>
</tr>
<tr>
<td>4</td>
<td>727/737/A320/DC9/MD80/MD90</td>
<td>Large, Large, Large, Large, Large, Large</td>
</tr>
<tr>
<td>5</td>
<td>Commuter/Turbo Props</td>
<td>Small</td>
</tr>
<tr>
<td>6</td>
<td>Other/GA</td>
<td>Small</td>
</tr>
</tbody>
</table>

Using a combination of OAG data and the total operational counts from ATADS requires calculating the ratio of Heavies to B757s to Large aircraft from the OAG data. The OAG data cannot be used to determine the complete fleet mix because a large percentage of itineraries flown by Small aircraft are general aviation (GA) flights which are not required to file flight plans and hence do not appear in the OAG data. The ATADS data is used to determine the percentage of Smalls. It is assumed that all flights accounted for in the aggregate monthly flight counts provided in ATADS beyond the total number of flights found in the OAG data are flown by Small aircraft.

### 3.4.5 Capacity Curve Generation

With the identified runway configurations and the calculated fleet mixes ARCC (see Chapter 5) was used to determine the impact of the reduced IFR arrival-arrival wake vortex separation minima. For each candidate airport, ARCC was used to generate eight different capacity curves, one for each of the seven selected sets of reduced
Table 3.9: Calculated Fleet Mixes

<table>
<thead>
<tr>
<th>Airport</th>
<th>Heavies(%)</th>
<th>B757(%)</th>
<th>Larges(%)</th>
<th>Smalls(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATL</td>
<td>12.3</td>
<td>11.0</td>
<td>54.5</td>
<td>22.2</td>
</tr>
<tr>
<td>BOS</td>
<td>8.8</td>
<td>6.8</td>
<td>39.4</td>
<td>45.0</td>
</tr>
<tr>
<td>EWR</td>
<td>6.9</td>
<td>10.2</td>
<td>77.9</td>
<td>5.0</td>
</tr>
<tr>
<td>IAH</td>
<td>2.1</td>
<td>1.0</td>
<td>72.2</td>
<td>24.7</td>
</tr>
<tr>
<td>JFK</td>
<td>39.0</td>
<td>6.6</td>
<td>17.9</td>
<td>36.5</td>
</tr>
<tr>
<td>LAX</td>
<td>16.8</td>
<td>8.4</td>
<td>42.7</td>
<td>32.1</td>
</tr>
<tr>
<td>LGA</td>
<td>3.0</td>
<td>3.8</td>
<td>2.5</td>
<td>30.7</td>
</tr>
<tr>
<td>ORD</td>
<td>3.8</td>
<td>2.8</td>
<td>48.1</td>
<td>44.3</td>
</tr>
<tr>
<td>PHL</td>
<td>11.1</td>
<td>1.9</td>
<td>42.0</td>
<td>45.0</td>
</tr>
<tr>
<td>PHX</td>
<td>1.2</td>
<td>7.9</td>
<td>59.9</td>
<td>31.0</td>
</tr>
<tr>
<td>SFO</td>
<td>11.7</td>
<td>17.7</td>
<td>51.7</td>
<td>19.0</td>
</tr>
</tbody>
</table>

separation minima and one for VFR. The generated capacity curves for each candidate airport are shown in Appendix A.

### 3.4.6 Simulation

Using the ARCC generated capacity curves as inputs, MEANS (see Chapter 6) was used to evaluate the impact of the reduced IFR arrival-arrival wake vortex separation minima on NAS operations in terms of flight delay. NAS operations were simulated for January 1999 under each of the reduced separation minima. For each simulation run, the ARCC generated capacity curves corresponding to a set of reduced IFR arrival-arrival wake vortex separation minima were used to model the capacity at each of the eleven candidate airports while the capacity was left unchanged at all other airports in the NAS. The resulting operations were then compared in terms of total flight delay, flight delay by airport and flight delay by day of the month.

In order to accurately model the relative contribution in terms of delay reduction as a function of the IFR arrival-arrival wake vortex separation minima of each candidate airport, MEANS was provided with the historical schedule and weather data for January 1999. Different airports are expected to contribute different levels of delay reduction as a result of the variation in schedule loading, available capacity and the percentage of operations under IMC. The schedule loading impacts the relative de-
lay reduction contribution simply because airports with more flights in general have
greater delays, which means there is more delay available to recover. The fraction of
time an airport spends under IMC directly restricts the possible benefit from reduc-
ing the IFR arrival-arrival wake vortex separation minima as the reduced separations
only increase the available capacity during IFR. As a result, some airports, such as
PHX which only sees a few hours of IMC during January 1999, can only contribute
a relatively small amount of delay reduction. On the other hand, more northern
airports such as BOS or ORD which frequently experience prolonged periods of IFR
stand to benefit more from the reduced separations.
Chapter 4

Event Sequencing

4.1 Overview

The realized throughput at an airport depends on the sequence of events on the available runways, both in terms of the order of flights processed through the runways and the runway assignments. The problem of determining an event sequence is referred to as the event sequencing problem. Because the inter-event separation requirements are dependent on the event order in terms of the event type (arrival or departure), runway assignment and aircraft weight class, the event sequencing problem is combinatorial in nature. For example, the separation required for a departure trailing an arrival on the same runway differs from that required for an arrival trailing a departure (Table 5.3), both due to the different event orders and the possibly different weight classes of the two aircraft. The variation in event times due to weight class can be seen by examining a sequence of three arrivals, one Heavy, one Large and one Small. Assuming a single runway, there is a difference of three minutes between the six possible event sequences (Table 4.1). The variation in event times grows with the number of flights and the inclusion of departure. Similarly, for airports with multiple dependent runways, the required flight separations depend on the runway assignments as well as the order of the operations. Looking at a sequence of three Large arrivals and two available parallel runways separated by 2,500 feet, there is a variation of approximately four minutes between the four possible event sequences (Table 4.2).
The event sequencing problem is further complicated by the uncertainty inherent in actual arrival and departure times as distinct from the scheduled times.

Table 4.1: Sequence Throughput Variation: Weight Class

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Process Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-Large-Small</td>
<td>298.5</td>
</tr>
<tr>
<td>Heavy-Small-Large</td>
<td>309.2</td>
</tr>
<tr>
<td>Large-Heavy-Small</td>
<td>300.0</td>
</tr>
<tr>
<td>Large-Small-Heavy</td>
<td>220.0</td>
</tr>
<tr>
<td>Small-Heavy-Large</td>
<td>198.5</td>
</tr>
<tr>
<td>Small-Large-Heavy</td>
<td>129.2</td>
</tr>
</tbody>
</table>

Table 4.2: Sequence Throughput Variation: Runway Assignment

<table>
<thead>
<tr>
<th>Runway Sequence</th>
<th>Process Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left-Left-Left</td>
<td>415.4</td>
</tr>
<tr>
<td>Left-Left-Right</td>
<td>178.4</td>
</tr>
<tr>
<td>Left-Right-Left</td>
<td>218.4</td>
</tr>
<tr>
<td>Left-Right-Right</td>
<td>178.4</td>
</tr>
</tbody>
</table>

There are a number of available techniques for solving the event sequencing problem. Currently, at most US airports, air traffic controllers use experienced-based heuristics to determine a solution in real time. Often, the resulting event sequence fails to fully utilize the available capacity. If the lost capacity could be regained, the throughput could be increased and flight delay and airport congestion reduced. Ideally, the solution to the event sequencing problem should minimize the lost capacity, thereby maximizing the runway throughput. At the very least, the solution technique should improve upon the currently used heuristics. Two candidate alternative solutions of particular interest are the Serve-the-K-Longest-Queues algorithm, a simple rule based approach, for flight sequencing coupled with a greedy heuristic algorithm for runway assignment, and event sequence optimization via mixed integer programming. The main benefit of simple rule based approaches is that they can be implemented by controllers without decision support tools. However, simple rule
Based algorithms frequently yield suboptimal event sequences which fail to fully utilize the available runway capacity. Event sequence optimization via mixed integer programming does require the use of decision support tools and may take significant time to return a usable solution; however, it does ensure that for a given set of flights, the runway throughput is maximized.

4.2 Simple Rule Based Sequencing

The simple rule based sequencing algorithm of the greatest interest is actually a combination of two simple rule based algorithms: the Serve-the-K-Longest-Queues algorithm for flight sequencing coupled with a greedy heuristic algorithm for runway assignment. It is shown in Neely et al. [13] that for a set of queues, which may be in one of two states (on or off) and a set of K servers, allocating the K servers to service the K longest queues will stabilize the system. Additionally, this server assignment policy proves optimal when the available servers are set to service the selected queues as quickly as possible. While Neely et al. [13] derives these results in terms of power allocation for packet processing in multibeam satellite, they are also applicable to the event sequencing problem.

For the event sequencing problem, the set of service queues correspond to the set of aircraft queues at the TRACON entry points, called arrival fixes, plus a single departure queue. Each queue has two possible states, empty and non-empty, corresponding to OFF and ON, respectively. Each set of independent runways is treated as a single server. In the case of EWR, there are a total of four queues requiring service, three arrival queues and one departure queue, and a single server. Aircraft enter the queues in an approximate poisson process, as assumed in Neely et al. [13], and by scaling the arrival processes to the departure process, the queue entry processes are approximately i.i.d. due to conservation of aircraft. Neely et al. [13] also assumes the packet lengths are fixed and that the available server power is ergodic with calculable time-average probabilities. Due to the combinatorial nature of the event sequencing problem neither assumption is strictly true. However, at each decision point, the
time for each possible next event is fixed assuming a greedy algorithm is used to
determine the runway assignment as a function of the previously processed flights
and the current flight rules. As a result, at each decision point, the available runway
capacity which corresponds to the sever condition can be thought of as being a func-
tion of the previously processed flights and the current weather conditions, for which
time-average probabilities can be calculated from the airport fleet mix and weather
state transition probabilities. However, the server state is non-ergodic due to the
dependence on the perviously processed flights. Hence, Serve-the-K- Longest-Queues
strategy coupled with a greedy algorithm to determine runway assignment should
supply an event sequence that stabilizes the queues but is suboptimal in terms of
runway throughput.

