A STRATEGIC PLANNING APPROACH FOR OPERATIONAL-ENVIRONMENTAL TRADEOFF ASSESSMENTS IN TERMINAL AREAS

A Thesis
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Aerospace Engineering

Georgia Institute of Technology
2009

A STRATEGIC PLANNING APPROACH FOR OPERATIONAL-ENVIRONMENTAL TRADEOFF ASSESSMENTS IN TERMINAL AREAS

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ACKNOWLEDGEMENTS

prospective infrastructure projects at ATL, some of which have been included in my work.

Lastly, but certainly not least important, I must recognize several family members and friends who have played an important role in my life and have supported me unequivocally:

- My father Humberto, whose lifelong dedication to aviation and incessant pursuit of excellence is the model by which I strive to build my own academic and professional life. Beyond our relationship as father and son, the passion that we share for aviation, aircraft, and all things related to flight, is our most cherished bond.

- My mother Anna Susana, who has never ceased to encourage me, knowing exactly how to say "yes you can" or "I know you can do this", and daring me to embark in difficult journeys to challenge myself when others never saw an opportunity.

- My brother Daniel, whose vocation for the arts contrasts dramatically with my own, but whose wisdom and opportune advice about the fundamental aspects of life have served to keep me centered and sane.

- Dear family members who have followed my progress closely throughout the years and who have always shared with me the joy of my academic achievements: my uncle Hernando and aunt Leyla, my cousin Andres, my uncle Hector and aunt Lucia, my grandmother Anna, and my aunt Ligia.

- My dear and closest friends who have witnessed up-close the progression of this experience, and who in time became a part of it with each word of support and encouragement: Alejandra, Bernardo, Jorge, Mauricio, Santaigo, and Erik.

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LIST OF ACRONYMS

ACARE Advisory Council for Aeronautics Research in Europe

ACES Airspace Concept Evaluation System

ACI Airports Council International

ACM Airport Capacity Model

ADS-B Automatic Dependent Surveillance - Broadcast

AEDT Aviation Environmental Design Tool

AGL Above Ground Level

AIP Airport Improvement Program

ALPA Air Line Pilots Association

ANOVA Analysis of Variance

ANSP Air Navigation Service Provider

APA Airline Pilots Association

APMT Aviation environmental Portfolio Management Tool

APU Auxiliary Power Unit

ARMD Aeronautics Research Mission Directorate

AROT Arrival Runway Occupancy Time

ARTCC Air-Route Traffic Control Center

ASAC Aviation System Analysis Capability

ASDE-X Airport Surface Detection Equipment - Model X

ASM Available Seat Miles

ASPM Aviation System Performance Metrics

ASQP Airline Service Quality Performance

ATA Air Transport Association

ATC Air Traffic Control

ATCT Air Traffic Control Tower

ATCSCC Air Traffic Control System Command Center

ATM Air Traffic Management

ATO Air Traffic Organization

AVOS Automated Vortex Sensing System

AVOSS Aircraft VOrtex Spacing System

CAEP Committee on Aviation Environmental Protection

CAFE Committee on Aircraft Engine Emissions

CAN Committee on Aircraft Noise

CAASD Center for Advanced Aviation System Development

CDA Continuous Descent Arrival

CDTI Cockpit Display of Traffic Information

CNS Communication, Navigation and Surveillance

CTRD Certified Tower Radar Display

DHS Department of Homeland Security

DoA Department of Aviation

DoC Department of Commerce

DOC Direct Operating Cost

DCIA Dependent Converging Instrument Approaches

DNL Day-Night average sound Level

DoD Department of Defense

DoE Design of Experiments

DoT Department of Transportation

DPAT Detailed Policy Assessment Tool

EDMS Emissions and Dispersion Modeling System

EDS Environmental Design Tool

EIS Environmental Impact Study

EPA Environmental Protection Agency

EPNL Effective Perceived Noise Level

ETMS Enhanced Traffic Management System

ETMSC Enhanced Traffic Management System Counts

FAA Federal Aviation Administration

FAR Federal Aviation Regulations

FESG Forecasting and Economic analysis Support Group

FIFO First In First Out

FMA Final Monitors/Aids

FMS Flight Management System

FOC Flight Operations Center

FWG Futures Working Group

GDP Gross Domestic Product

GIS Geographic Information System

GPS Global Positioning System

GSE Ground Support Equipment

HSR High Speed Research

IAP Instrument Approach Procedure

IATA International Air Transport Association

ICAO International Civil Aviation Organization

ICCAIA International Coordinating Council of Aerospace Industries Associations

IFR Instrument Flight Rules

IIWG International Industry Working Group

ILS Instrument Landing System

IMC Instrument Meteorological Conditions

INM Integrated Noise Model

IPCC Intergovernmental Panel on Climate Change

IPSA Interagency Portfolio and Systems Analysis

IRMA Interactive Reconfigurable Matrix of Alternatives

JPDO Joint Planning and Development Office

LaHSO Land and Hold Short Operations

LAAS Local Area Augmentation System

LDA Localizer type Directional Aid

LEQ Equivalent Continuous Sound Level

LL Loudness Level

LMI Logistics Management Institute

LMINET LMI Network Model

MAGENTA Model for Assessing Global Exposure to the Noise of Transport Aircraft

MECE Mutually Exclusive, Collectively Exhaustive

MEANS MIT Extensible Air Network Simulation

MLS Microwave Landing System

MMC Marginal Meteorological Conditions

M&S Modeling and Simulation

NACA National Advisory Council for Aeronautics

NAS National Airspace System

NASA National Aeronautics and Space Administration

NATCA National Air Traffic Controllers Association

NEF Noise Exposure Forecast

NextGen Next Generation Air
Transportation System

NGATS Next Generation Air
Transportation System

NPIAS National Plan of Integrated Airport
Systems

NRC National Research Council

NRP National Route Program

NTSB National Transportation Safety
Board

NTZ No Transgression Zone

OAG Official Airline Guide

OEP Operational Evolution Plan

OMB Office of Management and Budget

OPSNET Operations Network

OSTP Office of Science and Technology
Policy

PM Particulate Matter

PNL Perceived Noise Level

POM Production and Operations
Management

PRM Precision Runway Monitor

RAMS Reorganized ATC Mathematical
Simulator

RF Radiative Forcing

RHSM Reduced Horizontal Separation
Minima

RNAV Area Navigation

ROT Runway Occupancy Time

RPE Revenue Passenger Enplanements

RPK Revenue Passenger Kilometers

RPM Revenue Passenger Miles

RSE Response Surface Equation

RSM Response Surface Methodology

RTM Revenue Ton Miles

RVSM Reduced Vertical Separation
Minima

R&D Research and Development

SAGE System for assessing Aviation's
Global Emissions

SARP Standards and Recommended
Practices

SBR Standard Busy Rate

SCIA Simultaneous Converging Instrument
Approaches

SID Standard Instrument Departure

SIMMOD Airport and Airspace Simulation Model

SEL Sound Exposure Level

SOIA Simultaneous Offset Instrument Approach

SRS Same Runway Separation

STAR Standard Terminal Arrival Route

TAAM Total Airspace and Airport Modeler

TAF Terminal Area Forecast

TIPH Taxi Into Position and Hold

TFM Traffic Flow Management

TMA Traffic Management Advisor

TPHP Typical Peak Hour Passengers

TRACON Terminal Radar Approach Control

TRB Transportation Research Board

UN United Nations

VAMS Virtual Airspace Modeling and Simulation

VFR Visual Flight Rules

VLJ Very Light Jets

VMC Visual Meteorological Conditions

VOC Volatile Organic Compounds

WHO World Health Organization

WTMD Wake Turbulence Mitigation for Departures

WVAS Wake Vortex Advisory System

SUMMARY

The *air transportation system* plays a crucial role in modern society, comprising a major industrial sector as well as a key driver for adjacent economies. Moreover, it is a prime enabler of the modern way of life, characterized by access to products and services from around the world, and access to remote locations. Therefore there is a strong incentive to maintain the system and promote its growth. None the less, important challenges have plagued civil aviation, particularly the commercial aviation sector. On one hand, demand for air travel has grown dramatically and at an accelerated pace, in part due to the deregulation of airlines in 1978, providing airlines with the freedom to arrange their operational schedule freely and compete for markets. The dynamic nature of demand and its fast-paced growth contrasts with the relative rigidity of air transportation infrastructure development and the sluggish evolution of its operational architecture. The supply-demand mismatch that results has led to degradation in system efficiency, excessive delays, and substantial economic losses. This phenomenon is particularly exacerbated in the *terminal area* of major airports which have inevitably become operational choke points. On the other hand the environmental impact of air transportation, embodied primarily by the emissions and noise caused by aircraft operations, has also grown as a result of the increase in aviation activity, and has therefore become a major issue of public interest. Airport communities experience said environmental impact most intensely, particularly those associated with bottleneck airports, and thus represent a uniquely strong force opposing further expansion of air transportation in these areas where it is most needed.

