MODELING OF GROUND OPERATIONS USING END-AROUND (PERIMETER)
TAXIWAYS FOR THE MODERNIZED CHICAGO O’HARE INTERNATIONAL AIRPORT

BY

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THESIS

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Abstract

By 2031, U.S. air carriers are projected to transport 1.3 billion passengers within the U.S. National Airspace System, with system capacity projected to increase an average of 3.6 percent per year (FAA Aerospace Forecasts 2011-2031). Through the Next Generation Air Transport System project, a comprehensive overhaul of the airspace infrastructure is envisaged which includes major hub airports like Chicago’s O’Hare International Airport (ORD). Constantly affected by delays, incursions and capacity constraints, the risks of the airport layout modifications at ORD after completion of the O’Hare Modernization Program (OMP) have been identified in this thesis. Further, the use of perimeter or end-around taxiways (EAT) have been tested in ARENA© using a full-scale post-OMP airport layout of ORD. Impacts on safety, runway occupancy times and overall airport efficiency in future high traffic scenarios have been analyzed. Results show that the implementation of EATs will drastically reduce the potential for incursions with a 15-25 percent increase in global-level airport taxi-times. While the significant rise in taxi-times can be considered as a drawback of EATs, it can be argued that the improvement in safety levels compensate for it.
Acknowledgements

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Acronyms

AOSC      Airport Obstruction Standards Committee
ASDE-X    Airport Surface Detection Equipment – Model X
ASIAS     Aviation Safety Information Analysis and Sharing
ATC       Air Traffic Control
ATL       Hartsfield-Jackson International Airport
BTS       Bureau of Transportation Statistics
CAASD     Center for Advanced Aviation System Development
CPS       Constrained Position Shifting
CVQ       Collaborative Virtual Queue
DEPARTS   Departure Enhanced Planning and Runway/Taxiway Assignment System
DFW       Dallas Fort-Worth Airport
DOT       Department of Transportation
EAT       End-Around Taxiway
FAA       Federal Aviation Administration
FAROS     Final Approach Runway Occupancy Signal
FCFS      First-Come-First-Served
FY        Fiscal Year
GAO       Government Accountability Office
GPS       Global Positioning System
JPDO      Joint Planning and Development Office
HS        Hot-Spot
IAH       George Bush International Airport
IATA      International Air Transport Association
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>LAX</td>
<td>Los Angeles International Airport</td>
</tr>
<tr>
<td>MIA</td>
<td>Miami International Airport</td>
</tr>
<tr>
<td>MILP</td>
<td>Mixed Integer Linear Programming</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>NACO</td>
<td>National Aeronautical Charting Office</td>
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<tr>
<td>NAS</td>
<td>National Airspace System</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>Next Gen</td>
<td>Next Generation Air Transport System</td>
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<tr>
<td>NM</td>
<td>Nautical Mile</td>
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<tr>
<td>OAG</td>
<td>Official Airline Guide</td>
</tr>
<tr>
<td>OMP</td>
<td>O'Hare Modernization Program</td>
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<tr>
<td>ORD</td>
<td>O'Hare International Airport</td>
</tr>
<tr>
<td>ROT</td>
<td>Runway Occupancy Time</td>
</tr>
<tr>
<td>SRMD</td>
<td>Safety Risk Management Document</td>
</tr>
<tr>
<td>SWIM</td>
<td>System-Wide Information Management</td>
</tr>
<tr>
<td>U.S.</td>
<td>United States</td>
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Chapter 1

Introduction

1.1. The National Airspace System

The United States’ National Airspace System (NAS) is the network of United States (U.S.) airspace: air navigation facilities, equipment, services, airports or landing areas, aeronautical charts, information, regulations, procedures, material and manpower (FAA, Handbook 8083-15A Chapter 8). Figure 1.1 shows the average flights within the U.S. NAS at a single instance. The number of flights varies based on number of airlines, passenger/cargo demand, and time of day/year.

Figure 1.1: The United States’ National Airspace System
(Source: FAA Handbook 8083-15A Chapter 8)
As one of the busiest air transportation networks in the world, it handles approximately 30 percent of world-wide air traffic and conducts around 26 million operations throughout the year. By 2031, U.S. commercial air carriers are projected to transport 1.3 billion enplaned passengers (figure 1.2) a total of 1.7 trillion passenger miles (FAA Aerospace Forecast 2011-2031).

The rate of increase of international enplanements is growing annually at 4.8 percent per fiscal year (FY), which is significantly more than the annual rate of increase for domestic enplanements at 3.0 percent (FAA, Aerospace Forecast 2011-2031). Most international flights

† Mainline Flights – most large passenger airlines flights that are operated by an airline’s main operating unit to and from airports that attract high service demand;

Regional Flights – flights operated by airlines that use smaller, regional aircraft without attracting mainline service demand. These could be regional flights operated by mainline air carriers.
utilize large hub airports within the NAS. These airports face the biggest challenge to meet the increasing traffic and passenger demands.

To address these demands, the United States’ Congress established the Joint Planning and Development Office (JPDO), which is comprised of members from different departments including the Department of Transportation (DOT), the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA). The objective of this taskforce is to prepare the NAS for the high volume of traffic whilst improving safety, security and reliability. The product of these efforts will be a new era of air traffic control (ATC) systems and infrastructure within the NAS known as The Next Generation Air Transportation System (Next Gen).

1.2. The Next Generation Air Transportation System

Next Gen is an umbrella term for the ongoing, comprehensive transformation of the NAS. At its most basic level, Next Gen represents an evolution from a ground-based system of ATC to a satellite-based system of air traffic management. The progress of Next Gen relies upon the development of aviation-specific applications for existing, widely-used technologies, such as the Global Positioning System (GPS) and technological innovation in areas such as weather forecasting, data networking and digital communications. Hand in hand with state-of-the-art technology will be new airport infrastructure and new procedures, including the shift of certain decision-making responsibility from the ground to the cockpit. The implementation of Next Gen will result in fewer delays, reduced taxi-times and holding in the air, with more flexibility to get around weather problems at capacity constrained airports.
Measuring the 2007 capacity against the forecast for the 2015 (figure 1.3) mid-term planning period revealed that 18 airports and seven metropolitan areas are projected to require additional capacity if the existing airfield configurations remained constant without any capacity enhancements (MITRE, Capacity Needs in the National Airspace System 2007-2025). If the existing airfield configurations remain constant without any capacity improvements by 2025, 27 airports and 15 metropolitan areas are forecasted to require additional capacity (MITRE, Capacity Needs in the National Airspace System 2007-2025).

Figure 1.3: Capacity constrained airports and regions in 2015
(MITRE, Capacity Needs in the National Airspace System 2007-2025)
From an airport development perspective, the targets of Next Gen have been identified as (FAA, Next Gen Implementation Plan, 2010):

- **Information Sharing:** Improving data-management by getting the right information to the right person at the right time using system-wide information management (SWIM\(^\ddagger\)). This will be a key component during ground operations;

- **Environmental Impact:** Reducing aviation’s impact on the environment through quieter, cleaner and more fuel-efficient flights;

- **Increased Safety:** Enhancing safety through proactive methods and preventing accidents with advanced safety management to better predict, identify and resolve hazards;

- **Infrastructure:** Adding design flexibility and making better use of ground infrastructure through airport development (runways, taxiways, etc.) and advanced navigational ground aids (such as the Airport Surface Detection Equipment – Model X (ASDE-X\(^\ddagger\)), Final Approach Runway Occupancy Signal (FAROS\(^\ddagger\ddagger\)), etc.)

Although, Next Gen involves the overhaul of the ATC system, airport-centric improvements will maximize its near-term and long-term benefits. Next Gen begins and ends at the airport (FAA, Next Gen Implementation Plan, 2010), which has made airport development a key factor in its success, especially at large hubs.

\(^\ddagger\) SWIM is the network structure that will carry Next Gen digital information. SWIM will enable cost-effective, real-time data exchange and sharing among users of the NAS [FAA].

\(^\ddagger\) ASDE-X is a surveillance system using radar and satellite technology that allows air traffic controllers to track surface movement of aircraft and vehicles to help avoid incursions [FAA]

\(^\ddagger\ddagger\) FAROS is a technology designed to prevent accidents and incursions on airport runways by activating a flashing light visible to the pilot of an approaching aircraft to warn that the runway being approached is occupied and hazardous [FAA]
1.3. Large Hub Airports

The airports in the U.S. are classified into (FAA Airport Planning and Capacity website, 2011):

1) Commercial Airports - publicly owned airports that have at least 2,500 passengers boarding each calendar year and receive scheduled passenger service. They are further classified into:
   - Primary Airports – having more than 10,000 passengers boarding each year;
   - Non-Primary Airports – having 2,500 to 10,000 passengers boarding each year;

2) Cargo Service Airports – that, in addition to any other air transportation services that may be available, are served by aircraft providing air transportation of only cargo with a total annual landed weight of more than 100 million pounds;

3) Reliever Airports - designated by the FAA to relieve congestion at Commercial Service Airports and to provide improved general aviation access to the overall community.

The remaining airports, while not specifically defined by the FAA, are commonly described as General Aviation Airports.

Primary commercial airports are further categorized into the following by the percentage of passenger enplanements annually within the U.S. (FAA Airport Planning and Capacity website, 2011):

- Non-hub airports – Less than 0.05 percent passengers;
- Small Hub Airports – At least 0.05 percent but less than 0.25 percent;
- Medium Hub Airports – At least 0.25 percent but less than 1 percent;
- Large Hub Airports – More than 1 percent.
Hence, by definition, large hubs are primary airports that each account for at least one percent of total U.S. passenger enplanements annually (FAA Airport Planning and Capacity website, 2011). There are 30 large hubs in the NAS located in or near major metropolitan areas (figure 1.4) and also serve as hubs for airline operations. These cities also function as global hubs, transit points and will continue to experience a high growth in international passenger volume (Airbus, Global Market Forecast, 2011-2030). At current traffic levels, most large hubs face flight delays, capacity issues and safety concerns.