4.3 Sequence Optimization

By using mathematical programming techniques to solve the event sequencing prob-
lem, an event sequence can be found which is guaranteed to maximize the runway
throughput. While the resulting sequence is guaranteed optimal, the solution time
may prove prohibitive if the problem size is large because the natural problem for-
mulation is of a mixed integer form and most commercially available solution suites
utilize branch-and-bound techniques to solve integer programs. In addition to the
possibly prohibitive solution times, event sequence optimization is further compli-
cated by the uncertainty inherent in queue entry time estimation for both arriving
and departing aircraft. Arriving aircraft can be delayed by any number of factors
including, but not limited to, departure delays, enroute weather or sector conges-
tion. For departures there is uncertainty in taxi-out times which vary as a function of
tarmac congestion and gate and runway assignments [14]. This uncertainty requires
frequent resolving of smaller event sequencing subproblems for overlapping subsets of
flights as revised flight information becomes available. Because the event sequence
is quasi-memoryless in that the future sequence is dependent on only a small subset
of the most recently processed flights, breaking the problem into small overlapping
subproblems returns an optimal sequence. For EWR during IFR, the future flight sequence depends at most on the last two processed flights and during VFR, the dependency only encompasses the last three processed flights. Dividing the event sequence problem into smaller overlapping event sequencing subproblems avoids the problem of the uncertain queue entry times by allowing the queue entry times and the event sequence to be updated as improved information becomes available and the problem solution time is kept within an acceptable range.

4.4 Approach

The operations at a single impacted airport (EWR) were studied under different event sequencing algorithms to enable comparison of their impact on NAS operations in terms of flight delay. Two algorithms were examined: a Serve-the-Longest-Queue algorithm for flight sequencing coupled with a greedy heuristic algorithm for runway assignment and a mixed integer programming optimization algorithm for simultaneous flight sequencing and runway assignment. Both algorithms were integrated into MEANS which was then used to simulate NAS operations for a set of days where EWR experienced prolonged periods of IMC. The results of each MEANS simulation run was then compared in terms of total flight delay and on-time performance.

4.4.1 Study Airport

For an airport to benefit from improved capacity utilization, the airport must be scheduled at or near the available capacity limit for portions of the day such that the queues build up and delay is introduced into the system. EWR is an ideal airport for this study due to the high level of delay that results from the scheduled demand exceeding the available capacity under both VFR and IFR. Additionally, EWR has only three available runways, a set of parallel runways with a centerline separation of 950 ft (4L/22R, 4R/22L) and a single crossing runway (11/29). The limited runway availability restricts the complexity of EWR’s runway configurations (Figure 4-1) which simplifies the formulation of the mixed integer programming optimization algorithm.
During normal operations arrivals approach EWR in three distinct arrival streams which must be merged to utilize the shared runway resources. The arrivals enter the TRACON through arrival fixes along the boundary. EWR’s arrival fixes can be grouped into three sets: a set of fixes to accommodate the northern flow, a set of fixes to accommodate the eastern flow and a set of fixes to accommodate the southern flow (Table 4.3). EWR has no arrival fixes to accommodate an eastern arrival flow due to the presence of JFK and LGA directly to the east. To simplify the TRACON model for EWR, a representative fix was selected for each set of arrival fixes: SHAFF in the north, PENNS to the west and ARD in the south [15]. Assuming that the tracks used for arriving aircraft match those identified in the FAA’s National Flight Data Center (NFDC) Preferred Routes Database, which gives the preferred routing for aircraft from any origin airport to any destination airport, and that all identified fixes can be mapped to the appropriate representative fix, a preferred arrival fix can be identified for each origin airport (Appendix B). Modeling EWR as using all three preferred fixes fails to capture the impact of fix closures or flight re-routing due to enroute weather or congestion, but as MEANS models neither enroute weather nor congestion, further granularity is unnecessary.
Table 4.3: Arrival Fixes (EWR)

<table>
<thead>
<tr>
<th>Representative Fix</th>
<th>Associated Minor Fixes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARD (South)</td>
<td>DYLIN, METRO, OWBIE</td>
</tr>
<tr>
<td>PENNS (West)</td>
<td>BWZ, SBJ, WILLIAPORT</td>
</tr>
<tr>
<td>SHAFF (North)</td>
<td>COATE, SAX</td>
</tr>
</tbody>
</table>

4.4.2 Event Sequencing Algorithms

The two event sequencing algorithms of interest are the Serve-the-Longest-Queue algorithm for flight sequencing coupled with a greedy heuristic algorithm for runway assignment and a mixed integer programming optimization algorithm for simultaneous flight sequencing and runway assignment. Both methods determine the flight sequence, the runway assignments and the process times based on the minimum FAA separation requirements and flight times.

Serve-the-K-Longest-Queues

For EWR, the Serve-The-K-Longest-Queues algorithm simplifies to the Serves-the-Longest-Queue algorithm as EWR has only one set of dependent runways and hence only one server under both IFR and VFR. EWR has four event queues to service, three queues corresponding to the three arrival fixes and a single queue for the departures. To ensure the algorithm’s queue selection is unbiased, each of the four queues must have approximately equal time averaged arrival rates /citeModiano. Hence, the length of the departure queue, which will be on average three times longer than the arrival queue by aircraft flow conservation, must be scaled when the queues are compared. At each time step when the server/runway system is not in use, the first flight in the longest scaled queue is selected for processing. During IFR, there is one runway each for arrivals and departures and hence the selected flight is assigned to the appropriate runway. During VFR, there are two options each for arrivals or departures, and the selected flight is assigned to the runway which results in the minimum service time.
Optimization Program

The flight sequencing problem at EWR can be modeled as a slot assignment problem. Given a set of N flights, these flights must be assigned to N slots. Additionally, each slot must be assigned to a runway. The slot processing times are determined based on the FAA minimum separation requirements or on the time required for the aircraft to transit from its queue to the assigned runway, whichever is greater. Additionally, the model includes primer flights which ensure the slot processing times reflect the required separation from the previously processed flights. Here primer flights are defined to be a set of the most recent processed flights, the size of the set depends on the problem formulation. To simplify the problem, each arrival queue is required to operate in FIFO order. This is a realistic model of TRACON operations because the limited TRACON airspace makes it difficult to swap the order of aircraft in the queue while maintaining the required aircraft separations without dangerous increases in controller workload.

To model the flight sequencing problem at EWR, two separate mixed integer programs were developed, one for IFR and one for VFR. Two separate programs were developed to take advantage of the relative simplicity of IFR operations which do not require the runway assignment portion of the model. Additionally, for IFR operations at EWR, future flight processing times are dependent on at most the two most recently processed flights and hence only two primer flights are needed, while for VFR operations, future flight processing times are dependent on at most the three most recently processed flights and three primer flights are needed. As a result the IFR model is smaller than the equivalent VFR model both in terms of variables and constraints and can generally be solved in less time than the VFR model for the same set of flights.

IFR Program

Variables

\[ x_{ijr} \in [0, 1] \quad \text{event slot assignment variable} \]
$t_r \geq 0$ event processing time variable

$w_r \geq 0$ single separation variable

$v_r \geq 0$ double separation variable

**Parameters**

$I$ number of arrival fixes, I+1 is the departure fix J

$R$ number of slots

$T_{ij}$ queue entry time for flight $ij$

$E_{ij}$ event type for flight $ij$

$H_{ij}$ aircraft weight class for flight $ij$

$P$ number of primer flights

$tp_i$ event processing time for primer event $i$

$E_{pi}$ event type for primer event $i$

$H_{pi}$ aircraft weight class for primer event $i$

**Functions**

$S(E_{ij}, E_{kl}, H_{ij}, H_{kl})$ spacing function

$X(H_{ij}, i)$ transit time function

**Objective Function**

$\min \ t_r$

**Slot Assignment Constraints**

$\sum_{r=1}^{R} x_{ijr} = 1 \quad \forall i \in 1..I + 1, j \in 1..||i||$

$\sum_{i=1}^{I+1} \sum_{j=1}^{||i||} x_{ijr} = 1 \quad \forall r$

**FIFO Operation**

$x_{i(ur)} \leq 1 - x_{i(js)} \quad \forall i \neq (I + 1), l > j, r \in 1..R, s \in r..R$

$x_{i(ur)} \leq 1 - x_{i(js)} \quad \forall i \neq (I + 1), l < j, r \in 1..R, s \in 1..r$

**Separation Constraints**

$t_{r+2} \geq t_r + v_r \quad \forall r \in 1..(R - 2)$

$t_{r+1} \geq t_r + w_r \quad \forall r \in 1..(R - 1)$

$t_r \geq \sum_{i=1}^{I+1} \sum_{j=1}^{||i||} x_{ijr} \cdot (T_{ij} + X(H_{ij}, i)) \quad \forall r \in 1..R$
\[ w_r \geq (x_{ijr} + x_{lk,r+1} - 1) \cdot S(E_{ij}, E_{kl}, H_{ij}, H_{kl}) \quad \forall i \in 1..(I + 1), j \in 1..\|i\|, \]
\[ k \in 1..(I + 1), l \in 1..\|k\| \]
\[ v_r \geq (x_{ijr} + x_{lk,r+2} - 1) \cdot S(E_{ij}, E_{kl}, H_{ij}, H_{kl}) \quad \forall i \in 1..(I + 1), j \in 1..\|i\|, \]
\[ k \in 1..(I + 1), l \in 1..\|k\| \]