Past efforts to address these challenges have been notably stovepiped and have failed to recognize the importance of the relationship between the operational nature of the system and its environmental impact. Only recently have research efforts begun to incorporate a joint view of the *operational-environmental problem* that attempts to formulate solutions accordingly. However, the state of the art has yet to answer some of the most fundamental

questions. First, the relationship between operational and environmental elements has not been quantified conclusively. Doing so is vital to understand the operational-environmental nature of terminal areas before any solutions can be considered. Secondly, many different types of solution alternatives have been proposed, such as the construction of new runways, redesign of operational procedures, introduction of advanced aircraft concepts, and transformation of airspace capabilities. However, a direct comparison between dissimilar alternatives that accounts for operational and environmental issues is rarely found, and yet remains crucial in the formulation of a solution portfolio. More importantly, the additive and countervailing interactions that different solutions have on each other are widely recognized but remain, for the most part, unknown.

Because all solutions under consideration require an extended period of time to develop and represent very large economic commitments, the selection of a portfolio demands a careful look at the future to determine the adequate measures that should be pursued in the present. In response to this methodological need, this thesis proposes a *strategic planning* approach to investigate the operational-environmental nature of the air transportation system, as well as the adequacy of solution alternatives for terminal areas in the formulation of a portfolio. The state of the art currently incorporates elements of strategic planning, but has yet to address two important methodological gaps. First, the inherent systemic complexity of airport performance obfuscates its quantitative characterization, which is paramount in attaining adequate insight and understanding to support informed strategic decision-making in the selection of terminal area solutions. Second, there is significant uncertainty about the evolution of the aviation demand and its operational context, making the use of forecasts grossly inadequate for this application. A scenario-based approach is used in its place, but the current frameworks for the generation, evaluation, and selection of an adequate scenario set currently lack traceability and methodological rigor.

To address the first gap, this thesis proposes the use of well established statistical analysis techniques, leveraging on recent developments in interactive data visualization capabilities, to quantitatively characterize the interactions, sensitivities, and tradeoffs prevalent in the complex behavior of airport operational and environmental performance. Within

the strategic airport planning process, this approach is used in the assessment of airport performance under current/reference conditions, as well as in the evaluation of terminal area solutions under projected demand conditions. More specifically, customized designs of experiments are utilized to guide the intelligent selection and definition of modeling and simulation runs that will yield greater understanding, insight, and information about the inherent systemic complexity of a terminal area, with minimal computational expense. Regression analysis leverages the creation of response surface equations that explicitly and quantitatively capture the behavior of system metrics of interest as functions of factors or terminal area solutions. This explicit mathematical characterization enables a variety of interactive visualization schemes that allow analysts and decision makers to confirm or rectify expected patterns of behavior, and to discover the unknown and the unexpected. Said visualization schemes are also instrumental in communicating, in a very direct and succinct fashion, complex relationships, sensitivities, tradeoffs, and interactions, that would be otherwise too complex to explain or communicate transparently. More importantly, this approach provides a rigorous and formalized mathematical framework within which the statistical significance of different factors or terminal area solutions can be quantitatively and explicitly assessed, primarily by means of statistical hypotheses testing of regression parameter estimates, such as the analysis of variance, or the t-statistic test.

This proposed approach does not suggest a new strategic planning process, but rather improves specific steps pertaining to performance assessments, and builds upon established practices and the recommended planning process for airports to leverage on the decades of experience supporting the existing strategic airport planning paradigm. On the other hand, the proposed approach recognizes the methodological limitations and constraints that lead to the lack of terminal area performance characterization within the strategic planning process, embodied primarily by computational constraints and unmanageable systemic complexity, and directly addresses these shortcomings by incorporating mature statistical analysis techniques into key steps of said process. In turn, the proposed approach represents a novel adaptation of the strategic airport planning process that results in greater knowledge, insight, and understanding, at a resource cost comparable to current airport planning

practices. As such, this proposed approach is demonstrated using the Atlanta Hartsfield-Jackson International Airport as a representative test case, and constitutes a contribution to strategic airport planning given that it supports strategic decision making by revealing, at an acceptable analysis and computational expense, the various sensitivities, interactions, and tradeoffs of interest in operational-environmental performance that would otherwise remain implicit and obfuscated by systemic complexity.

For the research documented in this thesis, a modeling and simulation environment was created featuring three primary components. First, a generator of schedules of operations, based primarily on previous work on aviation demand characterization, whereby growth factors and scheduling adjustment algorithms are applied on appropriate baseline schedules so as to generate notional operational sets representative of consistent future demand conditions. The second component pertains to the modeling and simulation of aircraft operations, defined by a schedule of operations, on the airport surface and within its terminal airspace. This component is a discrete event simulator for multiple queuing models that captures the operational architecture of the entire terminal area along with all the necessary operational logic pertaining to simulated Air Traffic Control (ATC) functions, rules, and standard practices. The third and final component is comprised of legacy aircraft performance, emissions and dispersion, and noise exposure modeling tools, that use the simulation history of aircraft movements to generate estimates of fuel burn, emissions, and noise.

A set of designed modeling and simulation experiments were conducted to examine the interactions between exogenous and endogenous factors, as well as their main and quadratic effect, on operational metrics such as delay, and on fuel burn as the primary environmental metrics. Results show that for a gate-hold scheme used to manage surface traffic density, the departure queue threshold features a statistically significant interaction with the increasing number of operations, but that otherwise the relative percent change in the number of operations remains as the predominant exogenous factor driving operational and environmental performance. A separate design of modeling and simulation experiments was conducted to test the statistical significance of proposed geographical regional categories that could potentially be used to classify operations and capture operational demand characteristics

such as fleet mix, time of day distribution, and arrival/departure route distribution. Results show that whereas the proposed categorization is statistically significant for a few metric of interest, marginally significant for others, and not statistically significant for most metrics, the proposed regional classification scheme is not appropriate for operational demand characterization.

The implementation of the proposed approach for the assessment of terminal area solutions incorporates the use of discrete response surface equations, and eliminates the use of quadratic terms that have no practical significance in this context. Rather, attention is entire placed on the main effects of different terminal area solutions, namely additional airport infrastructure, operational improvements, and advanced aircraft concepts, modeled as discrete independent variables for the regression model. Results reveal that an additional runway and a new international terminal, as well as reduced aircraft separation, have a major effect on all operational metrics of interest. In particular, the additional runway has a dominant effect for departure delay metrics and gate hold periods, with moderate interactions with respect to separation reduction. On the other hand, operational metrics for arrivals are co-dependent on additional infrastructure and separation reduction, featuring marginal improvements whenever these two solutions are implemented in isolation, but featuring a dramatic compounding effect when implemented in combination. The magnitude of these main effects for departures and of the interaction between these solutions for arrivals is confirmed through appropriate statistical significance testing. Finally, the inclusion o advanced aircraft concepts is shown to be most beneficial for airborne arrival operations and to a lesser extent for arrival ground movements. More specifically, advanced aircraft concepts were found to be primarily responsible for reductions in volatile organic compounds, unburned hydrocarbons, and particulate matter in this flight regime, but featured relevant interactions with separation reduction and additional airport infrastructure.