![Figure 1.4: Large Hubs in the National Airspace System](image)

**Figure 1.4: Large Hubs in the National Airspace System**
(MITRE, Capacity Needs in the National Airspace System 2007-2025)

### 1.3.1. Delays

In 2011, airlines within the U.S. recorded an on-time arrival and departure record of 79.6 percent. A breakdown of the flight delay causes has been presented in figure 1.5 and explained below (BTS-Airline On-Time Statistics and Delay Causes, 2011):
- Approximately 32 percent flights were delayed because the aircraft arrived late, i.e. the previous flight with same aircraft arrived late causing the present flight to depart late. Since, delays due to this phenomenon tend to ripple through the NAS, it is commonly known as the ‘Ripple Delay Effect’.

- Almost 30 percent flights were delayed due to aviation system delays (such as non-extreme weather conditions, runway closures, heavy traffic volume, and air traffic control).

- Exactly 26 percent flights were delayed due to air carrier delay (circumstances within the airline's control such as maintenance or crew problems, aircraft cleaning, baggage loading, fueling).

- Around 10 percent of the delays were attributed to cancelled or diverted flights while the remaining 3 percent were due to weather and security.

![Figure 1.5: Breakdown of all commercial aviation delays in the U.S. for the calendar year 2011](source: BTS- Airline On-Time Statistics and Delay Causes, 2011)

The ‘Ripple Delay Effect’ and the NAS delays account for more than 60 percent of all commercial aviation delays (figure 1.5). Hub-to-hub analyses of flights from Chicago O’Hare
international airport (ORD) to Hartsfield-Jackson Atlanta International Airport (ATL) have revealed how local and system level factors combine to affect components of delay (Laskey et al., 2008). These components contribute to the final arrival delay at the destination airport, thereby delaying the aircraft for its next leg of flight. Therefore, improvements at the most congested hub airports will have a positive impact on other hub airports as well.

From strictly an airport perspective, several factors have an impact on delays: runway configurations, taxiway design, traffic density, etc. Their impact is not only limited to ground delays but also increase the probability of a missed approach, representing airport coupling effects which need to be accounted for in the future design of metropolitan airports and high-density operations (Gariel et al., 2011).

1.3.2. Capacity

Aircraft capacity is defined as the total number of seats per aircraft. Historical data indicates a steady growth in the average aircraft capacity since 1999 (Airbus OAG 2009). By 2030, there are expected to be 7,420 new aircraft in North America growing at 3.7 percent per year, representing a $US 446 billion market (Airbus, Global Market Forecast, 2011-2030).

![Figure 1.6: Projected number of new aircraft in North America by 2030](source: Airbus, Global Market Forecast, 2011-2030)
Passenger trip length is projected (FAA, Aerospace Forecasts 2011-2031) to be 1,342 miles in 2031 (up 11.3 miles annually). The growth in passenger trip length reflects the faster growth in the relatively longer international and domestic trips (figure 1.7) as compared to shorter-haul flights. In order to meet the high demand for longer-haul flights and accommodate the larger generation of aircraft, increasing airport capacity has emerged as a priority for most large hubs (MITRE, Capacity Needs in the National Airspace System 2007-2025).

![Graph showing number of long-haul routes worldwide]

**Figure 1.7: Number of long-haul routes worldwide**  
(Source: Airbus, Global Market Forecast, 2011-2030)

Airport Capacity is defined as a modeled estimate that calculates the number of arrivals which can be handled at a fixed level of delay for an individual or set of airports (FAA, 2006). The U.S. Airport System capacity is expected to grow at an annual average rate of 3.6 percent through 2031 (FAA, Aerospace Forecast 2011-2031) mainly due to increases in aircraft size and number. The use of smaller reliever airports has often been suggested as an alternative to congestion at large airports (Bonnefoy et al., 2005). However, the growing population and economic activity at hub airports do not support the argument of using reliever airports. Various
airfield modifications have been planned until 2018 to accommodate the forecasted capacity increase (figure 1.8).

<table>
<thead>
<tr>
<th>NEW RUNWAYS</th>
<th>RUNWAY EXTENSIONS</th>
<th>AIRFIELD RECONFIGURATION</th>
</tr>
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<tbody>
<tr>
<td>• Houston (IAH)</td>
<td>• Fort Lauderdale (FLL)</td>
<td>• Philadelphia (PHL)</td>
</tr>
<tr>
<td>• Denver (DEN)</td>
<td>• Portland (PDX)</td>
<td>• Chicago (ORD)</td>
</tr>
<tr>
<td>• Chicago (ORD)</td>
<td>• Atlanta (ATL)</td>
<td>• Los Angeles (LAX)</td>
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**Figure 1.8: Airport improvements planned until 2018**

(FAA, Next Gen Implementation Plan, March 2010)

Most of the projects envision a modernization plan that includes the use of parallel runways. One of the best examples that illustrate the impact of parallel runways is the fifth runway at Hartsfield-Jackson airport, Atlanta (ATL), which opened in May 2006. Often referred to as the most important runway in USA, it averages more than 100,000 landings and take-offs per year (ATL website, Fifth Runway Construction Project, 2011). The runway has decreased delays at ATL by 50 percent and the increased operational capacity is estimated to save the airline industry $260 million a year in delay costs (ATL website, Fifth Runway Construction Project, 2011).

1.3.3. Safety

Runway incursions have been the most concerning factor in aviation safety since 2005. This is mainly due to the steady increase in the total number of incursions between 2005 and 2008 (figure 1.9). The total number runway incursions in the NAS have not decreased significantly since peaking in 2008.

The FAA has stated that the most probable causes for runway incursions are poor airfield geometry, the presence of incursion Hot-Spots, lack of information exchange and lack of pilot
and ATC situational awareness. A detailed methodology has been presented in Chapter 2 to understand these concepts better.

![Figure 1.9: Total number of Runway Incursions per Fiscal Year](Source: FAA Runway Incursion Statistics, 2011)

The large hub examined in this thesis is ORD, a fitting example of a large hub in the NAS plagued with delays, capacity and safety issues. It is ranked in the top five airports in the U.S. for number of runway incursions and worst on-time performance (FAA, ASPM database, 2011). Facing a high annual rate of growth of passengers in the next decade (BTS, T-100 market, 2010), it will be crucial for ORD to increase capacity while focusing on reducing the incursion rate.

### 1.4. O’Hare International Airport

Located in one of the largest metropolitan cities in the U.S., ORD caters to over 30 million passengers every year (FAA, ASPM database, 2011). It has been ranked consistently in the top five large hubs in the U.S. in the past decade (BTS, T-100 market, 2010). Traffic statistics at ORD between 2009 and 2011 indicate that over 128,000 flight operations†† were conducted every

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†† A single flight operation is defined as “the airborne movement of aircraft in controlled or noncontrolled airport terminal areas, and counts at en route fixes or other points where counts can be made”. (FAA, 14 CFR 170.3)
year with average delays (arrival and departure) of 20 percent (FAA, ASPM database, 2011). Figure 1.10 shows the arrival and departure delays with respect to the number of operations conducted at ORD from 2002 to 2011. The data for the calendar year 2011 is projected. The airport has had the lowest percentage of on-time arrivals in the NAS since 2006, with almost 70 percent of these delays due to volume, equipment and airport inadequacies (City of Chicago website, O’Hare Modernization Program, 2011).

![Figure 1.10: Operations and Delay Statistics at O'Hare as of August 2011](Source: FAA ASPM database, 2011)

O’Hare airport not only has a reputation of repeatedly recording one of the worst on-time performances in the NAS, but also the highest number of runway incursions over the past decade (FAA, Aviation Safety Information Analysis and Sharing (ASIAS) system, 2011). Its complex taxiway layout, number of runway intersections, hot-spots and round-the-clock traffic congestion
all contribute to low safety levels (City of Chicago website, O’Hare Modernization Program, 2011).

Figure 1.11: The present airport layout at Chicago O’Hare – October 2010
(Source: City of Chicago, OMP website, 2011)
Forecasts suggest that the number of enplanements at ORD will reach almost 50 million per year by 2025 (figure 1.12) (Ricondo and Associates, 2009). The high demand of domestic and international passengers is due to the following:

- The geographical location of ORD within the U.S. – It is one of the largest airports in the central part of the country and acts as a transit point for cross-country and international flights;
- The proximity to one of the largest population densities within the U.S. – the Chicago area, which the largest city in the Midwest and also the commercial capital of the central part of the country;
- The hub for United-Continental Airlines – one of the biggest airlines in the world in terms of number of passengers transported per year and number of aircraft in its fleet (International Air Transport Association (IATA), 2011). The airline is expected to expand its fleet, increase frequency of flights through the country and increase code-sharing with international airlines (IATA, 2011).
In order to ensure that the increased traffic levels of the future are not subjected to the low level of safety, immediate action is required. Hence, the FAA has undertaken the expansion and redevelopment of the airport called the O’Hare Modernization Program (OMP).

1.4.1. O’Hare Modernization Program

ORD delays cause a ripple effect throughout the entire air traffic system. The number of delays at ORD as a function of the total NAS delays peaked in 2004. Following improvements at some major airports, the delays remained close to an average of 6 percent. But since 2009, the trend of increases in delays is similar to the early 2000s, when traffic began to exponentially increase (figure 1.13).

![Figure 1.13: Number of delays at ORD as a percentage of NAS delays](image)

*Source: BTS-Flight Delays at a Glance, 2011*

The OMP, an integral part of the Next Gen plan, is the city of Chicago’s proposal to realign three existing runways, extend two existing runways, and construct one new runway at O’Hare. This will result in an eight-runway configuration consisting of six parallel east/west runways and
two crosswind runways (figure 1.14). Overall delays will be reduced by 66 percent, and the annual operational capacity will be increased from 974,000 to 1,194,000 aircraft operations (City of Chicago website, O'Hare Modernization Program, 2011).