Primer Constraints

\[ t_r \geq t_{p_r} + \sum_{i=1}^{I+1} \sum_{j=1}^{\|i\|} x_{ijr} \cdot S(E_{p_r}, E_{ij}, H_{p_r}, H_{ij}) \quad \forall r \in 1..\min(R, 2), p \in P \]

The basic variable for the IFR event sequencing program is the binary variable indicating the event slot assignments \((x_{ijr})\). The event, indexed by the first two subscripts, is differentiated by the assigned fix (the first subscript) and its queue index number (the second subscript). The third index indicates the slot assignment. The processing time variables \((t_r)\), simply indicates the time either the arrival assigned to slot \(r\) crosses the runway threshold or the departure assigned to slot \(r\) has begun its takeoff roll. The remaining variables \((w_r, v_r)\) correspond to the required minimum separation between slot \(r\) and slot \(r+1\) and slot \(r\) and slot \(r+2\) respectively. In addition to the basic variables, there are two functions utilized in the IFR event sequencing program. The spacing function returns the required minimum separation between event \(ij\) and event \(kl\) based on the event types \((0\ for\ an\ arrival\ and\ 1\ for\ a\ departure)\) and their weight classes. The transit time function returns the time required for an event of a particular weight class to transit from fix \(i\) to the appropriate runway.

There are four categories of constraints for the IFR event sequencing program: slot assignment constraints, FIFO constraints, separation constraints and primer constraints. The slot assignment constraints ensure each flight is assigned to one and only one slot and that each slot is assigned to one and only one flight, constraints one and two respectively. The FIFO constraints (constraints three and four) ensure that the arrival queues operate in FIFO order. The departure queue has no such constraint. There are two types of separation constraints. The first separation constraint ensures that the minimum processing time for a slot is at least as large as the scheduled time plus the time required to transit from the fix to the threshold of the assigned runway. The remaining separation constraints serve to ensure that the
minimum FAA separation requirements are taken into account in determining the slot times. The primer constraints ensure that the slot times for the first few slots take into account the minimum FAA separations from the primer flights.

VFR Program

Variables

\( x_{ijr} \in [0, 1] \) event slot assignment variable
\( z_{rn} \in [0, 1] \) runway slot assignment variable
\( t_r \geq 0 \) event processing time variable
\( w_r \geq 0 \) single separation variable
\( v_r \geq 0 \) double separation variable
\( u_r \geq 0 \) triple separation variable
\( s_{pr} \geq 0 \) primer separation variable

Parameters

\( I \) number of arrival fixes, \( I+1 \) is the departure fix \( J \)
\( R \) number of slots
\( N \) number of runways
\( T_{ij} \) queue entry time for flight \( ij \)
\( E_{ij} \) event type for flight \( ij \)
\( H_{ij} \) aircraft weight class for flight \( ij \)
\( P \) number of primer flights
\( t_{pi} \) event processing time for primer event \( i \)
\( z_{pi} \) assigned runway for primer event \( i \)
\( H_{pi} \) aircraft weight class for primer event \( i \)

Sets

\( \text{ArrRunway} \) set of arrival runways, \( \subset 1..n \)
\( \text{DepRunway} \) set of departure, \( \subset 0\text{f}1..n \)

Functions

\( S(n, m, H_{ij}, H_{kl}) \) spacing function
\( X(H_{ij}, i, n) \) transit time function
Objective Function

\[ \min t_r \]

Slot Assignment Constraints

\[ \sum_{r=1}^{R} x_{ijr} = 1 \quad \forall i \in 1..I+1, j \in 1..||i|| \]

\[ \sum_{i=1}^{I+1} \sum_{j=1}^{||i||} x_{ijr} = 1 \quad \forall r \]

Runway Assignment Constraints

\[ \sum_{n=1}^{2} z_{rn} = 1 \quad \forall r \in 1..R \]

\[ z_{rn} \leq 1 - \sum_{i=1}^{I} \sum_{j=1}^{||i||} x_{ijr} \cdot (1 - E_{ijr} \% 2) \quad \forall n \in \text{ArrRunways}, r \in 1..R \]

\[ z_{rn} \leq 1 - \sum_{i=1}^{I} \sum_{j=1}^{||i||} x_{ijr} \cdot (E_{ijr} \% 2) \quad \forall n \in \text{DepRunways}, r \in 1..R \]

FIFO Operation

\[ x_{ilr} \leq 1 - x_{ijr} \quad \forall i \neq (I + 1), l > j, r \in 1..R, s \in r..R \]

\[ x_{ilr} \leq 1 - x_{ijr} \quad \forall i \neq (I + 1), l < j, r \in 1..R, s \in 1..r \]

Separation Constraints

\[ t_{r+3} \geq t_r + u_r \quad \forall r \in 1..(R - 3) \]

\[ t_{r+2} \geq t_r + v_r \quad \forall r \in 1..(R - 2) \]

\[ t_{r+1} \geq t_r + w_r \quad \forall r \in 1..(R - 1) \]

\[ t_r \geq (x_{ijr} + z_{rn} - 1) \cdot (T_{ij} + X(H_{ij}, i, n)) \quad \forall r \in 1..(R - 1), n \in 1..N, \\
\]

\[ i \in 1..(I + 1), j \in 1..||i|| \]

\[ w_r \geq (x_{ijr} + x_{lk,r+1} + z_{rn} + z_{r+1,m} - 3) \cdot S(n, m, H_{ij}, H_{kl}) \quad \forall i \in 1..(I + 1), \\
\]

\[ j \in 1..||i||, \]

\[ k \in 1..(I + 1), \]

\[ l \in 1..||k||, \]

\[ n, m \in 1..N, \]

\[ r \in 1..(R - 1) \]

\[ v_r \geq (x_{ijr} + x_{lk,r+2} + z_{rn} + z_{r+2,m} - 3) \cdot S(n, m, H_{ij}, H_{kl}) \quad \forall i \in 1..(I + 1), \\
\]

\[ j \in 1..||i||, \]

\[ k \in 1..(I + 1), \]

\[ l \in 1..||k||, \]

\[ n, m \in 1..N, \]

\[ r \in 1..(R - 2) \]
The VFR program has the same basic variables as its IFR counterpart with a few notable additions. The VFR program has an additional binary variable to indicate runway assignments \( z_{rn} \) where the subscript \( r \) indicates the slot and subscript \( n \) indicates the runway. Also a third separation variable \( u_r \) and a primer separation variable \( s_{pr} \) have been added to calculate the minimum separation required between slots \( r \) and \( r+3 \) and the separation between primer flight \( p \) and slot \( r \) respectively. In addition to the new variables, the form of one of the functions has been altered to account for multiple possible runway assignments. The spacing function now determines the required separation between event \( ij \) and \( kl \) when they have been assigned to runways \( n \) and \( m \) respectively. The different event types are accounted for in the runway definitions, with runways utilizing both arrivals and departures appearing in both the ArrRunways set and DepRunways set.

There are five categories of constraints for the VFR flight sequencing program: slot assignment constraints, FIFO constraints, separation constraints, primer constraints and runway assignment constraints. The first four constraint categories mirror the functionality of the equivalent constraint categories in the IFR flight sequencing program. The remaining constraint category, the runway assignment constraints, has two purposes. The first runway assignment constraint serves to ensure that each slot is assigned to one and only one runway. The remaining runway assignment constraints ensure that slots which have an arrival assigned to them can only be assigned to
arrival runways and that slots which have a departure assigned to them can only be assigned to departure runways. Note that the modulus operator is used in the second and third runway assignment constraints to take advantage of the definition of the event type for flight $ij$, $E_{ij}$, which is set to one for arrivals and zero for departures.

**Implementation**

Both optimization models were implemented as variations of the Controller Agent version of the Tower module in MEANS (see Chapter 6) using GLPK, a set of free-ware C libraries that utilize branch-and-bound techniques to solve mixed integer programs. For each new queue entry, MEANS generates and solves a new optimization problem. If a new queue entry occurs before all of the previously sequenced flights have been processed, the previously determined sequence is discarded and a new optimization problem is formulated with the unprocessed flights from the previously solution and the new queue entry. In order to limit the simulation run times the size of each optimization problem was limited to four aircraft, which can be processed within the desired time frame. Due to the quasi-memoryless property of the solution, the required FIFO operation of the queues and the re-optimization on each queue entry, limiting the size of the problem does not alter the final flight sequence.