To address the second gap, pertaining to the selection of scenarios for strategic airport planning, a technique for risk-based scenario construction, evaluation, and selection is proposed, incorporating n-dimensional dependence tree probability approximations into a morphological analysis approach. This approach to scenario construction and downselection

is a distinct and novel contribution to the scenario planning field as it provides a mathematically and explicitly testable definition for an H parameter, contrasting with the qualitative alternatives in the current state of the art, which can be used in morphological analysis for scenario construction and downselection. By demonstrating that dependence tree probability product approximations are an adequate aggregation function, probability can be used for scenario construction and downselection without any mathematical or methodological restriction on the resolution of the probability scale or the number of morphological alternatives that have previously plagued probabilization and scenario downselection approaches. In addition, this approach requires expert input elicitation that is comparable or less than the current state of the art practices.

CHAPTER I

INTRODUCTION

1.1 Opening Remarks and Thesis Title Terms

Air transportation is without a doubt a paragon of technical and industrial achievement, not only embodying man's conquest of flight but essentially becoming one of the most influential industries in modern society. Aviation has been a driving force that has helped forge history and will surely continue to shape the future. However, air transportation is far from perfect; its evolution over time bears witness that there have always been gaps and challenges, that there has always been space for improvement, and that flaws and solutions will continue to surface as technological advances and society's need for air transportation continue to develop. In the last few decades air transportation has experienced dramatic growth and has consequently faced new and growing challenges. One of them is the issue of operational capacity and efficiency. As demand for air travel has increased and service providers were given the freedom to meet that demand by configuring their business operations at will, the air transportation system struggled to keep up with these elevated levels of activity. The development of air transport infrastructure and evolution of its operational architecture is an inherently slow process that contrasts with the rate at which airlines have increased their operations. Another issue is that of environmental impact, particularly in terms of how emissions and noise produced primarily by aircraft adversely affect human life, and how said emissions can contribute to climate change. Both problems exist and are readily observable across the entire operational architecture of the air transportation system. However, they are particularly exacerbated in *terminal areas*, which are comprised of airports and their immediate airspace, as well as their surrounding communities.

There are many factors driving these issues, but perhaps the most critical one is the tradeoff that exists between these two problems. There is a profound an inherent connection between the nature of operational activity in the air transportation system and the

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environmental impact that it produces. It is well known that insufficient capacity results in operational inefficiencies that cause delay, economic losses, and exacerbate the environmental impact of aviation activity. On the other hand, it is imperative to increase capacity so as to accommodate growing demand, but the increase in air traffic volumes drives the growth of the environmental footprint. This is the fundamental problem addressed in this thesis, referred to as the *operational-environmental tradeoff* of air transportation systems.

With this thought in mind, it is vital to consider carefully how operational and environmental challenges need to be jointly addressed so that progress can be achieved on both fronts. This observation has important implications regarding how different solutions are studied and treated, given that each will alter the operational and environmental behavior of the system in a particular way, and that combinations of solutions will likely feature interactions that should also be studied and measured. Otherwise, efforts will likely result in improvements for one part and degradations for the other, or will produce little improvement at a very high cost. Many different types of solutions have been proposed in the past, such as the construction of runways and airport surface, aircraft performance technologies, and new air traffic procedures and enhancements. However, proponents rarely compare them relative to one another. Rather than facilitating the study of the operational-environmental relationship, this attitude has led to a disjoint view of the problem and has impeded the successful definition of a joint solution portfolio.

There are also important temporal considerations when investigating air transportation system solutions. As mentioned before, infrastructure investment programs are fairly complex and costly processes that extend over several years, and sometimes even decades, between the identification of a problem and the full implementation of an infrastructure solution. The same can be said about technology development programs, aircraft design and manufacturing programs, or operating procedures design/redesign requiring changes in regulation and standards. Yet the evolutionary pace of modern society is relentless and unforgiving, and changes are continuously observed even while these programs are taking place. The chronological divide between performance gap identification and solution

implementation that results imposes an additional degree of difficulty on the operational-environmental tradeoff of air transportation systems. Without an appropriate methodological approach, problems identified at some point will not have a solution available for years to come. Moreover, the conditions that spawned an operational or environmental gap may change, causing the nature of the problem to evolve accordingly. By the time a solution has been implemented the problem could have grown, diminished, or otherwise changed significantly, rendering the vast investment of resources utterly useless. This problem-solution time lag calls for an appropriate methodological approach that leverages on knowledge about the air transportation system to account for potential evolutionary developments that describe notional futures, as well as the operational and environmental challenges that would result, permitting the timely identification of solution portfolios that yield desired operational-environmental performance goals. Such a methodology is *strategic planning*, which specifically addresses the matter of selecting and implementing solutions over a long time horizon.

However, strategic planning presents a critical flaw for this application. Given the considerable uncertainty associated with air transportation demand, the adoption of forecasts as a standard practice in strategic airport planning to generate depictions of future conditions has been questioned, and in many ways deemed inappropriate. A scenario-based approach has been suggested instead to manage uncertainty and risk associated with the selection of appropriate long-term strategic solutions for terminal areas. However, the state of the art lacks methodological rigor for the generation, evaluation, and selection of scenarios.

These observations reveal important methodological gaps in strategic airport planning. Relevant research questions can be formulated accordingly: What are the driving factors and interrelationships in the operational-environmental tradeoffs? How can it be assessed within the context of strategic airport planning? How can the operational-environmental performance of terminal areas be quantitatively characterized? How can a comparative evaluation of different types of terminal area solutions be conducted so as to adequately account for the operational-environmental tradeoff, their impact on the system, and their mutual interactions? How can scenarios used in strategic airport planning be rigorously

constructed, evaluated, and selected, to leverage the strategic airport planning effort? The research documented in this thesis seeks to answer these questions and addresses the aforementioned methodological gaps collectively.

1.2   Thesis Research Objectives

Based on these observations, research objectives for this thesis, from here on referred to as *Thesis Objectives*, are stated as follows:

Thesis Objective 1: To formulate the operational-environmental tradeoff with ample depth and breadth, highlighting the incentive for a joint solution portfolio and articulating the fundamental relationships at the crux of the problem.

Thesis Objective 2: To quantitatively characterize the operational-environmental performance of terminal areas by investigating the interactions between exogenous and/or exogenous factors, the sensitivity of operational and environmental performance metrics to different factors, and the tradeoffs and correlations between operational and/or environmental metrics.

Thesis Objective 3: To quantitatively characterize the effect that different solutions, and combinations thereof, have on the operational-environmental behavior of terminal areas, both in terms of solutions main effects and their mutual interactions.

Thesis Objective 4: To formulate a traceable, repeatable, and rigorous approach for the definition, generation and down-selection of future scenarios in the context of strategic planning.

Thesis Objective 5: : To demonstrate the synergistic and integrated implementation of the proposed methodological approach in a relevant and realistic sample problem

1.3   Thesis Content and Structure

To address the aforementioned research objectives, this thesis has been organized in the following way: First, the *air transportation system* is clearly defined in the final section of this chapter to avoid ontological or semantic ambiguity throughout the remainder of this

thesis document. Next, Chapter 2 introduces the operational-environmental tradeoff and presents key arguments that embody the motivation driving this research. The incentive to address both sides of the problem, particularly in a joint fashion that treats directly the existence of their interrelationship, is articulated and supported with ample information that provides a contextual background.

Chapter 3 then characterizes the operational-environmental tradeoff in three ways. First, it revisits the the thematic focus of the thesis and frames it in terms of *focus items*. Next, it illustrates the different terminal area solutions that have been proposed or implemented, and identifies major solution type families. Finally, strategic planning is identified as a fundamental approach well suited for the evaluation and selection terminal area solutions as strategic alternatives. Noting the inherent systemic complexity of terminal areas and the need to manage the multiple degrees of freedom in the strategic planning process, methodological gaps in the strategic planning framework relevant to this application are then clearly noted, specifically addressing the characterization of operational-environmental performance for the reference state, the characterization of the impact of strategic solutions on terminal area performance, and the generation and selection of appropriate planning scenarios.

Methodological improvements to performance characterization and solution impact assessment address the issue of understanding system behavior, accruing insight, and communicating that understanding transparently to others, all while observing limitations in available resources. On the other hand, improvements to scenario generation and selection address the issue of process formalism and rigor to adequately manage the gamut of degrees of freedom that are present in scenario planning. Consequently, although these three gaps exist within the strategic planning framework, the first two are addressed concurrently, whereas the third one is addressed separately.