![The new Airfield Layout at Chicago O'Hare](figure14.png)

*Figure 1.14: The new Airfield Layout at Chicago O'Hare
(Source: City of Chicago OMP website, 2011)*

There have been certain negative observations about this project. The Del Balzo Report (Hinson D, Howe J, 2011) suggests that the addition of runways will add to the delays and increase bottle-necks. ORD is currently ranked first amongst all U.S. airports based on total number of runway incursions (FAA, ASIAS system, 2011). It is claimed that the OMP will result in fewer active runway crossings in the middle third of the runway than the current airfield (City
of Chicago OMP website, 2011). However, comparisons between the old and new airport configurations reveal that multiple incursion Hot-Spots will prevail (discussed in section 2.3).

### 1.4.2. Thesis Objective and Organization

From a safety perspective, the use of perimeter taxiways or End-Around taxiways (EATs) at ORD has been suggested and modeled in this thesis. In order to determine the effectiveness of this strategy for ORD, and to benchmark this proposed taxiway configuration, a full-scale simulation of modernized O’Hare has been conducted. The thesis will aim to answer the following questions:

- Will the new OMP layout increase or decrease the number of incursion Hot-Spots, thereby affecting the safety levels?
- Would implementation of EATs be a feasible option to avert potential incursion scenarios?
- What will be the impact of EATs at ORD in future high traffic load scenarios on
  - Local-level taxi-times
  - Global-level taxi-times
  - Runway Occupancy Times
  - Incursions or conflicts

This thesis has been organized as follows: In Chapter 1, we have been introduced to the NAS, large hub airports and taken a closer look at the OMP as an integral part of the Next Gen program. Chapter 2 provides a background of research conducted in ground operations modeling at airports. Further, the concepts of runway incursions, hot spots and EATs have been reviewed. Chapter 3 discusses ground movement theory, explaining the premise of each parameter used in the simulation. Chapter 4 explains the simulation, with an introduction to the software used to
model the ground operations at ORD. The simulation setup is discussed in detail using flowchart modules and a sample algorithm is provided. Chapter 5 presents the results of the simulation, including taxi-time comparisons, runway occupancy analysis and conflict assessment. Chapter 6 concludes the thesis, summarizing the simulation and the results. Future research directions have also been outlined.
Chapter 2

Background and Methodology

2.1. Background

Since 1985, when capacity and delays were projected due to traffic increase, many theoretical and simulation-based models have been created to examine airport efficiency. Most of these models, however, have focused on individual aspects of operations dynamics. Arrival planning has been one such unit where considerable research has been conducted towards analysis of separation and throughput (Ignaccolo, 2003) (Ren, 2008). The Constrained Position Shifting (CPS) system or sequencing of like-category aircraft together during approach (Balakrishnan, 2006) (Harikiopoulo, 2010) is considered to be the preferred solution to optimal arrivals on a single runway (Subramanian, 2002) (Kohler, 2004). Research has been conducted on factors such as taxiway queuing dynamics (Carr et al., 2002) and airport slot optimization (Andersson, 2000) that contribute to overall airport efficiency. The above publications, however, have approached their problems from a purely optimization perspective.

Departure planning has been another research problem tackled ever since runways were identified as constraints. Researchers at the Massachusetts Institute of Technology (MIT) are considered to be the pioneers in departure planning architecture (Anagnostakis et al., 2001) with
most of their analysis conducted using the test-bed models of Boston Logan Airport (Shumsky, 1997) (Husni, 1998) (Anagnostakis et al., 2000). Many other laboratory prototypes have been developed (Barrer et al., 1989) (Cooper et al., 2001) (Burgain, 2008) with the objective of optimizing departure sequencing. Although these researches have used simulation models instead of optimization techniques, they have focused on singular aspects of airport efficiency only.

In order to examine and model airport operations in its entirety, full-scale models of the airports are required. Such simulations are required to analyze all operations contributing to airport efficiency, especially at large hub airports. Unlike past full-scale models (Chin, 1997) (Andersson, 2000) that have been developed using transportation engineering platforms, the model presented in this thesis have been created using a business simulation software. Most publications focusing on taxi-times (Pesic, 2001) (Smeltink, 2004) have highlighted its complex nature due to dependencies with path selection, aircraft category, movement speeds and conflicts. One of the simpler full-scale modeling tools with theoretically-driven parameters used to simulate ground operations has been MATLAB © (Voulgarellis et al., 2005), which inspired the approach used in this thesis with a different process modeling software.

The simulation inputs used in this thesis are obtained from theoretically-derived parameters along with real-world data from the OMP. The model used in this thesis attempts to combine these various aspects does not use any optimization techniques for departure / arrival processes. Rather, it addresses the entirety of airport operations, by concentrating on runway efficiency (departures and arrivals), safety (conflicts) and taxi-times. The model facilitates the benchmarking of real-world results with simulation results obtained with the modified EAT layout at ORD.
The concept of EATs has been well-documented after its success at various large hub airports throughout the NAS (Satyamurti, 2007) (Chandler, 2009) (Engelland, 2010). Their impacts on runway operations, taxi-times and runway incursion mitigation have aided in recognizing the coupling relationship between airport surface traffic and airport efficiency (Kistler, 2009). Further, these factors have led to a better understanding of the propagation of delays throughout the NAS (Chin, 1997), giving more insight on the way delays ripple through the air transportation network of the U.S. (Laskey, 2007). Hence, airport efficiency has gained vital importance, emerging as one of the most important targets for Next Gen.

2.2. Runway Incursions

Beginning FY 2010 the International Civil Aviation Organization (ICAO) defines a runway incursion as: “Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and take-off of aircraft.” (ICAO, Manual on the Prevention of Runway Incursions, First Edition, 2007). Runway incursions are classified into four categories, tracked by the ICAO and FAA:

- **Category A**: Separation decreases to the point that participants take extreme action to narrowly avoid a collision.
- **Category B**: Separation decreases, and there is a significant potential for a collision.
- **Category C**: Separation decreases, but there is ample time and distance to avoid a collision.
- **Category D**: There is little or no chance of collision, but the definition of a runway incursion is met.
ORD has been ranked 1st based on number of runway incursions since 2004 (figure 2.1). As of April, 2011 there have been 132 incursions at ORD in the last decade, 11 of which have been category A or B (FAA, ASIAS data, 2010).

Figure 2.1: Incursions at major airports 2004-2008
(Source: GAO, Testimony Before the Subcommittee on Aviation, Committee on Transportation and Infrastructure, House of Representatives, Aviation Safety, 2008)
2.3. Hot-Spots

The ICAO defines an Incursion Hot-Spot (HS) as “a location on an aerodrome movement area with a history or potential risk of collision or runway incursion and where heightened attention by pilots/drivers is necessary” (ICAO, Manual on the Prevention of Runway Incursions, First Edition, 2007). There are currently approximately 50 airports with Hot-Spot brochures developed prior to the adoption of the ICAO definition. The FAA has added Hot-Spots to National Aeronautical Charting Office (NACO) diagrams to bring attention to movement areas that have previously contributed to the occurrence of runway incursions. The Airports Diagram Order JO7910.4D makes identification of hot spots standard and mandatory. The FAA has identified 23 airports as potential candidates to receive official hot spot markings on their respective NACO diagrams (FAA, Annual Runway Safety Report, 2009).

As of September, 2011, 11 hot-spots have been identified at ORD (figure 2.2). The changes that will be brought about to the airport layout after the OMP will eliminate only some of the hot-spots shown in the diagrams above. Some prominent intersections like HS 2 and HS 8 will remain the same with no changes projected with the runway-runway intersection and the apron design respectively. Although the post-OMP hot spots have not been officially identified by the FAA and NACO, the construction of new runways, especially 9C-27C and 10C-28C, clearly indicate potential hot-spots. These intersections will involving a higher density of traffic converging at high speeds, thereby increasing the risk of an incursion. Hence, it can be concluded that the number of incursion hot-spots at ORD will not decrease after the completion of the OMP.
Figure 2.2: (a) NACO airport diagram of ORD emphasizing the incursion hot spots
(Source: FAA Airport Charts website)

Figure 2.2: (b) Magnified view of the highlighted (red) sub-section from Fig. 2.3 (a)
(Source: FAA Airport Charts website)
A unique way to reduce intersections and improve efficiency at a busy airport like ORD is to construct a taxiway around the end of a runway as an alternative to having aircraft cross an active runway. Continued focus on other measures, termed Alternative Capacity Enhancement Measures, can help reduce delay without substantial investment (FAA, Engineering Briefing No. 75, 2007).

2.4. End-Around Taxiways (EATs)

By definition, EATs are taxiways that are constructed around a runway. They allow an aircraft unrestricted taxiing to the terminal rather than having aircraft hold and cross an active runway. The time taken to the runway is a variable depending upon the number of aircraft in arrival/departure queue, the distance between them and the category of the aircraft (in order to adhere to ground separation standards). Figure 2.3 shows an EAT that was used by NASA to analyze its effects and simulate traffic patterns.

![Figure 2.3: End-Around Taxiway screenshot at ORD acquired from a NASA simulation](Source: NASA SimLabs, 2009)
Aircraft using perimeter taxiways generally taxi farther and experience longer unimpeded taxi-times than aircraft on conventional taxiways. Perimeter taxiway advocates argue that these negatives are offset by reduced potential for runway incursions due to fewer required clearances (i.e. reduced frequency congestion), increased runway throughput, potential fuel and emissions savings due to non-stop taxi flows.