**4.4.3 Fix to Runway Threshold Transit Time**

In order to accurately calculate the event processing times it is necessary to estimate the transit time between each of the three arrival fixes and each runway threshold as a function of the aircraft weight class. Approximate values can be found for the fix to runway threshold transit time by determining the vectoring from the fix to the runway threshold and using standard fix speeds and approach profiles. Aircraft are assumed to fly directly from the arrival fix to the initial approach fix and from there to follow the approach path depicted in the Jeppesen Airway Manual [16]. In order to determine the transit times, it was assumed that the aircraft speed at the runway threshold was the same as that used for arriving aircraft in ARCC (Table 5.1).
Table 4.4: Arrival Fix to Runway Routings (EWR)

<table>
<thead>
<tr>
<th>Arrival Fix</th>
<th>Runway</th>
<th>Fix Vector List</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARD</td>
<td>22R</td>
<td>ARD METRO VERDE AYRON KEWR22R</td>
</tr>
<tr>
<td>ARD</td>
<td>22L</td>
<td>ARD METRO GIMEE AYRON KEWR22L</td>
</tr>
<tr>
<td>ARD</td>
<td>11</td>
<td>ARD METRO JARIT JEENO KEWR11</td>
</tr>
<tr>
<td>PENNS</td>
<td>22R</td>
<td>PENNS SWEET VERDE AYRON KEWR22R</td>
</tr>
<tr>
<td>PENNS</td>
<td>22L</td>
<td>PENNS SWEET GIMEE AYRON KEWR22L</td>
</tr>
<tr>
<td>PENNS</td>
<td>11</td>
<td>PENNS SWEET JARIT JEENO KEWR11</td>
</tr>
<tr>
<td>SHAFF</td>
<td>22R</td>
<td>SHAFF SAX VERDE AYRON KEWR22R</td>
</tr>
<tr>
<td>SHAFF</td>
<td>22L</td>
<td>SHAFF SAX GIMEE AYRON KEWR22L</td>
</tr>
<tr>
<td>SHAFF</td>
<td>11</td>
<td>SHAFF SAX JARIT JEENO KEWR11</td>
</tr>
</tbody>
</table>

velocity 280 kts 280 kts 250 kts 200 kts ARCC speed

Additional assumed fix speeds and the complete fix to runway threshold vectoring are shown in Table 4.4.

The fix to runway transit times found via this method were scaled such that the minimum transit time is sixty seconds. The scaling is done to enable incorporation into MEANS, because MEANS assumes that the identified enroute travel time is the complete time from take off to touch down. Additionally, it is assumed that all departures have the base transit time of sixty seconds from the departure queue to the entrance of the assigned runway. The calculated transit times are shown in Table 4.5.

Table 4.5: Normalized Fix to Runway Transit Times

<table>
<thead>
<tr>
<th>Run</th>
<th>ARD</th>
<th>SHAFF</th>
<th>PENNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Heavy</td>
<td>84s</td>
<td>84s</td>
</tr>
<tr>
<td></td>
<td>B757/Large</td>
<td>102s</td>
<td>102s</td>
</tr>
<tr>
<td></td>
<td>Small</td>
<td>156s</td>
<td>156s</td>
</tr>
<tr>
<td>22L</td>
<td>Heavy</td>
<td>276s</td>
<td>126s</td>
</tr>
<tr>
<td></td>
<td>B757/Large</td>
<td>294s</td>
<td>138s</td>
</tr>
<tr>
<td></td>
<td>Small</td>
<td>342s</td>
<td>192s</td>
</tr>
</tbody>
</table>

4.4.4 Study Days

In order to compare the relative functionality of the two sequencing method, four study days were identified. Two factors contributed to the candidacy of any given
day. First EWR must have experienced prolonged periods of IMC during the day. Although the sequencing algorithms would improve operations during VFR operations, it is more likely that full capacity will be needed during IFR operations. Additionally, during IFR operations, there is more likely to be queue backlogs making it vital to maximize capacity utilization. While there are a number of days during which EWR experiences prolonged periods of IMC, the required data was only available for four of these days (February 18 2000, February 27 2000, January 15 2001, and January 19 2001). In order to accurately model the lengths of the arrival fix queues during the day it is necessary to have as complete a schedule as possible. ASQP data, which MEANS usually uses to generate flight schedules, only contains data on scheduled domestic flights for the major US carriers. If only ASQP is used, a queue imbalance will result as a majority of the flights using arrival fix SHAFF originate in Europe or eastern Canada. To prevent this imbalance, ASQP data was augmented with full ETMS data which contains information on all flights, including GA and foreign flights, which were actually flown on the day in question. The full ETMS data was not used to generate the complete schedule because it does not contain aircraft tail numbers and as a result the aircraft flight legs cannot be recreated. The hourly weather conditions for the four study days is shown in Figure C-3 in Appendix C.

4.4.5 Simulation

For each of the four study days, MEANS was used to evaluate the impact on the NAS in terms of delay when EWR was operating under both of the event sequencing algorithms utilizing the tower controller agent module. Tower operations at all other modeled airports were simulated using the simulated pareto frontier implementation of the tower module. The resulting operations were then compared in terms of total flight delay and on-time performance.
Chapter 5

ARCC

5.1 Overview

The Airport Runway Capacity Calculator (ARCC) is a Monte Carlo simulation tool designed to generate pareto frontiers, curves which depict the trade off between an airport's arrival and departure rates [17]. The pareto frontiers produced by ARCC describe the maximum runway capacity envelope for an airport as a function of the runway configuration, fleet mix and separation requirements. ARCC generates pareto frontiers by simulating the processing of randomly generated flight schedules through a runway system with the specified minimum required separations. For example, the required separations may be those specified in the standard FAA operating rules (IFR or VFR). The simulation occurs in two stages, flight generation and flight processing. During the flight generation stage, a set of arrival and departure queues are populated with flights based on a specified arrival rate. In the flight processing stage the generated flight schedule (the populated queues) is processed through the runways and the number of operations are counted to define the pareto frontier. The flight processing stage is composed of two processes which run concurrently to determine the event sequence and event processing time for each flight: the event spacing process and the event sequencing process. The event spacing process calculates the minimum processing time based on the minimum separation requirements and the scheduled event times for each event identified by the event sequencing process. The
event sequencing process identifies a candidate event for each runway. The candidate event is the flight selected to be processed next on a particular runway. The event sequencing process then selects from among the candidate flights, the flight which will be processed next. The selected flight is then processed at the time calculated by the event spacing process. The two processes are then repeated to determine the next event in the sequence until the schedule is exhausted. The entire two-stage simulation (the flight generation and flight processing stages) is repeated for different arrival rates in order to define the complete capacity profile.

5.2 Flight Generation

At each iteration of the Monte Carlo simulation, ARCC generates a set of arrival and departure queues which are populated by flights. Flights are defined by two properties: a scheduled event time and an aircraft weight class designator. ARCC generates both an arrival and a departure queue for each runway in the runway configuration unless the configuration specifies that a given runway can only process one event type (either arrivals or departures). Two different runway assignment schemes for a set of parallel runways are shown in Figure 5-1. The top runway assignment scheme shown in Figure 5-1 calls for arrivals and departures on both parallels and hence four separate queues are generated, two arrival queues and two departure queues. The runway assignment scheme on the bottom of Figure 5-1 utilizes one runway exclusively for arrivals and the other exclusively for departures and as a result only two queues are generated, one arrival queue and one departure queue.

Once ARCC has generated the required queues, they are populated with flights. Each flight is assigned an aircraft weight class designator from among the four FAA weight class based on the user supplied fleet mix. Only the four weight classes are used to define the aircraft type as opposed to specific aircraft type because the FAA separation requirements are solely functions of the four weight classes. Hence, any further subdivision of aircraft type is unnecessary. The aircraft types are assigned using a uniform probability distribution and a random number generator.
Each flight also has a scheduled event time. For arrivals, the scheduled event time corresponds to the time at which the aircraft is able to cross the threshold of the assigned runway. For departures the scheduled event time corresponds to the time at which the flight can begin its take-off roll. The event times for arrivals are modeled as a Poisson process and hence the scheduled inter-arrival times are described by the exponential distribution ($f(x) = \lambda e^{-(\lambda t)}$). By solving the exponential distribution for the time ($t = \frac{\ln(f(x))}{\lambda}$), and using the arrival rate (lambda) of interest and random number generation to identify the probability ($f(x)$), a sequence of stochastic inter-arrival times can be found. The inter-arrival times can then used to find the scheduled runway threshold crossing times for each arrival.

Departures are not scheduled via a stochastic process; rather, all departures are scheduled to begin their take-off roll at simulation time zero. As a result, the departure queue is always full which ensures that the maximum capacity envelope is obtained for each arrival rate. If both arrivals and departures were scheduled via stochastic processes, then the resulting schedule could have periods where the runways
were not in use because there were no available events to be processed. Allowing such lulls in runway usages would generate arrival/departure rate pairs that underestimate the maximum capacity. The arrival schedule takes precedence over the departure schedule because of the comparatively higher cost of holding arrivals both in terms of fuel consumption, the limited available holding airspace and controller workload.

5.3 Flight Processing

Once the contents of the arrival and departure queues are set, the flights can be processed according to selected arrival/departure interaction rules to determine the arrival/departure rate pairs which define the pareto frontier. Flight processing occurs in two concurrent processes: event sequencing and event spacing. First the event sequencing processes determines for each runway, a candidate event utilizing a simple heuristic. From among the candidate events, one will be selected to be processed next in the event sequence. For each candidate event, the event spacing process determines the earliest possible event processing time under the assumption that each of the candidate flights will be the next event processed. Finally, the event sequencing process determines the runway priority if the runway configuration contains multiple runways and the selected flight is processed. After each flight is processed, the process is repeated until the schedule is exhausted. The flight processing stage runs for a period of ten simulation hours. While most major airports in the US do not experience peak operations for this length of time, it has been determined that with runs of ten simulation hours the fleet mix achieves the specified average fleet mix and the capacity curves converge.

5.3.1 Event Spacing

The first and most obvious requirement for determining the minimum event time is that no flight can occur before its scheduled time. Additionally, the calculated event times must ensure that the aircraft is separated by at least the minimum distance from the previous event on the same runway as well as the previous events on all other
dependent runways. As a default, ARCC uses the standard FAA separations outlined in reference [10] though the user can specify alternative separations if desired. The FAA separation minima are functions of event type (arrival or departure), the weight class sequence, the runway configuration and runway assignments, and the flight rules in use (IFR or VFR). For situations where the FAA does not provide numerical separation minima, namely for operations under VFR where pilots are allowed to self separate, ARCC uses average observed separations as measured by Weiss (Table 3.2).