Based on the this problem characterization, an approach to address gaps relevant to performance characterization and assessment of terminal area solutions is proposed first. This approach is articulated and presented in Chapter 4, where methodological requirements are identified and used to justify the selection of prescribed techniques and enablers

that bridge the aforementioned gaps. Additionally, the selection of the Atlanta Hartsfield-Jackson International Airport as a sample problem is discussed, noting that it serves as an illustrative application of the proposed methodology. Chapter 5 then addresses the modeling and simulation environment used to implement the proposed approach and generate relevant results. The modeling and simulation requirements are defined in terms of scope and metrics of interest, and used to select contributing modeling and simulation analyses.

The implementation of the proposed approach for improving terminal area performance characterization is presented in Chapter 6 alongside relevant results. In this chapter's discussion, relevant hypotheses are formulated in regards to the quantitative characterization of interactions between modeling parameters, sensitivities of performance metrics with respect to factors, and the characterization of operational demand. In a similar fashion, Chapter 7 presents the implementation of the proposed approach and discusses results generated to test hypotheses relevant to the quantification of interactions between terminal area strategic solutions and sensitivities of performance metrics to said solutions.

Chapter 8 then addresses the methodological gap relevant to scenario generation and selection within strategic planning. Appropriate techniques for scenario development are reviewed and used to formulate a morphological approach with which a risk-based selection method is proposed and tested. The implementation of this risk-based scenario selection method to the sample problem is also presented and discussed. Concluding remarks and promising items for future work are then addressed in Chapter 9. A number of Appendices are also provided at the end of this thesis with a wealth of supporting information relevant to various points and issues throughout the document.

In conducting the research reported in this thesis every effort has been made to follow the principles of scientific philosophy and scientific reasoning. Though an overview of this field is well beyond the practical scope of interest, it is worth noting that a hypothesis is nothing more than a contingent statement, namely, one that can be true or false. It is the duty of the researcher to conduct appropriate experiments and tests, and generate observations to support the veracity or falsity of a hypothesis.[141] However, it is possible to generate hypotheses that cannot be directly tested. Such is the case of top-level hypotheses that

make claims about the adequacy of a general approach adopted for a given problem. The adequacy of the proposed approach is demonstrated through a practical implementation, but not tested in the rigorous sense of scientific reasoning. None the less, such hypotheses can be formulated, and used to develop lower-level hypotheses that inherently contain more detailed information and are more naturally given to be directly tested through a properly designed experiment. By directly testing these lower-level hypotheses, and demonstrating the proposed approach with a practical implementation, the veracity/falcity of top-level methodological hypotheses can be sufficiently supported. Such is the approach taken for the body of work reported in this thesis.

1.4   Definition of the Air Transportation System

Before proceeding with the main sections of this document an adequate definition of air transportation system must be provided. Although many efforts are currently dedicated to the transformation and improvement of the air transportation system, and a plethora of published resources have been made available documenting past and current programs, a succinct and universally accepted definition of what the *air transportation system* is, what it entails, and what assets and services it contains, remains notably elusive. One approach at providing a candidate definition in this thesis is to examine the meaning of its constituent terms. *Air transportation* simply refers to the movement of people and goods through the air.[76] While a universally accepted definition of *system* is also lacking, one that is widely accepted defines it as "*a combination of interacting elements organized to achieve one or more stated purposes.*"[177] It follows logically that the air transportation system can be defined as *the combination of elements organized to achieve the movement of people and goods through the air.*

Though intuitive, this definition can appear to be vague as it lacks specificity in delineating the system, and hence provides little or no indication of what elements are actually considered part of it. Yet, recognizing that the definition of a system, its elements, and their relations, depends strongly on the observer's perspective, a truly universal definition for the

air transportation system that specifies constituent elements may not be possible.[1] This observation appeals to the concept of a *system-of-interest*, which is that whose life-cycle, or part of it, is under consideration by a given party.[179] Different parties will feature distinct interests and responsibilities, and thus will include and exclude a different set of elements and their relations in the definition of what constitutes the air transportation system. The concept of *enabling system* is also beneficial for this definition. An enabling system is one *"that complements a system-of-interest during its life cycle stages but does not necessarily contribute directly to its function during operation."*[179]

For instance, consider fuel production and distribution. It is evident that fuel is needed to operate aircraft, which in turn are necessary to achieve air transportation. An airport official in charge of fuel supply and reserves may very well consider oil refineries and fuel distribution infrastructure key elements of the air transportation system, given that his/her interests and responsibilities require their inclusion in the consideration of its life-cycle (or part of it). On the other hand, whereas an airline dispatcher's responsibilities are different, he/she would probably consider fuel distribution an enabling system. None the less, there would be an important subset of elements and relationships common to these two parties' definition of the air transportation system, such as aircraft, personnel, airport surface, and service vehicles.

It is therefore paramount to define what is the system-of-interest in the context of this thesis. This task is greatly facilitated by examining relevant sectors and subsystems of air transportation that have been sufficiently delineated. Two of them are of particular importance. *Civil aviation* is a sector of air transportation that *"includes all airports, airlines, general aviation, and service providers of various kinds such as air navigation, passenger-related, and airfreight services. It also includes the related manufacture and maintenance of aircraft systems, airframes and engines which are often referred to as the civil aerospace sector."*[12] Civil aviation is segmented into *commercial aviation*, which addresses operations conducted by airlines and carriers, and *general aviation*. The *National Airspace*

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[1]This may arguably be the reason why such a universal definition is difficult to find in the published literature.

System (NAS) refers to the collective set of U.S. airspace, its air navigation facilities, all airports and aerodromes, the various air traffic services provided, and all relevant human, material and information resources. Though mostly relevant to civil aviation, some resources of the NAS are actually shared and operated jointly with military bodies.[127, 65]

The system-of-interest in this thesis is defined to include all elements of commercial aviation with the exception of passenger-related services. Airlines are only considered from an operational perspective, namely, as entities responsible for the operation of a given aircraft fleet according to some schedule. Finally, and as per the definition provided, the NAS is also included in its entirety within the system-of-interest. From this point forward in this thesis document the term *air transportation system*, as utilized in the thesis title, will specifically refer to the system-of-interest defined.

CHAPTER II

MOTIVATION

2.1 Introduction

This chapter presents the issues, ideas and general arguments that altogether constitute the primary motivation for this thesis. It also serves to set the stage for the gaps, challenges and potential solutions that will be identified in later chapters as well as for the decisions, analyses, and general research efforts conducted. However, this chapter does not attempt to provide an exhaustive background on the subject matter but rather to provide a sufficiently complete picture and articulate key motivational issues balancing breadth and depth. The observations presented in this chapter transition from general to more specific, progressively narrowing down to the key concepts and issues that shape the *focused problem* addressed by this thesis. Ultimately, this chapter attempts to answer the following questions: What is the problem to be addressed? What motivates interest? Why is it difficult? Why is it important?

In answering these questions, the motivation for this thesis also tackles the first thesis objective, stated as follows:

Thesis Objective 1 : To formulate the operational-environmental tradeoff with ample depth and breadth, highlighting the incentive for a joint solution portfolio and articulating the fundamental relationships at the crux of the problem.