In accordance with the Safety Risk Management Document (SRMD) for departure-end EATs, application of these standards is limited to airports with “greater than 150,000 departure operations and greater than 10,000 minutes of delay annually” (or approximately the 30 largest airports), which qualifies ORD (FAA, Engineering Briefing No. 75, 2007). A national standard for EATs for the arrival end of the runway (under approaching aircraft) is under development but not yet available. Through the runway safety management strategy, the implementation of perimeter taxiways as a form of improved infrastructure has been highlighted in the FAA Annual Runway Safety Report for FY 2009 to improve the physical safety infrastructure at airports.

2.4.1. Best Practices

Hartsfield-Jackson Atlanta International Airport (ATL) is the busiest airport in the world in terms of aircraft operations. In June 2006, the airport opened a new runway. In April 2007, it became the first airport in the U.S. to install an EAT, eliminating about 612 runway crossings per day (ATL website http://www.atlanta-airport.com/).

Dallas/Ft. Worth International Airport (DFW) is the third busiest airport in terms of aircraft operations. The airport has approximately 1,700 runway crossings a day with some aircraft required to cross two runways to get to the terminal environment. Significantly reducing the number of daily runway crossings has the potential to reduce the chance of aircraft getting too
close to each other. A perimeter taxiway went operational at DFW in December 2008. Between December 2008 and March 2009 there were 2 runway incursions at DFW (figure 2.4 (a)). This represents a decrease of 50 percent when compared to the same time period in the previous year. Also partly responsible for this statistic was the FAROS system working in conjunction with ASDE-X to monitor the entire runway surface as opposed to monitoring specific zones on the airfield.

The movement area taxi-time analysis was performed at DFW to determine how use of the perimeter taxiway affected overall taxi-times. Local-level (comparison of pre-EAT and post-EAT times for that particular taxiway) results show taxi-times via the perimeter taxiway to be about forty-five seconds longer on average, but with significantly less variability. Global-level (change in overall airport taxi-times) results show average perimeter taxiway times to be a little more than one minute longer with variability that is comparable to that for other taxi paths (Engelland S. et al, 2010).
2.4.2. Limitations

The use of the perimeter taxiway is constrained by flow direction and aircraft tail height. The maximum tail height of 65 feet would not permit the use of the EAT by an Airbus A380 (figure 2.4 (b)). Also, current FAA policy established by the Airport Obstructions Standards Committee (AOSC) (FAA, AOSC 2004, 2005, 2006) permits only departing aircraft to overfly an operational perimeter taxiway. These constraining factors have been accounted for in the simulation setup which is discussed in detail in the following chapter.
Chapter 3

Theoretical and Experimental Setup

3.1. Taxi-Time

Based on ground movement theory, taxi-time can be defined as the sum of unimpeded taxi-time and variable waiting time (Smeltink, 2004). Unimpeded taxi-time is defined as the uninterrupted taxi-time from the gate to the runway threshold or vice-versa. This component is a function of:

- The path chosen
- The path distance
- Speed of the aircraft

Variable waiting time is the sum of the waiting time due to traffic flow management constraints, excess demand, imprecise planning and uncertainty. It is a function of:

- The number of conflicts
- The type of conflict
- Separation standards
3.2. Path Selection

It is important to ensure that aircraft follow a permitted route. If the route for each aircraft is pre-determined, the ground movement problem is reduced to finding the best possible schedule (Smeltink, 2004). The other extreme occurs when no restrictions are set for the routing of each aircraft. The last possibility is for the restrictions to lie somewhere in between these extremes, where there is a predefined set of routes for each aircraft and the algorithm can choose amongst them (Pesic, 2001).

The paths for each aircraft were selected in conformance with the airport layout plan for ORD after the completion of the OMP. Each path or taxiway had a fixed distance; hence the unimpeded taxi-time for an aircraft on a particular taxiway is a constant. The path, once chosen, would not be altered. Therefore, the component of an ‘unpredicted response to an existing plan’ was minimized. The path selection is also dependent upon the runway and gate assignment. The runway and gate assignment here was based on availability. Hence, the component of ‘additional waiting time caused by imprecise planning’ was minimized too. In other words, neither potentially available runway/gate slots were wasted nor aircraft were assigned unavailable/occupied runways or gates.

3.3. Aircraft Categories

Aircraft were divided into three weight categories:

- **Large aircraft**: gross take-off weight of more than 255,000 lbs. Examples: long range transport and cargo aircraft like the MD-11, B757, B747, A330, A340, etc. Note: The A380 was not used during the simulation since it does not conform to tail height requirements for EAT use.
- **Medium aircraft**: gross take-off weight between 41,000 - 255,000 lbs. Examples: large turboprop commuters, short and medium range transport aircraft like MD-80, B737, A320, etc.

- **Small aircraft**: gross take-off weight of more than 41,000 lbs. Examples: all single engine aircraft, light and very light business jets, light twin engine aircraft, etc.

### 3.4. Aircraft Movement Speeds

Different aircraft require different lengths of time for taxiing. Recent research has taken this into account, modeling the speed depending either upon the type or size of an aircraft (Balakrishnan, 2007) or the kind of taxiway that is being followed. The time for making a turn must also be taken into account (Pesic, 2001). In this simulation, a maximum speed of 20 knots, 15 knots and 10 knots was used for large, medium and small aircraft respectively. An aircraft would be able to accelerate to the maximum speed only if separation standards were met. During turns, regardless of turn angle, a 5 knot speed was applied to aircraft of all categories. The only exception to this rule was high-speed exit taxiways used by aircraft to exit the runway in an expedited manner. The speed on these taxiways for all aircraft categories was the speed that it decelerated to before turning onto the taxiway. It was approximately calculated to be an average of 9 knots for all arriving aircraft.

### 3.5. Separation Standards

It is crucial that aircraft do not conflict with each other and have a separation based on their size and jet blast. This is ensured during take-off and landing by applying separation constraints.
The arrival sequences for runway operations are important as the minimum time to avoid wake turbulence depends on the weight class of the leading and trailing aircraft. The following wake turbulence separation standards were taken into consideration in the simulation setup. The distance between the leading aircraft and trailing aircraft has been shown in nautical miles (nm).

<table>
<thead>
<tr>
<th>Arrival Separation</th>
<th>Trailing aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading aircraft</td>
<td>Large</td>
</tr>
<tr>
<td>Large</td>
<td>4 nm</td>
</tr>
<tr>
<td>Medium</td>
<td>3 nm</td>
</tr>
<tr>
<td>Small</td>
<td>3 nm</td>
</tr>
</tbody>
</table>

Table 3.1: Separation standards for arriving aircraft during the simulation

The separation standards during departure were slightly different from the arrival standards due to the nature of the operations. Controllers usually clear trailing aircraft for take-off once the leading aircraft has lifted off and is clear of the runway.

<table>
<thead>
<tr>
<th>Departure Separation</th>
<th>Trailing aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading aircraft</td>
<td>Large</td>
</tr>
<tr>
<td>Large</td>
<td>4 nm</td>
</tr>
<tr>
<td>Medium</td>
<td>3 nm</td>
</tr>
<tr>
<td>Small</td>
<td>3 nm</td>
</tr>
</tbody>
</table>

Table 3.2: Separation standards for departing aircraft during the simulation

During taxi, the required minimum distances between aircraft appear to vary between authors. For example, Pesic et al. required it to be at least 60 meters (Pesic, 2001), while Smeltink et al. required a value of 200 meters (Smeltink, 2004). Although, different regulatory authorities have different standards, taxi separation is often left up to the pilot’s discretion. In this simulation, a minimum distance of 150 meters was applied to all aircraft regardless of size during taxi. In the
event that the minimum distance was met, a conflict would occur. The taxiways were broken into smaller sub-modules to ensure that aircraft wouldn’t overtake each other.

3.6. Conflict Scenarios

A conflict usually occurs due to traffic flow management constraints. In this simulation, three types of conflicts could occur (figure 3.1):

- Two aircraft cross each other (using the same taxiway intersection at the same time);
- Two aircraft trailing each other. This will cause a conflict if the aircraft that is behind has a higher speed;
- Two aircraft taxiing towards each other on the same piece of taxiway.

Figure 3.1: The different types of possible conflicts due to loss of separation between aircraft on the ground

The conflict resolution was dependent upon the type of conflict and flow restrictions. The number of conflicts and the time taken during each conflict played a huge role in the variable waiting time, thus impacting the overall taxi-time.
3.7. O’Hare Setup

3.7.1. Air Traffic Flow

Since, the OMP will enable O’Hare to have eight runways; this creates multiple combinations for arrival and departure. OMP researchers have considered the combination of traffic flow possibilities using runways for departures, arrivals and overflow traffic. The most commonly used runway configuration will be the Alternative C - West Flow – Parallel 27s layout (Ricondo and Associates, Experimental Design for ORD Airport Layout Alternatives, 2009). By 2013, the demand level for this configuration will result in 3,169 daily operations and by 2018 it will have risen to 3,374 operations, resulting in 72 percent of average daily usage till 2018 (Ricondo and Associates, Experimental Design for ORD Airport Layout Alternatives, 2009). The arrival and departure runways were numbers in order from north to south (figure 3.2 a). Overflow arrivals and departures were assigned to the standby runway (figure 3.2 b) while an additional crosswind runway was kept unused. All aircraft navigated on a FCFS basis, i.e. no constrained position shifting was applied.
3.7.2. Ground Traffic Flow with EATs

All runway and taxiway configurations were made in conjunction with the OMP airport layout plans for ORD (Ricondo and Associates, Experimental Design for ORD Airport Layout Alternatives, 2009). Instead of arriving at gates, aircraft would arrive at gate sets. Figure 3.3 shows the virtually constructed EATs and five gate sets created based on the future ORD airport layout (circled).
A total of four EATs were virtually constructed and modeled in the simulation. With runways 9L-27R, 9C-27C and 10C-28C handling arrivals, the EATs were used by arriving aircraft on these runways. Runway 4L-22R was used only as a taxiway in this setup. Since none of the departing aircraft used the EATs, they were strictly unidirectional. Arrival runway 1 used EAT 1 and 2; arrival runway 2 used EAT 2 only; arrival runway 3 used EAT 3 only. Overflow arrivals on 10R-28L (whenever used) utilized a combination of EAT 4 and 3. This meant that the standard of using EATs only on the departure end of the runway was adhered to (section 2.4.2). Details about EAT dimensions are highlighted in section 4.5.1.
The assignment and input of the various variables discussed in this chapter play a crucial role in each replication of the simulation. It is important to note that these inputs do not encompass all real-world aspects of air traffic dynamics. The following factors are examples of variables not considered in this simulation model.