A majority of the FAA separation minima are specified in terms of spatial rather than temporal separations. Thus, they must be converted to temporal separations in order to determine the minimum event time. To convert the require separations, ARCC uses a set of average arrival and departure speeds for each weight class Table 5.1. For example, given two arrivals on a single runway, both Larges, there is a required 2.5 NM separation which corresponds to a temporal separation of 69.2 seconds. It is assumed that the trailing aircraft maintains a constant velocity and that the separation minimum is applied from the runway threshold. Hence the trailing arrival must cross the runway threshold at least 69.2 seconds after the leading arrival has crossed the runway threshold.

Table 5.1: Average Arrival and Departure Speeds

<table>
<thead>
<tr>
<th></th>
<th>Heavy</th>
<th>B757</th>
<th>Large</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival Speed (kts)</td>
<td>150</td>
<td>130</td>
<td>130</td>
<td>90</td>
</tr>
<tr>
<td>Departure Speed (kts)</td>
<td>170</td>
<td>150</td>
<td>150</td>
<td>100</td>
</tr>
</tbody>
</table>

ARCC accounts for a number of non-physical FAA operation requirements. One such requirement states that no two planes can occupy the same runway at the same time. Consequently, before an arrival or departure can be processed, the pervious arrival must have left the runway. This required buffer is termed the runway occupancy time. ARCC uses a set of average runway occupancy times found by analysis of historical data Table 5.2.

Another example is found in the case of crossing runway configurations, where, an event on one runway cannot commence until the preceding event on the other
Table 5.2: Average Runway Occupancy Times

<table>
<thead>
<tr>
<th>Runway Occupancy (sec)</th>
<th>Heavy</th>
<th>B757</th>
<th>Large</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70</td>
<td>60</td>
<td>60</td>
<td>50</td>
</tr>
</tbody>
</table>

Runway has reached and proceeded through the crossing point. Rather than using average times from historical data to determine the time to the crossing point, certain assumptions are made regarding the form of the arrival and departures profiles, which enable the calculation of the crossing times. For arriving aircraft, it is assumed that the aircraft reach the runway threshold at an elevation of fifty feet at the appropriate arrival speed for the aircraft’s weight class. It is further assumed that arrivals touch down 1,000 feet past the runway entrance and during this first arrival phase, perform a quarter g pull up. The arrivals are assumed to linearly decelerate until they reach zero velocity at a point 5,000 feet down the runway. If the crossing point is less than 5,000 feet from the threshold, the crossing time is the time to that point. If the crossing more than 5,000 feet from the threshold the crossing time is assumed to the full runway occupancy time. The assumed arrival profile is depicted in Figure 5-2.

For departing aircraft, it is assumed that the aircraft begin their take-off roll at the runway threshold and accelerate linearly until a point 5,000 feet down the runway, at which point the departing aircraft reaches the average departure speed and begins to pull up. It is assumed after this point the departure maintains a constant ground speed equal to the average departure speed. The assumed departure profile is depicted in Figure 5-3.

Figure 5-2: Arrival Profile

Figure 5-3: Departure Profile
The event times used by ARCC do not reflect a number of real world phenomena which may result in larger event separations. Namely, ARCC assume that TRACON congestion is not a factor and will not induce any delay into the system. Additionally, it is assumed that controllers will separate at the minimum event spacing except in cases where the scheduled arrival time dictates and elongation of the minimum event spacing. These factors have not been incorporated into the simulation as they do not affect the maximum available runway capacity, only the realizable runway capacity. Also land and hold short (LAHSO) and missed approach procedures are not modeled due to the infrequency of their use.

5.3.2 Event Separation

ARCC uses a two stage algorithm which is rerun at each decision point to determine the event sequence one flight at a time. The algorithm first determines the next event on each individual runway and then which runway in a multi-runway system should be given priority.

The next event on each runway is selected via a simple heuristic: arrivals and departures are alternated whenever possible. Because each queue is restricted to operate in first in first out (FIFO) order and flights are constrained to operate on the runway their queue is associated with the heuristic has at most two events to consider (one arrival and one departure) at any given decision point. The motivation for alternating arrivals and departures comes from analysis of the FAA separation minima for a single runway. The required temporal spacing between two Heavies
Table 5.3: Required IFR Same Runway Separation (Heavy-Heavy)

<table>
<thead>
<tr>
<th>Leading Aircraft</th>
<th>Arrival</th>
<th>Departure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trailing Aircraft</td>
<td>Arrival</td>
<td>96 sec</td>
</tr>
<tr>
<td></td>
<td>Departure</td>
<td>70 sec</td>
</tr>
</tbody>
</table>

Table 5.4: Processing Time for a Four Event Sequence (Heavies)

<table>
<thead>
<tr>
<th>Event Sequence</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dep-Arr-Dep-Arr</td>
<td>166</td>
</tr>
<tr>
<td>Arr-Dep-Arr-Dep</td>
<td>188</td>
</tr>
<tr>
<td>Dep-Arr-Arr-Dep</td>
<td>214</td>
</tr>
<tr>
<td>Arr-Dep-Dep-Arr</td>
<td>230</td>
</tr>
<tr>
<td>Arr-Arr-Arr-Dep</td>
<td>256</td>
</tr>
<tr>
<td>Dep-Dep-Arr-Arr</td>
<td>276</td>
</tr>
</tbody>
</table>

under IFR is shown in Table 5.3. Looking at the total time required for a sequence of four events, two arrivals and two departures, taking into account only the separation minima, it is obvious that the minimum event processing time corresponds to the two sequence which alternate arrivals and departures (Table 5.4).

If arrivals and departures were always alternated there would be periods where there runway was idle as a result of the arrival schedule and the runway capacity would be underestimated. Hence, the heuristic was modified to enable the selection of either sequential departures or sequential arrivals via the introduction of a maximum allowable arrival queue hold time. The maximum allowable arrival queue hold time is defined to be the longest hold time (the difference between the minimum event processing time and the scheduled event time) that any arrival in an arrival queue will experience if the next departure on the same runway is processed before the next arrival and only arrivals are processed subsequently. This does not take into account hold times that are incurred for reasons other than the processing of the next departure and hence the hold times are calculated for each queued arrival until a gap in the schedule which can absorb the incurred delay is encountered. As the arrival rate becomes large, the inter-arrival times become small with higher probability. As a result the probability that the maximum arrival queue hold time crosses the threshold
value (default is fifteen minutes) goes to one and multiple arrivals will be processed consecutively. In general, for small arrival rates, where multiple departures should be processed in a row rather than multiple arrivals, the maximum arrival queue hold time does not come into play. In this case, multiple subsequence departures are processed when there are no available arrivals. The decision logic for the modified heuristic is shown in Figure 5-4.

Each flight identified via the heuristic portion of the event sequencing process, one for each runway, are candidates to be the next event processed. ARCC uses a simple greedy algorithm to determine which runway receives priority and hence which candidate flight is processed next. The event that increases the simulation time by the smallest amount is selected and processed using the minimum calculated event processing time. The process is then repeated to determine the next flight to be processed until the simulation is complete.

5.4 Simulation Output

ARCC returns a set of arrival and departure rates for each iteration of the Monte Carlo simulation. The arrival and departure rates are found by simply counting the
number of each event type processed during the ten hours of simulation time and then dividing them by the simulation time. Figure 5-5 is a plot of the raw output of an ARCC simulation for a single runway system under IFR conditions with a fleet mix of ten percent Heavies, twenty percent B757s, sixty percent Larges and the remaining ten percent Smalls. The raw output is radially averaged in order to generate a smooth pareto frontier. The smoothed pareto frontier for the single runway case is shown in Figure 5-5.

![Figure 5-5: ARCC Raw Output - Single Runway IFR](image1)

![Figure 5-6: ARCC Radially Averaged Output - Single Runway IFR](image2)
Chapter 6

MEANS

6.1 Overview

The MIT Extensible Air Network Simulation (MEANS) is an event-base NAS simulation designed to evaluate novel Air Traffic Management and Robust Scheduling techniques [18]. MEANS simulates the flow of air traffic through a network of 205 major US airports, tracking on the order of 42,000 flights per simulation data, though not down to the detail of modeling secondary dynamics on the individual flight level. Additionally, MEANS tracks airline schedule changes, the impact of any recovery techniques employed, passenger itineraries and the variation in airport capacity due to scheduled demand, changing runway configurations and local weather conditions. The simulation emphasizes the modeling of NAS ground operations with a focus on capturing the impact of limited airport capacity and variations in demand loading.

6.2 Structure

Structurally, MEANS consists of several modules working together in order to simulate NAS operations. Four of these modules (gate, taxi, tower and enroute) represents the states through which a flight leg passes as it transverses the NAS (represented by the dashed arrows in Figure 6-1). Two other modules (the air traffic control system command center (ATC SSC) and airline modules) are decision-making modules, thusly
named because they make decisions concerning cancelation, rescheduling or reassignment (in terms of crew or equipage) of aircraft legs, and then notify the appropriate state module which executes the change. The remaining module, the weather module, is an informational module so named because it simply provides information to the system which other modules can then act on if necessary.