2.2 The Role of the Air Transportation System in Modern Society

2.2.1 Economic Impact

Air transportation plays a vital role in modern society, serving as a major economic driver and leveraging the development of adjacent industries within the global marketplace. Worldwide there are approximately 900 airlines operating a fleet of 22,000 aircraft that serve 1,670 airports and use navigation services from more than 160 providers. Estimates of this sector's economic impact are highly dependent on the set of underlying assumptions and metrics

observed, but still offer a good measure of its influence relative to other industries. As a generator of global employment and wealth, the air transport industry was responsible in 2005 for 5 million direct jobs contributing $275 billion in global Gross Domestic Product (GDP). An additional 5.8 million indirect jobs and 2.7 million induced jobs resulted in $375 billion and $175 billion of global GDP respectively.[1] The taxation of this economic activity makes aviation a significant tax payer and consequently a major contributor to government revenues. For instance airlines alone paid over US $42 billion worldwide for 2004 taxes. Most importantly, however, the economic impact of this sector lies in its role as facilitator and enabler of growth to other industries. A prime example is tourism which globally collected over $3 trillion in revenue during 2005.[12]

The United States is a global power in air transportation and key contributor to worldwide economy and trade. In the year 2000, for instance, the U.S. transported freight cargo equivalent to 40% of the international trade value (over 21.1 billion ton-miles).[225] Within a national scope the U.S. aerospace industry, which holds commercial air transport as a subset, is also recognized as a driving force of domestic economy. During 2000 it generated over $900 billion in total economic impact (approximately 9% of the GDP), and 11 million jobs. That year more than 600 million travelers were mobilized in scheduled airline flights and 150 million with general aviation services.[78] In 2001 its economic impact was approximately 15% of the GDP, and was responsible for 15 million of the estimated 127.5 million jobs across all sectors.[50, 292] A better sense of perspective and appreciation for these figures can be attained by comparing the aerospace industry with other key drivers of the U.S. economy such as the automotive sector which was responsible for 13.3 million total jobs for that same year.[216]

Within civil aviation the commercial segment has traditionally had a much greater economic impact relative to its general aviation counterpart. Economic data for 2004 [276] shown in Table 1 highlight the relative contributions among civil aviation segments and

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[1]Direct impact refers to activity within the air transport industry. Indirect impact addresses services and products supplied to the air transport industry from other sectors such as fuel or construction. Induced impact accounts for all employment that results from goods and services purchased by people directly or indirectly employed by the air transportation industry.[12]

reveal their significance relative to the total U.S. industries. Once again, comparison to other economic sectors provide a better appreciation for the relative magnitude of these figures. The figures for the U.S. motion picture and television production industry, which reported 1.3 million total jobs and \$60.4 billion in total economic output for 2005 [223], are dwarfed by those of commercial aviation reporting 11.4 million total jobs and \$1,247 billion in total economic output.

Table 1: Civil Aviation Economic Data, 2004.

	Commercial Aviation	General Aviation	Total	All U.S. Industries	Comm. Aviation % of U.S. Total
Output (Billion \$)	1,247	118	1,365	21,346	5.8%
Earnings (Billion \$)	380	38	418	7,567	5.0%
Employment (000)	11,393	956	12,349	129,278	8.8%

Considerations for economic impact are extended to specific segments within the civil aviation sector that have been identified as key financial contributors or as key players in the general performance of the system. Airports in the U.S., for instance, receive much attention given their significance to national infrastructure and local economies. In 2001 US airports generated \$507 billion in total economic output, 33.5 billion in local, state and federal taxes, and provided 6.7 million airport-related jobs equivalent to \$190.2 billion in personal earnings. Airports are also major developers of capital investment that further generates employment and spurs growth in other sectors. For example the Airports Council International (ACI) - North America capital program development survey, which tracked the top five programs for 91 U.S. airports in the 2001-2006 period, estimated a total of \$32 billion worth of capital investment.[14] Another notable example is the traffic management segment which provides various navigation services to operators across the nation. Estimates for the 2002 fiscal year indicate \$10.9 billion in total output and 90,000 total jobs. Capital investment, productivity and employment figures show that for every dollar generated by air traffic management \$2.6 were generated in other segments of the domestic economy.[68]

In brief, the impact that the air transportation system has on the global and domestic economy is well documented across its different segments, and represents a key driver whose

growth and health must be fostered enthusiastically.

2.2.2 Societal Benefits

The role of air transportation in modern society can also be expressed in terms of the benefits it provides to society as a whole. Though these benefits are tangible, they are often difficult to quantify and are often limited to qualitative and abstract observations. For instance, air transportation contributes to sustainable development by leveraging the growth of other sectors and supporting local economies . Living standards are improved as accessibility to remote areas and to products and services generated remotely broaden society's choice, thus exposing it to a broader view of the world and its cultures.[12]

Freedom of mobility, embodied in what many consider the fastest and safest form of personal and business travel, is a main component in the American quality of life.[50, 225] Recent developments in national security have placed an important responsibility on the air transportation system, particularly on airports, whose security functions ensure society's access to the rest of the world in the presence of concerted efforts to limit freedom of mobility and alter the way of life.[14]

It is not surprising that air transportation is considered part of the nation's *critical infrastructure*, defined by the the 2001 USA PATRIOT act[2] as "*systems and assets [...] so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, [and] national public health or safety.*"[57] In turn, the National Aeronautics Research and Development Policy of 2006 recognizes the crucial societal role of civil aviation by stating that "*Mobility through the air is vital to the economic stability, growth and security as a nation.*"[236]

These socioeconomic considerations about air transportation and its role in the modern world are the construct of a powerful argument in favor maintaining it and safeguarding it. Moreover they represent a particularly strong incentive for all its users, stakeholders, and society as a whole, to vigorously promote its growth and development in order to continue reaping all the benefits it brings.

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[2]The the name of the USA PATRIOT act is an acronym standing for Uniting and Strengthening America by Providing Appropriate Tools Required to Intercept and Obstruct Terrorism.[57]

2.3 Forecasted Growth of the Air Transportation System

2.3.1 Forecasts

Because of its relevance to economic development and living standards, the overall health of the air transportation system as well as the steady growth of civil aviation are subjects of much importance to numerous entities. Many key decisions, often involving vast investments over long periods of time, are made by government and private industry in support of the sector's continuous development. Though the decision-making process itself will inevitably change on a case-by-case basis, the use of industry forecasts are a common denominator. A field of study in its own right, forecasting is often conducted by leading players in the field who have access to key information needed as well as a deep understanding of the relationships between factors that govern sector growth.

The FAA Aerospace Forecast is one of the most widely known of such forecast for U.S. commercial aviation. The study is performed on a yearly basis for a period approximately 15 years into the future. The 2007-2020 forecast indicates an average air carrier capacity increase of 4.3% per year reaching 1.8 trillion Available Seat Miles (ASM). Demand, measured in Revenue Passenger Enplanements (RPE), is forecast to grow at an average rate of 3.5% a year reaching 1.2 billion in 2020. Revenue Passenger Miles (RPM), also a measure of demand, are expected to reach 1.4 trillion and to grow at an average of 4.4% per year. Air cargo demand, measured in Revenue Ton Miles (RTM), is also expected to grow significantly reaching 81.3 billion at an average 5.3% per year. Passenger travel forecast results are presented in Figure 1. This growth represents a return to pre-9/11 levels of air traffic control and management workload by the year 2012, reaching 81.1 million tower operations and 65.4 million instrument operations by 2020. [115]

The Forecasting and Economic analysis Support Group (FESG) of the International Civil Aviation Organization (ICAO) is responsible for generating another widely known forecast. Due to the transnational nature of ICAO, which works under the auspices and direction of the United Nations (UN), the FESG forecast is considered to be an authoritative document and is actively used by many entities worldwide. For instance, the Committee on Aviation Environmental Protection (CAEP), tasked with providing guidance to ICAO in