- **Weather** - Chicago has a reputation for having some of the most erratic weather patterns in the U.S. These patterns dictate the flow of traffic on many occasions at ORD. The addition of this input variable could have resulted in changes to traffic flow patterns multiple times, which would be difficult to incorporate in the simulation.

- **Variable Traffic Load** - The traffic load for the simulation was considered to be at high levels for the entire 24-hour day, whereas in reality the load changes based on rush hour.

- **Flow Pattern Changes** - Due to changes in traffic load and weather, the ATC and airport personnel decide to utilize the runways and taxiways differently. This is done circumstantially to either accommodate traffic or as a reaction to other random variables (like emergencies, high-alert levels, etc). The flow pattern was kept constant throughout all replications in the simulation.
Chapter 4

Simulation

4.1. Software

The main advantage of a simulation in the case of traffic capacity analysis is its realistic approach to modeling. Such a problem can also be solved analytically, but the results might not be applicable to real world scenarios. In this thesis, a software program called ARENA© has been used, which was initially developed as business simulation software by Rockwell Automation. Its user-friendly environment and range of functions has expanded its use in other fields. ARENA© enables demonstration of variability and dynamics of a particular system (Kelton et al., 1998) using different flowchart and data modules. ARENA© has been used to simulate a ground traffic flow meter (Nagarajan et al., 2007) and also used to model arrival flight traffic (Kim, 2008) at George Bush International Airport (IAH). Some of the main features of ARENA© are:

- Modeling of processes to define, document, and communicate.
- Simulation of the future system performance to understand complex relationships and identify opportunities for improvement.
- Visualization of operations with dynamic animation graphics.
• Analysis of how the system will perform in its “as-is” configuration and under a myriad of possible “to-be” alternatives so that results can be benchmarked and compared.

4.2. Modules

This section describes the various modules available in Arena©. The flowchart modules are used as building blocks in the simulation environment with each of them having contrasting functions. The Data Modules are mainly statistical in nature assist with input of variables and make grouped data outputs (like queue time, pre-defined schedule of flights) accessible. The purpose of each module and its specific usage in this simulation has been described below.

4.2.1. Flowchart Modules

Create: This module is intended as the starting point for entities in a simulation model. Entities are created using a schedule or based on a time between arrivals. Entities then leave the module to begin processing through the system. The entity type is specified in this module. Number of entities per creation, maximum number of entities and the frequency of creation must be specified. A variety of distributions can be used to specify the frequency like a Poisson Distribution, Exponential Distribution, Triangular Distribution, etc. In the validation phase of the simulation, a normal distribution was used while a Poisson distribution was used for the main simulation as it was over a 24-hour time period (section 4.2.3).

Dispose: This module is intended as the ending point for entities in a simulation model. Entity statistics are recorded before the entity is disposed. Only one Dispose module was utilized in the very end of the simulation.
**Decide:** This module allows for decision-making processes in the system. It includes options to make decisions based on one or more conditions (e.g., aircraft category, assigned gate, etc.) or based on one or more probabilities (e.g., 75 percent true; 25 percent false). Conditions can be based on attribute values (e.g., Emergency landing), variable values, the entity type, or an expression. There are two exit points out of the Decide module when its specified type is either 2-way Condition (an “OR” function). There is one exit point for “true” entities and one for “false” entities. The Decide Module was placed at various junctures in the simulation setup to enable path selection. The path selection was based on input variables (assigned gate or runway) given at the beginning of the model after entity creation.

**Assign:** This module is used for assigning new values to variables, entity attributes, entity types, entity pictures, or other system variables. Multiple assignments can be made with a single Assign module. For example: Destination, Entity type (arriving or departing aircraft), Aircraft Category, etc.

**Record:** This module is used to collect statistics in the simulation model. Various types of observational statistics are available, including time between exits through the module, entity statistics (time, aircraft type etc.), general observations, and interval statistics (from some time stamp to the current simulation time). A count type of statistic is available as well. Tally and Counter sets can also be specified. It is a very useful tool to calculate number of aircrafts passing through a taxiway or busy intersection.

**Assign-Record:** A combination of both these functions determines the taxi-times. For example: When assigned “Taxi-time TNOW”, the stopwatch begins for each entity and when assigned “record taxi-time STOP”, the taxi-time from TNOW to STOP is calculated.
**Process:** This module is intended as the main processing method in the simulation. Options for seizing and releasing resource constraints are available. Additionally, there is the option to use a “sub-model” and specify hierarchical user-defined logic. The process time is allocated to the entity and may be considered to be value added, non-value added, transfer, wait, or other. This function was used exclusively for all six runways. The command “Seize Delay Release” in the Process block would enable queuing of aircraft before the runway process. Only one entity can use a process at a given time. The Process Module combines well with various Data Modules to quantify sets, delays, waiting time, conflicts and other variables (if needed).

**Station:** The Station module defines a station (or a set of stations) corresponding to a physical or logical location where processing occurs. If the Station module defines a station set, it is effectively defining multiple processing locations. The station (or each station within the defined set) has a matching activity area that is used to report all times and costs accrued by the entities in this station. This function was used for all intersections and gate-sets. At certain Stations, a constraint could be applied restricting the usage of that Station by a single entity only. This characteristic was very useful in the case of tarmac intersections and gates.

### 4.2.2. Data modules

**Entity module:** This data module defines the various entity types and their initial values in a simulation. A live list of created, currently existing, disposed entities was available using this function.

**Queue module:** This data module may be utilized to change the ranking rule for a specified queue. The default ranking rule for all queues is First-Come-First-Served unless otherwise
specified in this module. There is an additional field that allows the queue to be defined as shared. This module was quite useful in identifying conflicts and could provide real-time data about existing queues, the entities involved in them and the elapsed queue time.

**Variable module:** This data module is used to define a variable’s dimension and initial value(s). Variables can be referenced in other modules (e.g., the Decide module), can be reassigned a new value with the Assign module, and can be used in any expression. A list of variables and a tabular list of statistics was accessible throughout the simulation.

**Schedule module:** This data module may be used in conjunction with the Create module to define an arrival schedule. Additionally, a schedule may be used and referenced to factor time delays based on the simulation time. The schedule function was not used in this simulation, but it can be used to replicate any known transit timetable.

**Set module:** This data module defines various types of sets, including resource, counter, tally, entity type, and entity picture. Resource sets can be used in the Process modules. Counter and Tally sets can be used in the Record module. This function is useful to group entities with similar properties, for example, aircraft with more than 10 minutes of queue delay.

### 4.2.3. Distribution

ARENA© contains a set of built-in functions for generating random numbers from the commonly used probability distributions. Each of the distributions in ARENA© has one or more parameter values associated with it. These parameter values must be specified to define the distribution fully. The number, meaning, and order of the parameter values depend on the distribution.
4.3. Model Architecture

This section described the architectural outcome of module combinations. The structure attempts to mimic a full-scale tarmac (runways, taxiways, intersections, gates) setup of ORD. The simulation was divided into 6 sub-models, each having its own set of logical operations. Entity statistics were recorded at during every phase. The specifics within each sub-model, algorithms and processes have been explained below.

4.3.1. Create/Assign Logic

This phase mainly involves creation of entities and assignment of various variables (figure 4.2). During the creation {Module: Create}, entity statistics (entity count, frequency of entities) were recorded. The variables were assigned {Module: Assign 1} in the following order: aircraft category (large, medium, small), aircraft approach speed (based on aircraft category), aircraft taxi
speed (also based on aircraft category), an airplane picture (for animation purposes) and stopwatch (to record time $T_{NOW}$ – can be combined with any Record module, see section 4.2.1).

Upon assignment of all variables, the aircraft were allocated {Module: Decide 1} to one of two initial zones – the airspace or the gate-set. The entities were evenly distributed amongst both zones based on chance, i.e. 50 percent probability of assignment. This was done in order to populate the airspace and airport to enable interfacing during taxi.

![Process Flowchart](image)

**Figure 4.2: The process flowchart for create/assign logic**

Each zone had 5 different sub-zones. An aircraft could be assigned one of 5 gate-sets {Modules: Station 1-5}. Once assigned a gate-set, an aircraft would be transferred to the gate logic architecture and be classified as a departing aircraft. In the case of the airspace, 5 sub-zones {Modules: Station 6-10} were created in order to evenly space out the aircraft. Once in their respective airspace areas, the aircraft would be assigned {Modules: Assign 2-6} an arrival
runway and an arrival gate. All the aircraft would then progress to the airspace {Module: Process 1}.

### 4.3.2. Approach/Arrival Logic

This phase comprises of the entire approach process and ends when the aircraft completes the landing process, i.e. turns onto a taxiway (figure 4.3). As seen in section 4.3.1, the aircraft were assigned arrival runways and arrival gates. Each aircraft would enter the approach corridor {Modules: Process 2-4} from the airspace depending on the assigned runway {Module: Decide 2}. Following a successful approach, the aircraft would land on the designated runway {Modules: Process 5-7} and reduce speed in order to turn onto a taxiway. In the event that an aircraft would execute a ‘missed approach’ or a ‘go around’ {Modules: Decide 3-5}, it would be redirected to the airspace {Modules: Process 8-10}. The time taken for the approach process was dependent upon the aircraft category and wake vortex separation standards (section 3.5). At the end of approach logic, every entity would directly enter the taxi logic (without exceptions).