For each of the modules shown in Figure 6-1 there are a number of available implementations, each with a different level of modeling fidelity or in the case of the airline module or the tower module, different recovery techniques and different flight selection algorithms respectively. Rather than introducing each of the available module implementations, only those relevant to the use of MEANS as part of this study will be discussed.
6.2.1 Gate Module

Each flight leg begins and ends with the gate module. The gate module is responsible for determining the amount of time a flight spends parked at the assigned gate as well as the aircraft pushback time. There are two components of the gate time. First the gate module determines the minimum required turn around time, which is the time required to prepare the plane for the subsequent flight leg including deplaning the arriving passengers and luggage, refueling and cleaning the plane, and boarding the new passengers and luggage. This time is calculated using the methodology developed by William Vanderson [19]. If the airline schedule does not allow enough time to turn the aircraft around, the aircraft pushback time is perforce rescheduled. The gate module sets the aircraft pushback time based on the minimum turnaround time, the airline schedule and any ATCSSC restrictions in effect.

6.2.2 Taxi Module

Once an aircraft has pushed back from the gate, or landed at the destination airport, it enters the taxi module. The taxi module determines the time that each departure spends taxiing out (the time between gate pushback and entry into the takeoff queue) and each arrival spends taxiing in (the time between aircraft touchdown and gate arrival). The module implementation used as part of this study uses deterministic taxi times based on historical data.

6.2.3 Tower Module

The tower module is responsible for controlling the arrival and departure queues and assigning the actual arrival and departure times. Each airport in MEANS has its own instance of the tower module which receives arriving aircraft from the enroute module and hands them off to the taxi module at the determined arrival time and receives departing aircraft from the taxi module and hands them off to the enroute module at the determined departure time. In order to accomplish this, the tower determines the available capacity at an airport based on a combination of the current local weather
conditions, the expected traffic and the Ground Delay Program (GDP) restrictions if a GDP is in effect. Two tower module implementations are of particular interest: the simulated pareto frontier implementation, which was used as part of the reduced IFR arrival-arrival wake vortex separation minima study and the controller agent implementation which is used as part of the event sequencing study.

**Simulated Pareto Frontier**

The simulated pareto frontier implementation uses pareto frontiers corresponding to specific runway configurations, fleet mixes and weather conditions to model airport capacity under different conditions. The tower module selects a curve appropriate to the operational conditions at the airport from among the available pareto frontiers and then chooses an operational point along the selected pareto frontier. The pareto frontiers used as part of this implementation are generated via ARCC for a subset of the 205 modeled airports. All other airports either use pareto frontiers generated by the FAA [1] or in the case of minor airports are treated as though the available capacity is unlimited.

The operational point along the identified pareto frontier is selected based on the expected demand over the next hour at the airport, specifically on the expected ratio of departures to arrivals as proposed by Gilbo [20]. The expected demand is found by counting both the flights that are scheduled for the next hour and the aircraft that are currently waiting in the arrival and departure queues. It is possible that the expected demand count is not an accurate reflection of the actual demand due to unpredictable taxi and enroute delays; however, it provides the best estimation available to controllers. In general, the operational point is set to be the point along the pareto frontier that yields the same ratio as the expected demand ratio (Figure 6-2).

There are two cases for which the selected operational point does not reflect the expected demand ratio. The first of these occurs when the capacity profile allows for free arrivals or departures. The capacity profile for Houston Bush Intercontinental (IAH) under IFR conditions, which allows for both free arrivals and free departures,
these are horizontal and vertical portions of the curve respectively is shown in Figure 6-3. Here, free arrivals or free departures refer to a situation where the number of arrivals or departures can be increased without a corresponding decrease in the rate of the other event. For capacity profiles with this property, the simulated pareto frontier implementation selects the point with the maximum number of free events, in Figure 6-3 point 1 is selected if the expected demand ratio returns a point anywhere on the free arrival portion of the curve and point 2 is selected if the expected demand ratio returns a point anywhere on the free departure portion of the curve. For all other expected demand ratios, the operational point is selected to match the demand ratio. The other instance for which the returned capacity point does not reflect the expected demand is if the airport is operating under a GDP. For GDP, a set ratio of arrivals to departures is used, and a point on the capacity curve is selected based on that ratio rather than the expected demand ratio.

Once the operational point has been selected setting the airport capacity, arrival and departure slots are generated. The arrival slots are generated by evenly dividing the time period, the default time period being an hour, based on the arrival rate. The departure slots are generated similarly based on the departure rate. The slots then can be used by arrivals and departure respectively, if and only if the flights are at the head of the appropriate queue at the beginning of the time slot. If there is no available flight, the slot goes unfilled.
Controller Agent

The controller agent tower implementation determines the airport capacity directly by determining runway assignments and applying the FAA spacing regulations on a flight by flight basis in a manner similar to ARCC. Of the available implementations, the controller agent implementation most accurately tracks the impact a given schedule, runway configuration and set of local weather conditions has on airport capacity.

The controller agent implementation has many variations which differ in the event sequencing algorithm used. The basic controller agent implementation uses the same algorithm employed by ARCC to determine the event sequence. Other available implementations utilize the mathematical program discussed in Section 4.4.2 or simple rule based algorithms that select events based on the earliest event time or the longest queue and then determine runway assignments based on a greedy heuristic algorithm. The controller agent implementation is easily expanded to utilize any desired event sequencing algorithm without changing the functionality of the remainder of the simulation.

6.2.4 Enroute Module

The enroute module is responsible for the portion of the aircraft leg between take-off and entry into the arrival queue at the destination airport. This module does not model the impact of enroute weather, secondary flight dynamics or enroute conges-
tion. Rather, the module implementation used as part of this work simply provides a deterministic transit time based on historical data, and once the time has elapsed, the aircraft appears in the arrival queue at the destination airport.

6.2.5 Airline Module

The airline module is composed of three submodules, the schedule submodule, the Airline Operations Center (AOC) submodule and the passenger submodule. The schedule submodule stores and keeps track of the schedule being flown, updates arrival and departure times based on delays and track changes that result from controller decisions or airline recovery techniques. The AOC submodule manages flight delay and invokes appropriate airline recovery procedures. A trivial AOC submodule is available whose only action is to cancel flights delayed more than two hours, which is used as part of this research. The passenger submodule is responsible for tracking passengers and passenger delay and supplying said information to the AOC module if required, though it is possible to run MEANS with no passenger information.

6.2.6 ATCSSC Module

The ATCSSC module is primarily responsible for initiating and managing GDPs and ground stops. The module accomplishes this by monitoring the expected demand and capacity in terms of arrival rate at each airport in the NAS. If the difference between the expected arrival demand and the arrival capacity exceeds a given threshold, the ATCSSC module initializes a GDP and begins the slot assignment process based on the Ration by Schedule algorithm [21]. It is possible to disable the use of GDPs and ground stops, and in such instances, the ATCSSC module performs no function.

6.2.7 Weather Module

The weather module is responsible for providing information about the current and future predicted local weather conditions at airports in terms of local ceiling, visibility and wind conditions. The weather module implementation used as part of this
research simply plays back historical weather conditions with one-hundred percent accurate predictions. This module does not currently provide information on enroute weather, as enroute weather is not used by the simulation. If no weather information is provided to the weather module, it is assumed that the local weather conditions enable the use of VFR.

6.3 Input Requirements

The inputs required by MEANS vary based on the specific module implementations being used. In order to run MEANS with the above discussed module implementation, the following data sources are required: a schedule file and associated list of airports, a set of capacity profiles, weather data, historical taxi and enroute times, and historically derived minimum gate turn around times. For a typical MEANS runs, the schedule file is generated from a combination of Airline Quality Performance (ASQP) and aggregate Enhanced Traffic Management System (ETMS) data, though other sources for schedule data can be used. The ETMS data is used to bring the demand up to the historical level because ASQP only contains information on domestic flights flown by the major US airlines. The required airport list, historical enroute and taxi times as well as the minimum gate turn around times can also be derived from the ASQP data. The required weather data can be derived from either of two sources: FAA CODAS weather data or from National Oceanic and Atmospheric Administration (NOAA) weather data.

6.4 Simulation Output

MEANS’ primary output is a set of files containing flow and state transition information for both flights and passengers. The flight information contains time stamps for each flight leg, indicating the gate push-back time, arrival and departure queue entry time as well as take off and landing times. Any changes made to the schedule by the airlines, tower or enroute delay are recorded, along with information about any
GDPs that affect the flight. The passenger information includes for each passenger both the originally scheduled flight legs and the flight legs actually flown. Additionally, MEANS provides data concerning the airport capacity at the start of each simulation hour.
Chapter 7

Results

7.1 Overview

The results in terms of delay statistics for both the reduced wake vortex separation study and the event sequencing study are presented below. For the reduced wake vortex study, the benefit of reducing the IFR arrival-arrival wake vortex separation minima is presented in terms of total system delay, delay by airport in terms of the eleven candidate airports and delay by day of the month. For the event sequencing study, the benefits of utilizing the different algorithms in terms of system delay, airport delay at EWR as well as on-time performance are presented.

7.2 Reduced Wake Vortex Separation Study

For each of the seven sets of arrival-arrival wake vortex separation minima, MEANS was used to simulate NAS operations for the month of January 1999. For each simulation, the capacity curve generated via ARCC for a given set of reduced separation minima were used to model the capacity at each of the eleven candidate airports while the capacity was left unchanged at all other airports in the NAS. The total system delay for each simulation run was computed as
\[ \sum_{f=\text{non-cancelledflights}}(\max(\text{arrivaldelay}, 0) + \max(\text{departuredelay}, 0)) + \sum_{\text{cancelledflights}}(\text{delay}) \]

where the arrival delay is the difference between the scheduled arrival time and the actual arrival time, and the departure delay is the difference between the scheduled departure time and the actual departure time. If a flight departed or arrived early, then the flight is said to contribute no departure or arrival delay respectively. The delay for the canceled flights can be calculated in one of two ways: it can be set to zero for each flight as they did not fly and hence could not be late, or it can be set to two hours for each flight as the utilized MEANS airline module only cancels flights that are delayed by two hours or more. The total system delay, utilizing both methods for calculating the delay contribution from canceled flights is shown in Figure 7-1. Note that there is little or no difference on the total delay between the two methods. There were a total of 1,292,920 flights flown during January, 1999 with a total of 22,880 canceled flights. With the full 100% separation reduction, the total system flight delay is reduced by 243,672 minutes for the month, an average of 7860 minutes per day. Because historical weather data was used in the simulation, the eleven candidate airports were only under IFR operations for a small percentage of the total time, approximately 2,092 out of a possible 8,184 hours. Taking this into account, the delay benefit averages 116 minutes per IFR hour with the full 100% reduction in IFR arrival-arrival wake vortex separation minima. Over two-thirds of the delay reduction benefit is garnered at the 40% reduction point, with an average benefit of 80.7 minutes of delay reduction per IFR hour.