Figure 1: Carrier Capacity and Passenger Demand, FAA Aerospace Forecast 2007 - 2020
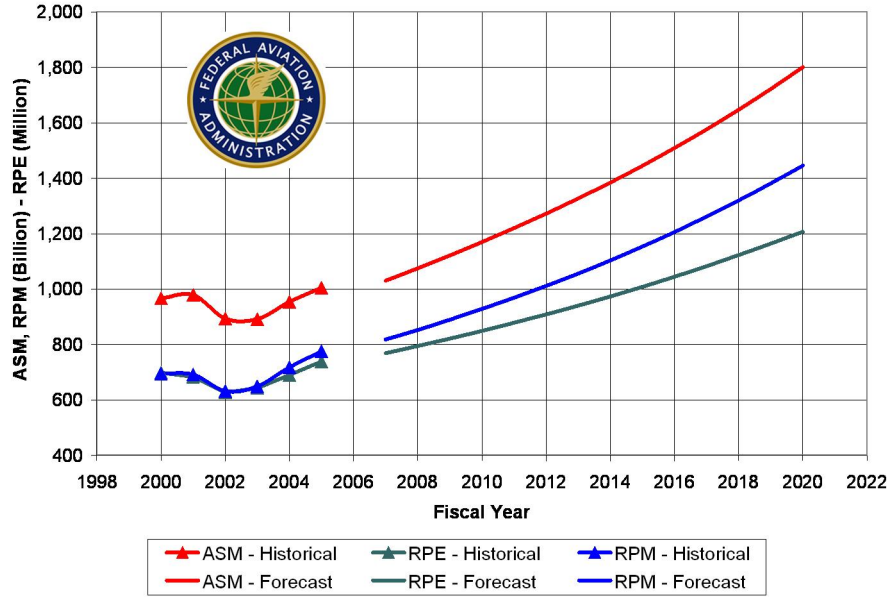
the formulation of policies and adoption of standards for aircraft noise and emissions [172], uses the FESG forecast as a basis for policy generation. The latest available version of the forecast, presented in CAEP's 6th meeting (2003), shows an expected increase in Revenue Passenger Kilometers (RPK) from 3 trillion to 7 trillion worldwide, a 4.3% average growth rate, for the 2000-2020 period.[52]

Another notable example is the trends, growth, and projections report by the International Industry Working Group (IIWG)[3]. In its revised 2007 edition global RPM are forecasted to grow about 4% annually, a trend that seems compatible with FAA estimates for the US market. [178]

The Boeing Company, global aircraft manufacturer and service provider, issues an annual Current Market Outlook report providing forecasts of sector growth and fleet mix change world wide for a 20 year period. The 2006 report (for the 2005 - 2025 period) indicates that global passenger traffic will increase by 4.9% annually. The forecast also warns

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[3]The International Industry Working Group (IIWG) is an industry organization directly supported by the International Coordinating Council of Aerospace Industries Associations (ICCAIA), the International Air Transport Association (IATA), and ACI.

about a decrease in average airplane size for the world fleet coupled with an increase in flight frequency. In North America alone it is expected that nearly 9,500 new aircraft will be delivered; of these 62% are single aisle aircraft and 21% are regional jets.[275]

While these examples are representative of the most popular and widely used forecasts for commercial aviation they are clearly not an all inclusive list of forecast studies. There is a multitude of forecast studies performed by government agencies, consulting companies and academic units which are available to the public. The key idea, however, is that significant growth in air transportation is observed as a common theme across the multitude of forecasts. This strongly suggests a very positive outlook given the economic and societal benefits of this sector and the way they would be enhanced by its growth.

2.3.2 General Considerations on Forecast Uncertainty

By definition, forecasting deals with uncertainties. It attempts to shed light onto the unknown future by using knowledge about the present and the past. Though this may be seem like an intuitive observation, end users of forecasts often underestimate how many uncertainties are involved, how they are addressed via assumptions, and how they impact the outcome of the analysis as well as its validity.

Forecasts often provide a single, deterministic solution, based on a specific combination of influencing factors considered by analysts to agree with existing trends. This common approach inherently assumes that the choice of these factors, often incorporated as assumptions, is valid based on their high probability of occurrence. For instance the FAA states in its annual Aerospace Forecast that it "*has developed a set of assumptions and forecasts consistent with the emerging trends and structural changes currently taking place within the aviation industry.*"[115] However there are combinations of other less likely values for key factors that, while generally not considered in the traditional forecasting approach, represent alternative forecasts which may be of interest to the end user.

Some studies attempt to directly incorporate the uncertainties involved in forecast analysis by providing a continuous range of values for the different estimates. A notable example is the growth forecast presented by the JPDO in the Next Generation Air Transportation

Figure 2: Range of Futures in JPDO Forecast. (Source: JPDO [191])
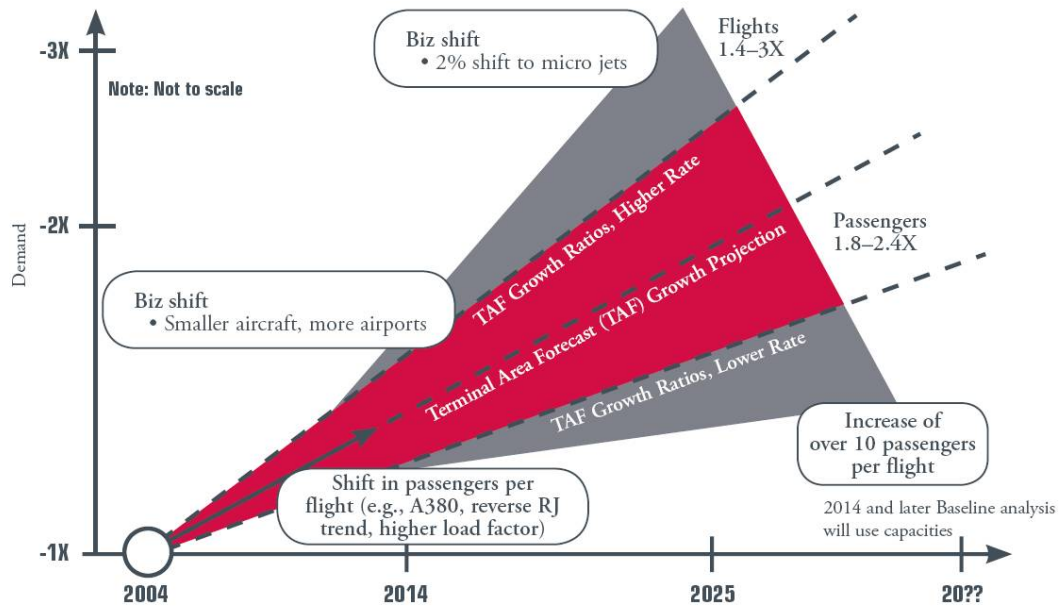
System (NGATS) Integrated Plan.[4] The forecasted growth of passenger volume and number of flights, shown graphically in Figure 2, is provided as a continuous range of values that varies over time. Using 2004 quantities as a datum the forecast states a 1.4 - 3.0 X increase in number of flights. The lower end of the estimate assumes a drastic shift to larger aircraft such as the A-380 and an increase in flight load factor (over 10 additional passengers per flight). For this extreme the increase in passenger demand would be served by a relatively low increase in aircraft operations but would impose challenging airport infrastructure requirements. The 3.0 X estimate on the other hand assumes a shift to smaller aircraft and more airports, as well as the introduction of Very Light Jets (VLJ), resulting in a relatively high increase in the number of aircraft operations.[191]

An extension to this approach is embodied by scenario-based forecasting, which replaces

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[4]The JPDO is a public/private partnership created in 2003 to manage the NGATS initiative as mandated by the VISION 100 - Century of Aviation Reauthorization Act (P.L.108-176)[56]. This partnership includes the Department of Transportation (DoT), FAA, Department of Defense (DoD), Department of Homeland Security (DHS), Department of Commerce (DoC), and the National Aeronautics and Space Administration (NASA).[190]

a continuous range of possible forecast figures with a discrete set of plausible, internally consistent scenarios. This approach has observed growing popularity, particularly in the context of strategic planning, and has been adopted by key entities such as the JPDO who adopted it in 2004 and implemented it via by the Futures Working Group (FWG).[197] ICAO has also adopted this approach recently based on observations about the many uncertainties surrounding forecasts. A CAEP document on this matter, presented in 2006 during its seventh meeting, states: *"Some CAEP members noted that there were many uncertainties, which could affect future traffic growth. For this reason, it was suggested that the forecasts include a range of possible scenarios. The FESG was assigned the task to review and maintain the CAEP traffic and fleet forecasts (as well as retirement curves and a range of possible scenarios)."*[174] While representing a rigorous approach, scenario generation faces important challenges in its practical implementation. As will be shown in later sections it is still subject to the use of assumptions and since it is traditionally based on expert opinion it is particularly affected by the lack of consensus among participant experts.