![Figure 4.3: The process flowchart for approach/arrival logic](image-url)

Figure 4.3: The process flowchart for approach/arrival logic
4.3.3. **Taxi Logic (Arrival)**

Considering the motive of this thesis, this is the most crucial phase in the entire architecture. It comprises of numerous taxiways – high-speed exit taxiways, EATs and regular taxiways (figure 4.4). The aircraft land on their designated runways and begin taxiing to their assigned gates. All the aircraft use designated taxiways based on their assigned gates.

Upon completion of the landing process on the runway, two variables are assigned:

- TNOW for calculating the taxi-time by placing a ‘Module: Record’ at the end of the taxi logic at the gate.
- The taxi path that an aircraft must take in order to get to its designated gate. The path is based on real-time feedback, i.e. if one of the taxiways that the aircraft is supposed to take has a queue or bottleneck, the aircraft is given an alternate taxiway path. The path, however, once assigned cannot be changed. The use of EATs was made mandatory for all arriving aircraft that needed to cross a runway.

![Figure 4.4: The process flowchart for a part of the taxi logic](image)
Upon landing, the aircraft then takes the first possible taxiway. In this case we will assume it is taxiway 9 (Module: Process 11). At any given intersection (Module: Decide 6), the aircraft is directed towards the path that will lead it towards its final destination. Unlike the Module: Decide 1 shown in section 4.3.1, the logic of this module is based on condition. In this case the condition that it follows is the destination gate of the aircraft. Hence, if the aircraft was going towards gate-set 2, it would take a particular path (taxiway 10) (Module: Process 12), if it was going towards gate-set 3, it would be directed to taxiway 11 (Module: Process 13) or finally, if it was going to gate-set 4 via taxiway 6 or taxiway 12, it would take the third possible option (Module: Process 14). Taking this option could lead to another intersection (Module: Decide 7), which would lead to either taxiway 6 (Module: Process 15) or taxiway 12 (Module: Process 16). The entire taxi logic architecture consisted of numerous complex combinations of taxiways (process modules) and intersections (decide modules). Please note that the architecture presented in figure 4.5 is just one of many logical combinations that were used in the simulation. The taxi logic ends when the aircraft completes the process on the final taxiway/apron leading to its gate.

4.3.4. Gate Logic

In this phase (figure 4.5), the aircraft reach their gates, are assigned new variables for departure (departure runway and taxi path) and begin pushback. When an aircraft arrives at the gate via the final taxiway/apron (Module: Process 17), the taxi-time is immediately recorded (Module: Record 1) in combination with the TNOW function used in section 4.3.3. Following arrival at the gate, a wait time was applied to each aircraft for unloading, loading, maintenance, etc. This time varied between 15 minutes and 90 minutes depending on the aircraft category and included a random delay time (Module: Process 18). The aircraft then begins the pushback process upon which the TNOW variable (Module: Assign 7) is assigned once again in order to begin calculation of the taxi-time. In addition, the aircraft is assigned its departure runway and
taxi path. Following the assignment of variables, the entities proceed to the taxi logic once again via pushback {Module: Process 19}.

![Diagram of taxi logic](image)

**Figure 4.5: The process flowchart for gate logic**

### 4.3.5. Taxi Logic (Departure)

The basic principles in the taxi logic during departure are the same as arrival. Since the taxiways were unidirectional, different sets of taxiways were used in the departure and arrival phases, but their intersections created conflicts (section 3.6). The phase begins once pushback is completed and ends when the aircraft makes the final turn onto the designated departing runway. This results in the ‘Module: Record’ being used again to calculate the departure taxi-time.

### 4.3.6. Departure/Ascent Logic

This is the last phase before an entity is terminated. The aircraft would take-off on their designated runways. The take-off (process) time would depend upon the aircraft category and departure separation standards applied. Once clear of the runway, the entity would be randomly directed to a post-departure airspace before being disposed.
4.4. Model Validation

In order to assess whether the results of the full-scale simulation are tangible, a model validation simulation was conducted. Low traffic levels were used in order to ensure that the unimpeded taxi-times were comparable. The validation used the current (pre-OMP) configuration at ORD.

4.4.1. Input Parameters

Based on the annual average taxi-times for arriving and departing aircraft at ORD in 2009, a one-hour slot was considered as a benchmarking unit. The FAA ASPM and OPSNET databases were accessed to retrieve data pertaining to traffic patterns and taxi-times at ORD. The date and time slot most representative of low traffic load for that year was the 11pm – 12am slot on the 15th of May, 2009. During the hour, there were 32 landings and 43 take-offs (FAA ASPM Database). The following parameters of the current ORD layout were used as input in the ARENA© software:

- Dimensions of the taxiways, gates, runways and aprons for pre-OMP configuration (ORD master-plan created by Ricondo & Associates, OMP Website 2011)
- A Normal distribution was used for the validation with approximately one entity created per minute representing a low-key hour at ORD (FAA OPSNET database). Note that all entities once created do not congregate in the airspace, as a substantial portion spawn as departure aircraft at gates (section 4.5.2).

4.4.2. Validation Results

A total of 81 entities were created, 35 landings and 44 take-offs occurred during the simulation hour. The throughput of arriving and departing entities in the simulation was relatively accurate to the real-world data. For each entity, simulation entry time, simulation exit time,
arrival taxi-time, departure taxi-time and waiting time were recorded. The arrival time calculated was the taxi-time from touchdown on the runway until the aircraft docks with the gate. The departure time calculated was the taxi-time from gate pushback until takeoff. Results (table 4.1) show that the model exhibits a positive error in the range of one to two percent. Compared to real-world data, the model exhibited +1.4% for arriving aircraft and +1.7% for departing aircraft. Since the difference between the real values and the simulation taxi-times were quite marginal, the validation was considered successful to proceed to the main simulation.

<table>
<thead>
<tr>
<th>Taxi-Time Validation Elements</th>
<th>Arrivals</th>
<th>Departures</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 Annual Average (m:sec)</td>
<td>9:56</td>
<td>17:23</td>
</tr>
<tr>
<td>Real ORD Low Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11pm-12am 15th May 2009 (m:sec)</td>
<td>7:57</td>
<td>10:50</td>
</tr>
<tr>
<td>Model Validation for Low Load (m:sec)</td>
<td>8:04</td>
<td>11:01</td>
</tr>
<tr>
<td>% Error - Real vs Model</td>
<td>+ 1.4</td>
<td>+ 1.7</td>
</tr>
</tbody>
</table>

Table 4.1: Comparison of various taxi-time elements used for the model validation

4.5. Main Simulation

The full-scale simulation was conducted using the post-OMP configuration of ORD. In addition, four virtually constructed EATs were added to the simulation. Since the validation phase yielded results with low error, the main simulation was conducted thereafter. Unlike the model validation, this phase involved the transition of entities through the virtual airport system over the period of 24 hours.
4.5.1. Input Parameters

The following input data was used:

- All airport layout parameters including taxiways, gates, runways and aprons were post-OMP configuration (Ricondo & Associates, OMP Website 2011)
- Dimensions of virtually constructed EATs were established based on FAA and ICAO regulations (AOSC data, NASA SimLabs), in accordance to which the centerline of the EAT was kept at 1,500 feet when perpendicular to the runway and 500 feet each side when parallel to the runway.
- The traffic input data was obtained from high load projections given by various OMP publications (Ricondo & Associates, 2010) (OMP Website 2011). Being most representative of the traffic projection pattern, a Poisson distribution was used for arriving and departing aircraft. Note that all entities once created do not congregate in the airspace, as a substantial portion spawn as departure aircraft at gates.

4.5.2. Entity Transit

The journey of an entity is described below along with the transit algorithm. In order to encompass the entire arrival and departure processes, an entity that was initially assigned to the airspace was chosen. The general transit algorithm is presented on the left while the individual entity characteristics corresponding to that particular module are shown on the right. The process algorithm was recorded from ARENA© on the 50th replication during the simulation of the ORD airport under high load traffic with a modified layout using EATs.

Create/Assign Logic

   Expression – Poisson (30) seconds

2. Record – Count – Number In
   Entity value: 387
3. Assign – Picture – Airplane  
   Entity value: Picture

Assign – Aircraft Category  
   Entity value: Medium

Assign – TNOW  
   Entity value: T = 0

4. Decide – N ways by chance (10) – 10%
   If N = 1...5
      Then Route to Gate 1,2,3,4 or 5
   Else Proceed to Airspace

5. Assign – Arrival Runway = 1,2 or 3  
   Entity value: 3

Assign – Destination = Gate Set 1,2,3,4 or 5  
   Entity value: Gate Set 2

6. Record – STOP  
   Entity value : T = 34 sec

7. Decide – Approach
   N ways by condition (Arrival Runway)
      If N = Arrival Runway 1
         Then Approach 1
      If N = Arrival Runway 2
         Then Approach 2
      If N = Arrival Runway 3
         Then Approach 3
   Entity value: N = 3

Approach/Arrival Logic

8. Process – Approach 3  
   Process time: 13 min 22 sec

9. Process – Arrival Runway 3  
   Process time: 2 min 8 sec

Taxi Logic (Arrival)

10. Assign – TNOW  
    Entity value: T = 0

Assign – Taxi Path

11. Process – Taxiway 19  
    Process time: 6 min 18 sec
12. Decide – Taxiway

N ways by Condition (Gate Set)