The total system delay can be broken down in terms of the delay experienced by each of the eleven candidate airports. The total delay, the sum of the arrival and departure delay at each of the eleven candidate airports is shown in Figure 7-2. The left hand plot has all eleven candidate airports. The plot on the right shows only ten of the candidate airports, ORD having been removed in order to better display the relative impact at the remaining ten airports. The total hours each of the candidate airports is under IFR during January 1999 is shown in Figure C-2 in Appendix C.
The airports that reap the largest benefit (ATL and ORD) are those that experience the most delay with the standard separations and the greatest scheduled demand. While neither ORD nor ATL experience the longest periods of prolonged poor weather, for both airports the high demand coupled with the large gap between VFR and IFR capacities enables large reductions in delay. The capacity profiles for ORD are shown in Figure 7-3: the VFR capacity curve is shown on the left, and the IFR capacity curves corresponding to the different sets of reduced IFR arrival-arrival wake vortex separation minima are shown on the right. Even with the full 100% reduction, there remains a significant gap between arrival and departure capaci-
ity at ORD, and as the demand approaches the VFR capacity limits, there remains significant flight delay. JFK and PHX reap the least benefit from the reduced IFR arrival-arrival wake vortex separation minima. In the case of JFK, little to no benefit was expected because JFK has the smallest level of demand. The minimal improvement seen by PHX was also expected, even though it has the fourth highest demand and loses a significant portion of its capacity during IFR operations because PHX experience no hours of IMC operations during January 1999. The small delay reduction at PHX results from arriving flights improving their departure times at one of the other candidate airports rather than the reduced separations at PHX. It is important to note that PHL experiences an increase in delay for the full 100% separation reduction, which is a direct result of a regime change that occurs at PHL with the full 100% reducing causing an increase in capacity (see Appendix A).

The total system delay for January 1999 can also be broken down by day of the month. The total system delay as a function of both the day of the month and the percent reduction of IFR arrival-arrival wake vortex separation minima is shown in Figure 7-4. For each day, the base-level system delay (corresponding to the maximum reduction of the standard IFR arrival-arrival wake vortex separation minima) has been subtracted from all other data points. The number of hours of

Figure 7-3: ORD Capacity Curves: (L) VFR (R) IFR Reduced Separations Capacity Curves
IFR experienced by each of the eleven candidate airports on each day of January 1999 is shown in Figure C-1 in Appendix C. As is evident from the plot, reducing the arrival-arrival wake vortex separation minima is most effective on days where the NAS is most impacted with delay in the base case scenario; for January 1999, the most impacted days are the 25th and 12th. There are four days (Jan 4th, 5th, 10th and 26th) which reap little or no benefit from the reduced separation minima. During these days, none of the eleven candidate airports experience prolonged periods of IFR conditions during peak operating hours, and hence there is no benefit to be gained from reducing the IFR arrival-arrival wake vortex separation minima.

![Figure 7-4: Total System Delay by Day, January 1999](image)

Breaking down the total system delay for the most impacted days into the contribution for each of the eleven candidate airports, it becomes evident that the benefit in terms of delay reduction is mostly due to benefits at ORD. This is a direct result of the high demand at ORD and the fact that on Jan 12th, 14th, 18th, 25th and 28th, ORD experienced prolonged periods of IFR conditions. The delay contribution from each of the eleven candidate airports for January 28th, 1999 is shown in Figure 7-5.

January 9th, 1999 is one day that experiences a moderate level of system delay without having poor weather conditions at ORD. The delay breakdown for this day
as a function of the separation reduction is shown in Figure 7-6. On this day, airports that experience prolonged periods of poor weather included: ATL, BOS, EWR, JFK, LGA and PHL. Of these six airports, ATL experiences the highest level of demand and hence a larger capacity/demand gap resulting in larger flight delays.

### 7.3 Event Sequencing Study

For each of the four study days, MEANS was used to simulate NAS operations while EWR employed different event sequencing and runway assignment algorithms. In addition to the two previously described event sequencing algorithms, MEANS was used to simulate NAS operations while EWR utilized a FIFO algorithm for flight sequencing in conjunction with a greedy heuristic algorithm for runway assignment. The simulation times for the two simple rule based algorithms were on the order of 90
seconds. The simulation times for event sequence optimization averaged 272 seconds (Table 7.1). The variation in the event sequence optimization simulation times, as much as 360 seconds, stems from the variation in demand, percentage of operations under VFR and of course the incoming event sequence. Larger demand levels result in MEANS solving more of the smaller overlapping subproblems due to both the increased volume and the decreased average separation between flights, increasing the simulation time. More hours of VFR operations require MEANS to solve the larger VFR problem formulation, increasing the simulation time. The impact of the incoming event sequence on the simulation time, which determines which subproblems need to be solved, stems from the fact that some optimization problems are harder to solve than others. This last factor has the greatest impact on the simulation time.

<table>
<thead>
<tr>
<th>Date</th>
<th>Simulation Time (sec)</th>
<th>Number of Subproblems</th>
<th>Hours of VFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 18, 2000</td>
<td>489.034</td>
<td>907</td>
<td>14.5</td>
</tr>
<tr>
<td>Feb 27, 2000</td>
<td>120.971</td>
<td>705</td>
<td>21.5</td>
</tr>
<tr>
<td>Jan 15, 2001</td>
<td>184.790</td>
<td>1017</td>
<td>18</td>
</tr>
<tr>
<td>Jan 19, 2001</td>
<td>294.368</td>
<td>1007</td>
<td>19</td>
</tr>
</tbody>
</table>

The total system delay for each simulation was computed in the same manner as in the reduced wake vortex separation study and is plotted in Figure 7-7. As is evident from the plot, the benefit in terms of delay reduction, if any, garnered from the Serve-the-Longest-Queue algorithm is marginal over simply processing flights in the order in which they enter the TRACON. In fact, the Serve-the-Longest-Queue algorithm results in less flight delay than the FIFO algorithm on only one of the four days, January 15, 2001, indicating that the relative performance of the two algorithms is schedule dependent. This dependence can be further seen by looking at two subsets from the final event sequences (Table 7.2 and Table 7.3). The first event sequence subset (Table 7.2) shows a sequence of flights where the FIFO order mirrors the optimal event sequence, though the Serve-the-Longest-Queue algorithm results in a different event sequence. The second event sequence subset (Table 7.3) shows a sequence of flights where the Serve-the-Longest-Queue order mirrors the optimal
event sequence, though the FIFO algorithm results in a different event sequence. Note that in both cases, while the simpler algorithms mirrors the optimal event sequence, the event processing times differ, as the optimal event sequence takes into account later flights when determining the runway assignments, which the other algorithms fail to do.

<table>
<thead>
<tr>
<th>No.</th>
<th>Optimal Sequence</th>
<th>FIFO</th>
<th>Longest Queue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flt No.</td>
<td>Time (sec)</td>
<td>Flt No.</td>
</tr>
<tr>
<td>271</td>
<td>CO302</td>
<td>33535</td>
<td>CO300</td>
</tr>
<tr>
<td>272</td>
<td>DL1166</td>
<td>33645</td>
<td>DL1166</td>
</tr>
<tr>
<td>273</td>
<td>DL2475</td>
<td>33645</td>
<td>DL2475</td>
</tr>
<tr>
<td>274</td>
<td>ACA771</td>
<td>33809</td>
<td>ACA771</td>
</tr>
<tr>
<td>275</td>
<td>US537</td>
<td>33869</td>
<td>US537</td>
</tr>
<tr>
<td>276</td>
<td>BLR492</td>
<td>33925</td>
<td>BLR492</td>
</tr>
<tr>
<td>277</td>
<td>ACA733</td>
<td>34200</td>
<td>CO1145</td>
</tr>
</tbody>
</table>

Table 7.3: Flight Sequence Subset, Feb 27, 2000

<table>
<thead>
<tr>
<th>No.</th>
<th>Optimal Sequence</th>
<th>FIFO</th>
<th>Longest Queue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flt No.</td>
<td>Time (sec)</td>
<td>Flt No.</td>
</tr>
<tr>
<td>111</td>
<td>CO651</td>
<td>32700</td>
<td>CO651</td>
</tr>
<tr>
<td>112</td>
<td>CO1265</td>
<td>33000</td>
<td>CO1265</td>
</tr>
<tr>
<td>113</td>
<td>US1122</td>
<td>33261</td>
<td>US1122</td>
</tr>
<tr>
<td>114</td>
<td>CO1477</td>
<td>33261</td>
<td>CO1477</td>
</tr>
<tr>
<td>115</td>
<td>CO1175</td>
<td>33321</td>
<td>CO302</td>
</tr>
<tr>
<td>116</td>
<td>CO105</td>
<td>33381</td>
<td>CO1175</td>
</tr>
<tr>
<td>117</td>
<td>CO267</td>
<td>33441</td>
<td>CO105</td>
</tr>
<tr>
<td>118</td>
<td>CO302</td>
<td>33527</td>
<td>CO267</td>
</tr>
</tbody>
</table>

For all four study days, the optimal event sequence results in a significant reduction in NAS delay, varying from a 13.7% to a 40.8% reduction (averaging 24.1%) from the FIFO algorithm and a 15.1% to a 35.9% reduction (averaging 24.7%) from the Serve-the-Longest-Queue algorithm. This level of delay reduction was reached with only one congested airport implementing the optimal event sequence, indicating that if other major airports in the US were to utilize the optimal event sequence,
the total system delay could be significantly reduced. The magnitude of the bene-
fit at the airport level can be seen in Figure 7-8. Just at EWR, the optimal event
sequence reduces delay between 55.6% and 81.0% relative the FIFO algorithm (aver-
aging 65.4%) and between 59.1% and 77.5% relative to the Serve-the-Longest-Queue
algorithm (averaging 67.0%).