Though a plethora of methods and techniques exist for managing uncertainty in forecasting analysis, the fact is that our lack of knowledge about the future remains virtually unchanged. Notably, these methods allow analysts to *manage* uncertainty, not to reduce it or eliminate it, following what could very well be conceived as a "conservation of uncertainty law". Uncertainty is, and will remain, inherently present in forecasting, making it a difficult and treacherous science that can be described at times more like an art. It is through the careful and traceable manipulation of assumptions that many of the degrees of freedom of a forecast are reduced.

2.3.3 The Unconstrained System Capacity Assumption

Recognizing how the underlying assumptions within forecasts have an impact on their interpretation, validity, and applicability, end-users should rigorously inspect all assumptions and their implications. The *unconstrained system capacity assumption* is consistently found in all the major aviation forecasts. For instance the FAA Aerospace Forecast assumes that

"*both demand and workload are unconstrained in that they assume that there will be suf-
ficient infrastructure to handle the projected levels of activity.*" [115] Similarly the JPDO
forecast shown in Figure 2 warns that that only 2014 and later baseline analyses will use
system capacity figures for their estimates. The FESG forecast, introduced in the previous
section, also uses an unconstrained approach: "*The forecasts [...] depict the unconstrained
demand driven forecasts for the major route groups, established by the FESG. This as-
sumes, for modeling purposes, that the world aviation system (ATC and airport capacity)
could accommodate all of the projected future growth on a regional and airport basis.*"[52][5]
For the FESG forecast, the unconstrained system assumptions is justified in the following
way: "*While the demand forecast is defined as unconstrained, the future is based on cur-
rent levels of aviation activity and thereby builds in the implicit constraints under which the
industry has developed thus far. Those same constraints (slot constraints, curfews, market
regulations, etc.) are assumed to perpetuate over the forecast period.*"[52]

As will be discussed in Section 3.4.3, the development of unconstrained forecasts is an
accepted practice in strategic airport planning. The value of these forecast studies is that
they provide quantitative, traceable data measuring the *full growth potential* of the sector.
They provide a quantitative answer to the question "how much *could* the system grow?",
but fail to answer the question "how much *will* the system grow?". Unfortunately decision
makers and stakeholders continue to use forecasts without any consideration for the uncon-
strained system capacity assumption, and inevitably remain in a state of misinformation
confusing the answer to both these questions.[73]

2.3.4   Air Transportation System Capacity Defined

It is critical to establish at this point a precise definition of *capacity* for the air transporta-
tion system that shall remain for the rest of this thesis. In its most generalized form *capacity*
is defined as "*the potential or suitability for holding, storing, or accommodating [...] the
facility or power to produce, perform, or deploy. [...] the maximum amount or number
that can be contained or accommodated.*"[279] The concepts in this general definition can

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[5]Air Traffic Control (ATC)

be used to procure a more workable and specific definition for air transportation applications, such as that of the JPDO where capacity refers to "*the maximum number of aircraft that can be accommodated in a given time period by the system or one of its components (throughput)*."[192]

There are two important implications in this definition. First, capacity is a measurable quantity and as such there are units of measurement, namely *number of aircraft*. Though this is form of capacity measurement is an intuitive one, and indeed a popular one in most air transport applications, it is not the only one available. Capacity may be measured in slightly different ways, for instance, as the number of certain types of operations performed in a period of time, like takeoffs and landings per hour at an airport, the number of flights handled by an airspace sector, the number of departures coordinated by a radar departure controller, etc.

Secondly, the ability to *accommodate* aircraft is contingent not only on physical space, as may be incorrectly interpreted from the definition, but also on the availability of all other system resources needed to ensure safe and efficient air transport operations. In fact, physical space is but one of many resources that enable said operations and that hence contribute to the capacity of the system. In this spirit, system capacity is prescribed by physical space on the surface of an airport as much as it is by the airspace above an airport, air traffic controller cognitive workload, pilot workload, communication equipment bandwidth, etc. Moreover, the capacity of a part of the system may be determined by one resource, say physical space on a runway, whereas capacity at another part of the system may be determined by another resource, like controller workload on an airspace sector.

These key concepts are explicitly observed in the field of *operations management*, sometimes called *Production and Operations Management (POM)*. The study of operations such as air transportation have been, for the most part, framed within the analysis of industrial processes, and as such are inherently associated with the concepts of demand and supply. The problem of matching supply with demand to avoid losses, explained in the next section, requires that processes be adjusted accordingly. Responsibility for resource allocation to address said adjustments in industrial processes has traditionally fallen under the purview

of managers. Operations management is a field that bridges the gap between industrial engineering and management, providing a knowledge base for the analysis and solution of supply-demand matching problems in operations. Understanding that *operations* are a transformative construct, operations management "*is concerned with those activities that enable an organization (and not just one part of it) to transform a range of basic inputs (materials, energy, customer's requirements, information, skills, finance, etc.) into outputs for the end customer.*"([36] pp. 10-11)

In operations management a *process* is used to represent the generation of a product such as in a car assembly line, or the provision of a service such medical attention at a hospital. Regardless of the application, processes are modeled as a flow of *process units* that move across *process activities*. These process activities, or *resources*, are limited by their *capacity*, which is the maximum number of units that can be processed per unit time. Since a process is comprised of multiples resources, the capacity of the entire process, or *process capacity*, is that of the resource with the smallest capacity.([40], pp. 32-40)

Studying air transport operations from an operations management perspective where air transport operations are conceived as processes, the phases and parts of each operation are its process activities, and aircraft are the process units, is not only intuitive but more importantly provides a solid framework with which to analyze system capacity as well as other process phenomena such as congestion and delay.[6] Operations management also provides a wealth of parameters and techniques with which to measure system performance and generate improvement. Moreover, this perspective also explains how the capacity of the system is defined and limited by the capacity of each of its resources found throughout the taxonomy of air transport operations as indicated by the JPDO definition.

Indeed, air transportation literature defines *capacity* as the *processing capability of a service facility over a period of time* ([70] p. 215, [159] p. 294). Airports are one of such facilities and are recognized to play a critical role in air transport operations. For this reason airports are often the object of focus and attention in capacity assessments leading

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[6]There is an inherent relationship between system capacity, throughput (supply), and resulting delay or congestion for varying levels of demand. This relationship is explained with appropriate detail in Section 2.4.

to a wealth of work in this specific area. Following the aforementioned observations from operations management, an airport's capacity is known to be "*constrained by its weakest link in the chain of (1) airway capacity, (2) runway capacity, (3) apron capacity, (4) terminal capacity, and (5) surface access capacity.*"([70] p. 204) There are two capacity definitions specific for airports that have gained ample acceptance in the field. *Practical capacity* refers to a level of operational activity that corresponds to a tolerable or acceptable level of of service, often times stated in terms of delay.[7] *Ultimate* or *saturation capacity*, sometimes referred to as *maximum throughput rate*, corresponds to absolute maximum number of aircraft, passengers, and/or cargo that the airport can process regardless of the service level.([70] pp. 215, 217, [159] p. 300) Operations at an airport that fall below the acceptability threshold of *practical capacity* are a sign that additional capacity is needed. For these purposes capacity planners use *peak demand* as an indicator of capacity needs. Some standard forms of peak demand exist, such as the *Standard Busy Rate (SBR)* used primarily in Europe, or the *peak profile hour* used by the FAA.([70] p. 210, [41] p. 174, [22] pp. 31-35) However, airport planners strive to enhance capacity before unacceptable levels actually occur, and thus are continuously attempting to forecast demand levels so that when *predictions* of performance below acceptable levels are identified, strategic airport planning efforts for capacity enhancement can be set into motion.([41] p. 52)

Airport capacity is recognized to depend on a number of factors. Some of the most important ones are ([159] p. 303, [70] p. 218):

- Number, configuration, and location of runways, taxiways, and runway exits

- Runway occupancy time

- Runway operation configuration

- Number, configuration, and location of gates (terminals and concourses)

- Airspace design, configuration

- Air traffic control procedures

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[7]See Section 2.4

- Environmental controls and noise abatement procedures

- Nature of existing air traffic control facilities, navigational aids, and Communication, Navigation and Surveillance (CNS) equipment

- Fleet mix, more specifically the size of aircraft

- Existence and frequency of wake turbulence and required wake separation between aircraft (see Appendix A, Section A.3)