If N = Gate Set 1

Then Taxiway 20

If N = Gate Set 2, 3, 4 or 5

Then Taxiway 21

Entity value: N = Gate Set 2

13. Process – Taxiway 21

Delay – Conflict (queue)

Process time: 8 min 1 sec

14. Decide – Taxiway

N ways by condition (Gate Set)

If N = Gate Set 1, 2, 3

Then Taxiway 27

Entity value: N = Gate Set 2

If N = Gate Set 4, 5

Then Taxiway 39

15. Process – Taxiway 27

Delay – Conflict (intersect)

Process time: 3 min 56 sec

16. Decide – Taxiway

N ways by condition (Gate Set)

If N = Gate Set 1

Then Taxiway 13

If N = Gate Set 2

Then Taxiway 6

Entity value: N = Gate Set 2

If N = Gate Set 3

Then Taxiway 12

If N = Gate Set 4 or 5
Then Taxiway 47

17. Process – Taxiway 6  
   Process time: 1 min 39 sec

18. Record – STOP  
   Entity value: T = 19 min 54 sec

Gate Logic

19. Process – Gate
   Delay – Random  
   Process time: 49 min 22 sec

20. Assign – Departure Runway = 1, 2 or 3
   Entity value: 2
   Assign – Taxi Path
   Assign – TNOW
   Entity value: T = 0

Taxi Logic (Departure)

   Process time: 2 min 3 sec

22. Decide – Taxiway

   N ways by condition (Departure Runway)
   If N = Departure Runway 1
      Then Taxiway 3
   If N = Departure Runway 2 or 3
      Then Taxiway 46
   Entity value: N = 2

23. Process – Taxiway 46  
   Process time: 2 min 9 sec

24. Decide – Taxiway

   N ways by condition (Departure Runway)
   If N = Departure Runway 1
      Then Taxiway 13
   If N = Departure Runway 2 or 3
      Then Taxiway 47
   Entity value: N = 2

25. Process – Taxiway 47
Delay – Conflict (queue)

Delay – Conflict (intersect) Process time: 3 min 31 sec

26. Decide – Taxiway

N ways by condition (Departure Runway)

If N = Departure Runway 1

Then Taxiway 27

If N = Departure Runway 2 or 3

Then Taxiway 39 Entity value: N = 2

27. Process – Taxiway 39

Delay – Conflict (queue) Process time: 4 min 8 sec

28. Decide – Taxiway

N ways by condition (Departure Runway)

If N = Departure Runway 2

Then Taxiway 40 Entity value: N = 2

If N = Departure Runway 3

Then Taxiway 41

29. Process – Taxiway 41

Delay – Conflict (queue) Process time: 10 min 32 sec

30. Record – STOP Entity value: T = 22 min 23 sec

Departure/Ascent Logic

31. Process – Departure Runway 2 Process time: 3 min 57 sec

32. Process – Ascent 2 Process time: 8 min 51 sec

33. Record – Count – Number Out Entity value: 361

34. Dispose – Entity (Aircraft)

Algorithm 1: The Process Algorithm Comprising of all phases and logical operations in the ORD simulation with the modified EAT layout using ARENA©
The algorithm shown above depicts the transit of a random entity from creation to disposal. The creation of the entity (or aircraft) follows a Poisson expression (Step 1), this being the 387th entity to enter the simulation (Step 2). They are assigned several values (Step 3), including aircraft category. The aircraft are assigned an origin value (Step 4), either one of the five gate sets (50 percent probability) or towards the airspace (50 percent probability), ensuring that the system is populated. In this case, the aircraft is directed to the airspace and then assigned Arrival Runway 3 and Gate Set 2 (Step 5), determining the approach it will take (Step 7). The entire create/assign process is timed (Step 6) to ensure that it remains at a negligible percentage of the simulation time. The entire approach/arrival process (Steps 8 and 9) was timed at a little more than 15 minutes.

Upon landing onto the runway, the taxi path is assigned and the taxi-time calculation begins (Step 10). The aircraft taxis onto the EAT/ taxiway 19 (Step 11), followed by taxiway 21 (Step 13), taxiway 27 (Step 15) with a delay and finally taxiway 6 (Step 17) leading to Gate Set 2. Before taking each taxiway, the entity decides (Steps 12, 14 and 16) its next course based on the pre-assigned taxi path when it arrived (Step 10). Each conflict is defined (queue, intersect or head-on) and accounted for in the total taxiway process time.

Once at the gate, the taxi-time is calculated (Step 18), which is slightly under 20 minutes in this case and the aircraft begins the turn-around process at the gate with a random delay (Step 19). During the turn-around period, which is a little under 50 minutes for this entity, the new values (departure runway, taxi path) are assigned (Step 20). The calculation of the taxi-time begins once again through the various taxiway combinations (Steps 21, 23, 25, 27 and 29) that the aircraft takes to taxi to Departure Runway 2. In this departure sequence, the aircraft faced various forms of delays and conflicts at multiple intersections (Steps 22, 24, 26 and 28) through its pre-assigned
path. The final conflict was in excess of 10 minutes queuing for the departure runway. The delay occurred on the ramp which is shared by departure runways 2 and 3, transforming it into a bottleneck during high traffic scenarios. The entity records a taxi-time of 22 minutes and 23 seconds (Step 30) before moving on to the departure process (Step 31) and ascent process (Step 32). After being counted as the 361st entity (Step 33) exiting the simulation, it is disposed (Step 34).

4.5.3. Summary of Computation

During the simulation, there were two primary statistical computations occurring: counting of entities and calculation of process times.

**Entity Count:** To ensure that an accurate number of entities entering or exiting a system or sub-system was known at any given time, counters were placed at their entry and exit points. In this case, the system is the entire simulation environment while a sub-system can be the airspace, any of the runways or any of the gate-sets. For most critical modules (Process, Create, Dispose, Station, Decide), in-built counters existed. The Record module was used to keep live count for other modules.

**Process-Time:** The computation of process times was conducted using a combination of the Assign and Record modules. Using the Assign module, a command “TNOW” was given to entities. The basic function of this command was to initiate recording of time until the Record module is reached and the “STOP” command is given. Hence, the process time is defined as the time from when the “TNOW” is applied until the “STOP” command is used. This pair of commands was utilized throughout the simulation to calculate taxi-times, runway occupancy times, gate turnaround times and delays (due to conflicts).
**Resultant Output:** The run time of the simulation was for 24 hours or 1440 minutes for ORD. A speed of 100X was applied to each run producing a simulation time of 14 minutes and 40 seconds per replication. 100 replications were conducted in total, all of which were successful. A total of 1,893 entities were created using the Poisson distribution. During the 24-hour period, 708 landings and 1,035 take-offs occurred. During the simulation, the above mentioned computations were conducted to record entity count and process-times. At the end of the simulation, the following statistics were made available using the Data Modules (section 4.2.2).

- Overall Simulation count of entities entering and exiting the system.
  Modules used: Create, Dispose

- Count of entities for each process, station and decide module.
  Modules used: Record, Process, Station, Decide, Queue

- Tabular data of process-times for all entities in all processes, stations and delays.
  Modules used: Process, Assign-Record, Queue

- Tabular data of process-times for all entities from arrival runways to gate-sets.
  Modules used: Assign-Record

- Tabular data of process-times for all entities from gate-sets to departure runways.
  Modules used: Assign-Record

This data was then cross-referenced and synthesized to be presented in conformity with the thesis objectives (section 1.4.2). The following chapter describes the results of the simulation and the data synthesis.
Chapter 5

Results and Discussion

5.1. Local-Level Taxi-Time Comparison

5.1.1. Concept

The local-level comparison compares taxi-times with and without the use of EATs between two points across a runway. It quantifies the difference in time required to taxi via the EAT versus the time required to taxi across the active runway.

5.1.2. Method

In order to examine the local-level taxi-times, benchmarking was conducted using start and end points on either sides of the runway crossings. As shown in figure 5.1, point A would be the origin and point B would be the end point for an aircraft taxiing across runways 9C-27C and 9R-27R, while a combination of using EATs 1 and 2 would be the benchmarking alternative. Similarly, point C would be the origin and point D would be the end point for aircraft crossing runways 10C-28C and 10L-28R, with a combination of EAT 4 and 3 acting as the benchmarking alternative. Average taxi-times were calculated for the entire 24-hour simulation.
Figure 5.1: Origin and end points used to conduct the local-level taxi-time comparisons (from figure 3.3)

5.1.3. Results

Results of the local-level comparison show an average difference of 2 minutes 41 seconds from point A to B and average difference of 2 minutes 7 seconds from point C to D. Note that the indicated time is inclusive of waiting time due to the runway being active.

![Graph showing taxi-time comparison]

Figure 5.2: Results of the local-level benchmarking depicting average taxi-times

5.1.4. Conclusion

Since all aircraft that required to cross the runway were enforced to use the EATs, the possibility of a runway conflict was eliminated. However, there is over a 50% increase in local-level taxi-times, which is quite high. The increase in taxi-times is substantially higher than at airports like DFW (see section 2.4.1), where the increase post-EAT implementation was just 45
seconds (~10%). Hence, it can be concluded that the local-level results in high traffic load scenarios do not support the implementation of EATs.

5.2. Global-Level Taxi-Time Comparison

5.2.1. Concept

The global-level comparison compares the effects of airport modifications on overall taxi-times. It is the quantitative difference between the average taxi-times using a modified EAT layout versus the current ORD configuration. For an accurate comparison, both periods analyzed must have similar traffic loads.

5.2.2. Method

As a benchmarking unit, the 27th of December, 2008 was selected as it represented high traffic levels during the holiday period. The overall taxi-times for the 24-hour period were substantially greater than the average ORD taxi-times in 2008. The average arrival taxi-time during this day was 17 minutes 29 seconds and average departure time was 23 minutes 59 seconds (FAA ASPM database, 2011).