Figure 7-7: Total System Flight Delay

Figure 7-8: EWR Total Flight Delay

Another important benefit measure is the percentage of delayed flights (the FAA
considers any flight that is more than fifteen minutes late to be delayed). The on-time
performance for EWR for each algorithm is shown in Table 7.4 for each study day.

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For each study day, the percentage of flights delayed by fifteen or more minutes is the smallest, for the optimal event sequence, which is as expected from the total delay statistics previously discussed. What was not expected from the previously discussed delay statistics is that for most cases (all except Feb 27, 2000), the Serve-the-Longest-Queue algorithm resulted in a smaller fraction of flights delayed by more than fifteen minutes, indicating that even though the Serve-the-Longest-Queue algorithm results in a higher level of total delay, it improves the airline on-time performance statistics over the FIFO algorithm.

<table>
<thead>
<tr>
<th>Date</th>
<th>FIFO</th>
<th>Longest Queue</th>
<th>Optimal Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 18, 2000</td>
<td>43%</td>
<td>60%</td>
<td>77%</td>
</tr>
<tr>
<td>Feb 27, 2000</td>
<td>70%</td>
<td>64%</td>
<td>86%</td>
</tr>
<tr>
<td>Jan 15, 2001</td>
<td>17%</td>
<td>25%</td>
<td>90%</td>
</tr>
<tr>
<td>Jan 19, 2001</td>
<td>43%</td>
<td>50%</td>
<td>95%</td>
</tr>
</tbody>
</table>
Chapter 8

Summary and Future Work

Airport capacity is a limiting factor in NAS performance. Currently, many of the major airports are scheduled to operate at or near their maximum fair weather capacity, with future demand predictions set to put the demand well over the maximum available capacity. When an airport’s demand exceeds the available capacity, delay, which can result in schedule disruptions that propagates through the NAS, is introduced into the system. The situation is exacerbated when an airport’s weather degrades to IMC and the capacity drops. This study looked at two methods of improving runway throughput and thereby ameliorate the effects of capacity shortfall: increasing the available IFR capacity by reducing IFR arrival-arrival wake vortex separation minima and increasing the realized capacity (both IFR and VFR) through the utilization of event sequencing algorithms.

The method examined for increasing the available capacity was the reduction of the IFR arrival-arrival wake vortex separation minima. Decreasing these separations, which are functions of the aircraft sequence, by a maximum of 1.5 NM at eleven congested US airports decreased the total NAS delay by 31.8% over the month of January 1999. The largest contribution to the delay reduction comes from ORD. The large benefit results from the high schedule demand and the fact that it has the highest level of delay under standard separation rules. Additionally, of the studied airports, ORD has the largest capacity gap between VFR and IFR, and during January 1999 spends 47.8% of the time operating under IFR, the largest percentage of any of the
studied airports. However, even airports that do not experience any IFR reap benefit from the reduced separations due to the NAS schedule connectivity. While the reduced separations have been shown to improve operations in terms of flight delay under the schedule loading of January 1999, their performance under future schedule loading and runway configurations warrants future study. Before any of the studied separations can be implemented in practice, it must be determined whether the reduced separation minima allow for safe operations both in terms of the strength of wake vortex impingements, pilot response time and whether current radar technology provides sufficient sensor resolution. Another avenue is to study whether reducing other IFR separations will produce similar reductions of delay. For example the IFR departure-departure wake vortex separation minimum which require a two minute waiting period after a Heavy departure could be reduced, resulting in an increase of available departure capacity in a manner similar to the current study.

Two event sequencing algorithms aimed at increasing the efficiency of capacity utilization were examined: the Serve-the-Longest-Queue algorithm for flight sequencing coupled with a greedy heuristic algorithm for runway assignment and a mixed integer programming optimization algorithm for simultaneous flight sequencing and runway assignment. The performance of these two algorithms in terms of flight delay was compared to the performance of a FIFO algorithm. The performance of the Serve-the-Longest-Queue algorithm and the FIFO algorithm were similar, though the relative performance is schedule dependant. The event sequence optimization out performs the other two algorithms significantly, cutting delay at EWR an average of 65.6% and 67.0% and NAS delay an average of 24.3% and 24.7% from delay levels under the FIFO and Serve-the-Longest-Queue algorithms respectively. Because this level of delay reduction was achieved with only one airport utilizing an optimal sequence, the next step should be to determine the impact of utilizing optimal event sequences at all of the congested airports in the US. In order to do this, optimization programs which handle more complex runway configurations used at many major US airports must be developed. These programs will perforce be larger and take longer to solve and as a result the solution times may prove prohibitory. Thus research should
be undertaken to reformulate the problem or develop solution techniques which allow for quicker solutions. Additionally, the impact of different problem definitions should be examined. For example, allowing limited arrival queue resequencing or utilizing different optimization goals, such as minimizing the delay for each flight or minimizing delay for certain subsets of flights that are more important to the airlines.
Appendix A

ARCC Generated Capacity Curves

ARCC was used to generate a set of capacity curves for each airport of interest to the reduced IFR arrival-arrival wake vortex separation minima study. These curves correspond to the runway configurations detailed in Table 3.7. Each IFR plot contains seven different curves corresponding to the seven sets of reduced separations (Table 3.6). In general, the curve with the smallest capacity corresponds to the 0% reduction and the curve with the largest capacity corresponds to the 100% reduction. An exception to this rule is PHL, which experiences a drop in capacity between the 80% and 100% separation reduction. It is assumed that during IFR operations, runway 17 is limited to turboprops and can only handle 25% of the available arrival traffic [1]. For the smaller reductions, the traffic utilizing runway 17 does not impact the traffic on the crossing runway (27R). However, at the 100% reduction, the throughput on runway 17 increases to the point that it causes a drop in throughput on 27R because the arrivals on 17 can no longer be squeezed between the departures on 27R.
Figure A-1: ATL VFR Capacity Curve

Figure A-2: ATL IFR Reduced Separations Capacity Curves

Figure A-3: BOS VFR Capacity Curve

Figure A-4: BOS IFR Reduced Separations Capacity Curves
Figure A-5: EWR VFR Capacity Curve

Figure A-6: EWR IFR Reduced Separations Capacity Curves

Figure A-7: IAH VFR Capacity Curve

Figure A-8: IAH IFR Reduced Separations Capacity Curves
Figure A-9: JFK VFR Capacity Curve

Figure A-10: JFK IFR Reduced Separations Capacity Curves

Figure A-11: LAX VFR Capacity Curve

Figure A-12: LAX IFR Reduced Separations Capacity Curves
Figure A-13: LGA VFR Capacity Curve

Figure A-14: LGA IFR Reduced Separations Capacity Curves

Figure A-15: ORD VFR Capacity Curve

Figure A-16: ORD IFR Reduced Separations Capacity Curves
Figure A-17: PHL VFR Capacity Curves

Figure A-18: PHL IFR Reduced Separations Capacity Curves

Figure A-19: PHX VFR Capacity Curve

Figure A-20: PHX IFR Reduced Separations Capacity Curves
Figure A-21: SFO VFR Capacity Curve

Figure A-22: SFO IFR Reduced Separations Capacity Curves
Appendix B

EWR Arrival Fix Routings

Table B.1: Preferred Arrival Fixes for Origin Airports

| ARD (South) | ACY ATL AUS BNA BWI CAE CHS CLT DAB DCA DFW FLL FMY GSO GSP HOU IAD IAH ILM JAX MCO MDSD MEM MIA MMMX MMUN MPPC MSY ORF ORL PBI PHL RDU RIC RSW SAT SAV SBGL SBGR SDF SKBO SKCG SKMD SPIM SRQ STL TPA TAPA TJSJ TNCA TXKF WAS WRI ZTL |
| PENNS (West) | ABE ANC AVP CLE CMH CVG CXY DAY DEN DTW EGE HDN HNL HUF ILN IND JFK LAS LAX LGA MCI MDT MDW MKC MKG MSP MTJ OAK ORD PDX PHX PIT SAN SEA SFO SLC SNA ZID |
| SHAFF (North) | ACK ALB AUG BDL BDR BGR BOS BTV BUF EDDF EDDL EDDM EGGG EGGK EGLL EGSS GON HFD HDN HYA ISP LEMD LFPG LMC LIFR LKPR LLBU LPPT MHT MVY ORH PSM PVD PVM PWM ROC SYR UCA YUL |
Appendix C

Weather Data

Figure C-1: Daily Hours of IFR by Airport, January 1999
Figure C-2: Total Hours of IFR by Airport, January 1999

Figure C-3: EWR Operational Rules by Hour for Select Days
Bibliography