A similar high load traffic input was used in the full-scale ORD layout with EAT modifications. Input data was obtained from the FAA ASPM database, it included approximate frequencies of aircraft per runway, average turnaround times and taxi-times. After recording the taxi-times for all entities in the full-scale simulation, the average taxi-times were calculated from each gate-set to each runway and vice-versa.
5.2.3. **Results**

Results show an approximate 4 minute increase in average arrival taxi-times. For arriving aircraft, taxying to gate-sets 3, 4, and 5 were particularly problematic and time consuming. For departing aircraft, results show an approximate 3 minute increase in average taxi-times. Averages are higher for departing aircraft mainly due to take-off queues and apron conflicts (section 5.4).

**Figure 5.3:** Results of the global-level arrival taxi-times during the simulation

**Figure 5.4:** Results of the global-level departure taxi-times during the simulation
5.2.4. Conclusion

Due to the larger distances for aircraft to travel after the OMP, the high average taxi-times aren’t unexpected under high traffic loads. When compared to DFW (see section 2.4.1) which exhibited an average one minute increase post-EAT implementation, the increase in global-level taxi-times is quite high. However, the percentage increase from benchmarking is around 15% for arriving and departing aircraft. Although the taxi-times are high, the global-level results are a positive sign due to their low percentage increase (compared to local-level results) under high traffic loads.

5.3. Runway Occupancy Time

5.3.1. Concept

The runway occupancy time (ROT) is defined as the amount of time an aircraft spends on the runway, thereby making it unusable by any other aircraft. The ROT is highly dependent on the aircraft category/type (see section 3.3). The ROT is considered to be the perfect tool to examine airport efficiency (Anagnostakis et al, 2001).

5.3.2. Method

During the simulation, the amount of time that each aircraft spent on the runway was recorded. Upon comparing it with the total modeling time, the runway occupancy percentages were calculated for each runway, where 100% runway occupancy would indicate maximum utilization of the runway. It is important to note that for arriving aircraft the ROT includes final approach time, i.e. when an aircraft was on final approach, no other aircraft could use the runway.
Similarly, for departing aircraft the runway was considered to be in use until a safe wake vortex distance was achieved post-takeoff from the runway threshold.

5.3.3. Results

![Figure 5.5: The runway occupancy percentages for all arrival and departure runways](image)

The results of the ROT modeling clearly indicate that the departure runways were much more efficiently utilized compared to the arrival runways. One of the major reasons for the arrival runways being under-utilized is aircraft separation due to different size categories. In the simulation, the aircraft were directed to the arrival runways based on a First-Come-First-Served (FCFS) basis. The FCFS system corresponds to the real-world sequencing of arriving aircraft at ORD (NASA SimLabs, 2009). This creates a mix of aircraft belonging to different size categories landing on the same runway.

The sharing of the same apron between runways 10L-28R and 4R-22L created bottlenecks. Since both these runways were used for departing aircraft (section 3.7.1), long queues were
formed on various occasions leading to both runways. In this case, runway 10L-28R had more aircraft queued onto taxiways and the apron leading to it, maximizing its ROT.

5.3.4. Conclusion

Although FCFS sequencing is used in real-world queuing dynamics, applying sequence optimization techniques (Balakrishnan, 2006) could maximize arrival efficiency in this case. These techniques have not been implemented at airports yet but can impact overall airport efficiency.

For departures, the presence of separate independent taxiways or aprons leading to different departure runways is quite crucial to runway efficiency. The taxiway and apron layout was the primary reason for under-utilization of departure runways, which is a critical part of high-load airport operations. In addition to placement of EATs within airport safety minimums and regulations, the presence of EATs should facilitate traffic flow in accordance with taxiways, aprons and runways (FAA, 2007). Although the EATs did not have a direct impact on the ROT, the results show improper tarmac infrastructure would not complement the implementation of EATs.

5.4. Conflict Analysis

5.4.1. Concept

Recapping section 3.6, a conflict usually occurs due to traffic flow management constraints. In this simulation, three types of conflicts could occur:

- Intersection: Two aircraft cross each other (using the same taxiway intersection at the same time);
• Queue: Two aircraft trailing each other. This will cause a conflict if the aircraft that is behind has a higher speed;
• Head-on: Two aircraft taxiing towards each other on the same piece of taxiway.

5.4.2. Method

Process or Station Modules were used to virtually portray taxiways, gates, aprons and intersections. A constraint was applied making the module available only to one entity at a time. A conflict was identified when a delay process occurred around a module with this constraint. By comparing the directions of the entity using the module and the entity approaching it (and stopping), the conflict could be classified as a head-on, intersection or queue.

For the sectional analysis based on taxi location, the airfield was broken down into runway area, gate area and en-route taxiways. The runway area encompassed the runways, high-speed exit taxiways and EATs while the gate area encompassed the apron connecting the gate to the main taxiways. The rest of the taxiways between the gate and runway areas were classified as en-route taxiways.

5.4.3. Results

During the simulation, a total of 1,040 conflicts occurred, most of which were of the queuing type (figure 5.6). There were no head-on conflicts due to the unidirectional nature of all taxiways and runways. The majority of the conflicts were queues (81%) while intersection conflicts occurred 19% of the time. A further analysis on queue and intersection conflicts has been conducted to determine their location on the airfield.
Analysis of the intersection conflicts (figure 5.7 (a)) reveals that most of them occurred on en-route taxiways (83%) and the remaining near the gate area (17%). The most encouraging aspect was the absence of intersection conflicts in the runway area. This strongly points towards a reduction in the number of runway incursions, if EATs are used.
A breakdown of the queue conflicts (figure 5.7 (b)) by location validates the concern raised in previous sub-sections. With 60% of the queues near the runway area, the common apron shared by the runways 10L-28R and 4R-22L can be classified as the most problematic bottleneck in the ORD layout.

5.4.4. Conclusion

The majority of conflicts being of the queuing nature points towards the need for a much improved departure queuing mechanism. From strictly a safety perspective, the analysis shows promising results due to no intersecting conflicts occurring near the runway. This statistic indicates that runway incursions (section 2.2) are nullified with EATs.
Chapter 6

Summary and Future Work

6.1. Summary of Results

In this thesis, an experimental analysis for ground operations at ORD has been modeled. The simulation setup was based on forecasted high traffic levels using a modified EAT layout. With similar parameter selection for any other modernizing airport, efficiency results for EATs at contrasting large hubs can be achieved. A summary of results is provided below.

6.1.1. Advantages:

Increased Runway Safety: The presence of the EATs completely eliminated runway crossings (section 5.4), establishing a higher level of safety due to the reduced risk of runway incursions. A total of 1,040 conflicts were noted during the simulation, none of which were on the runway.

Acceptable Increase in Global-Level Taxi-Times: Global-level results showed a 15% increase in overall taxi-times (section 5.2). Based on the validation phase, we can assume this increase could be 1-3% more than real-world results (section 4.4). Although there are no established yardsticks to measure tolerable increases in taxi-times, a 15% rise at high traffic load can be
considered as a pro. This deduction is supported by the expected 10-15% increase in taxi-times due to EAT implementation (FAA, 2007) (Engelland S., 2010) at large hub airports.

6.1.2. Disadvantages

High Increase in Local-Level Taxi-Times: The simulation showed an increase in local-level taxi-times due to the presence of EATs. Local-level taxi-time analysis showed an average increase of approximately 2 minutes 30 seconds per aircraft, which is approximately 50% more than direct runway crossings (section 5.1).

Inefficient Runway Occupancy: The ROT analysis clearly showed that the ground movement infrastructure at ORD does not support the implementation of EATs (FAA, 2007). This resulted in poor runway usage for both arriving and departing aircraft (section 5.3).

6.1.3. Conclusion

With Next Gen progressing towards reducing separation using technology (FAA, 2010), the potential of implementing EATs at large hub airports in the NAS is still unclear. It is important to note that all the results and discussion presented in this thesis is based on forecasted high load scenarios only. The implementation of EATs is not envisioned at large hub airports catering to only medium and low load traffic throughout the day. Hence, at airports with mainly high traffic volumes, the application of EATs is subject to priorities given to individual factors like safety levels, capacity, airport efficiency and delays. At such airports, based on the results presented in this thesis, it is recommended that EATs be implemented where increase in safety levels have higher priority. For an airport like ORD with a non-singular problem (section 1.3), i.e. delays, capacity and safety, implementation of EATs would not be the optimal solution.
6.2. Future Research

The future of airport design has immense potential. As the population in major cities increases, their airports will need to expand to accommodate more aircraft in size and numbers. All large aircraft will rely on large hub airports within the NAS, while other aircraft will be more dependent on smaller and medium sized airports.

The ground expansion of hub airports is expected to be very limited due to geographical limitations. Similar to road and railroad infrastructure, these geographical limitations could encourage airport development to follow the trend of vertical expansion. Further enhancements will be made in the ARENA© model for ORD using the concepts of taxiways passing underneath the runway. Theoretically, this would eliminate runway-taxiway intersections and nullify the taxi-time on an EAT. However, a comprehensive simulation and structural analysis of infrastructure will need to be conducted to test the effects of high traffic loads. Financial and cost-benefit analyses of the construction and use of such underground taxiways will also need to be examined.

Another enhancement planned in the ORD simulation presented in this thesis will follow the progress of the SWIM technology (section 1.2). Future aircraft will strongly rely on various inputs of information from surface detection equipment and virtual queuing mechanisms. The impact of this technology on pilot/ATC decision-making can be tested. For example, when an aircraft arrives at a decision point just before crossing an active runway, using SWIM or a derived algorithm, an optimal decision can be made. The algorithm would calculate the time to cross the active runway and cross-check it with the information provided by the approaching aircraft, directing the pilot to cross the runway if deemed safe. As a result, an aircraft would not proceed to the EAT if a runway crossing was safely executable given the information provided.
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