- Weather and wind conditions

Capacity measures have also been appropriately developed for other elements of the air transportation system. For instance, there are several sector capacity metrics for for en-route segments, such as number of aircraft under track control within the sector, normalized average flight time within a sector, and the ratio of ATC-issued altitude changes to the number of aircraft in the sector.[222] Other work has attempted to develop a single capacity value for the entire NAS in units of operations per time period, by means of a weighted average of airport capacities throughout a day's distribution of demand which is then normalized by total system demand.[308]

2.4 Supply-Demand Mismatch in the Air Transportation System
2.4.1 The Supply-Demand Mismatch Phenomenon

Supply-demand mismatch is one of the fundamental phenomena studied by a variety of fields such as economics and operations management. In its most basic formulation the laws of supply and demand predict that the quantity (availability) and price of a given resource define the equilibrium point between supply and demand. A supply-demand mismatch is a perturbation in the balance between the two forces, resulting in a departure from equilibrium. To economists the central premise is that prices and quantity adjust to match supply with demand, assuming perfect competition market conditions.([40], p. 1)

These basic laws do not provide information about the time frame in which the price adjustment takes place, nor do they contend for the relative rigidity and fluidity characteristic of the supply and demand forces. While it is acceptable to assume instantaneous

price adjustments under perfect competition, imperfect (more realistic) markets feature non-instantaneous price re-adjustments. In fact they may take a long time to occur resulting in prolonged periods of supply-demand mismatch. The consequences of this mismatch are generally recognized to be negative and undesirable. From a management perspective instances where demand exceeds supply translate to losses relative to the potential of fully met demand, i.e. lost revenues. Instances where supply exceeds demand translate to waste of resources, underutilized capacity, and poor return on investment.([40] Ch. 1, [284]) Thus there is a strong motivation to match supply and demand at all times.

Supply-demand matching is a difficult and challenging task for several reasons common to almost all operational environments and markets. The most important is that demand varies over time, often in unpredictable or in-exact ways. Supply on the other hand is usually rigid and plagued with inflexibilities driven by cost, time, and other constraints. As noted before, a large enough supply can match high demand levels but represents resource waste for low demand periods. Conversely, a lower level of supply will avoid resource waste but will lead to losses during high demand. [8] It is also recognized that variations in demand are meaningful in a relevant time frame. Demand can vary on an hourly basis, as is the case for air travel, but it may also depict gradual changes over longer time frames such as months or years. Different approaches for supply-demand matching may be more suitable for specific time frames.([40], pp. 3,4) Later sections will explain the two main approaches towards supply-demand matching, namely demand management and capacity enhancement, and show the appropriateness of their applicability for different temporal scopes. For the purpose of this section however it is sufficient to note that demand management measures, such as price adjustments, are traditionally perceived as easier to implement and thus are used for supply-demand matching in the short and medium term. For instance flights at convenient times of the day experience high demand and airlines offer seats in these flights at a higher price than others in lower demand periods. The same can be said about flights during different days of the week or during different times of the year. On the other hand

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[8]Though supply-demand mismatch is often formulated in terms resource deficits, it is not uncommon to find situations where resources are available but misallocated. Relocation of resources can also represent costly solutions that must therefore be carefully examined.([40] Ch. 1)

capacity enhancement measures, such as the purchase of aircraft or the addition of a runway, are costly, lengthy, and usually more difficult to implement than demand management. As a result these enhancements are used for long-term matching responding to the growth of a system beyond its seasonality and other short term variability effects.

In the case of the air transportation system a supply-demand mismatch can have disastrous consequences; ignoring the possibility of such a mismatch occurring is therefore a very risky proposition. For instance the unconstrained capacity supply assumption in the FAA forecast, presented in the previous section, negates considerations for a mismatch where demand exceeds supply. Yet as part of its forecast risks the FAA indicates: "*should infrastructure be insufficient [...], it is likely that the forecasts of both demand and workload would not be achieved.*"[115] Forecast risk assessments such as these strongly suggest that system capacity limitations hinder the full potential growth of air transport in the forecasted future, thus impeding the market to fully capitalize on all the economic and societal benefits associated with it. Recent studies have even estimated these losses due to unmet demand, indicating for instance that for the 2015-2025 period the anticipated capacity deficit could yield cumulative losses ranging between \$91.6 billion and \$229.4 billion.[301][9]

This point is of critical concern since the air transportation system is already experiencing, and has been for a while, a supply constrained mismatch. As will be shown in the following sections the strain experienced by the air transportation system can be evidenced by increases in congestion and delay, and degradation of safety. There is no reason to believe that a business-as-usual approach would minimize or eliminate the effects of this mismatch, but rather that an increase in demand as suggested by the forecasts would only exacerbate them.

It should be noted that entities that embody demand and supply vary with the context and point of view adopted. From a passenger perspective, demand is embodied by the traveling public, supply is embodied by airlines and other service providers, and the service/product in question is air travel. From an operational perspective, however, demand is embodied by airlines and operators who require access to the resources and services that

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[9]Constant, undiscounted 2002 dollars

comprise the system infrastructure such as air traffic control, CNS services, runways, gates, etc. Supply is embodied by federal and local governments, government agencies, and private industries responsible for providing the resources and services that compose the air transportation system infrastructure. The relevant context of this thesis focuses on the latter of the two aforementioned perspectives, namely an operational one. It is worth mentioning that while a passenger perspective is not directly treated, it is none the less recognized as an important element influencing the supply-demand dynamics that shape air transport elements.

2.4.2 Congestion and Delay

Delay can be easily explained as a process phenomenon from an operations management perspective. In its most basic form delay is the instance where process units spend time waiting for resources to become available.[10] One of the basic concepts in operations management is that these waiting times occur when there is enough competition for resources in a supply limited process.[11] Congestion refers to the points in the process flow where this elevated competition for resources occurs. The capacity of these congested points, called *bottlenecks*, limit the capacity of the entire process. As a result congestion and delay are clear symptoms of supply-demand mismatch; they are undesirable phenomena because waiting does not add any value to the process and requires cost-incurring buffers.([40] pp. 12,38)

These principles can be directly observed in air transportation operations. The relationship between key concepts is summarized by observing that "*when demand approaches capacity, delays to aircraft build up very rapidly. Congestion is usually associated with increasing delay, particularly when demand approaches capacity for more than very short*

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[10]Process units wait for resources in *inventories* or *buffers*, located just before the resources in the process flow.([40], p. 37)

[11]Waiting times are also linked to the inherent uncertainty in activities and demand, which contrasts with the predictability (and limitations) of supply.([40], p. 14)

periods."([159] p. 295)[12] The impact to customers and operators is directly observable, noting that "*when demand exceeds capacity, delay results, causing airlines and their passengers to lose productivity and efficiency*"([70] p. 217), as well as "*other more hidden inefficiencies such as non-optimum flight tracks and lower productive utilization of aircraft.*"([41], p. 61) The role of delay in a supply-demand mismatch context is so crucial, that the traditional paradigm for capacity assessment is to measure delay and use the resulting costs to justify funding of delay reduction measures.([41], p. 61) None the less, it is recognized that demand variability and supply rigidity are key challenges for providing acceptable levels service quality, and that having capacity to meet demand at all times (particularly during high levels) implies the acquisition of infrastructure that is difficult to justify economically.([159] p. 294)

The concentration of operations in big connecting hubs, due mainly to the evolution of hub and spoke networks, has transformed these regions into system bottlenecks.[13] The resulting congestion in these airports and their immediate area has been one of the most widely recognized causes of delays for many years. In 1994, for instance, the fifty busiest airports in the U.S. accommodated 80% of the air traffic and half of them experience more than twenty thousand delay hours during that year.[245] Some of the key choke points have been identified in New York, Chicago, and Atlanta, which are particularly affected during the summer months when yearly demand peaks and summer thunderstorms degrade capacity.[161] But congestion does not only occur in airports and their immediate airspace; as illustrated in the JPDO NGATS Integrated Plan (image reproduced in Figure 3) air traffic patterns can cause different sectors to face varying levels of congestion for a given demand increase.([191] p. 4) However, airports and their terminal airspace remain the primary choke points of the NAS, and continue to be recognized as such. In fact, many have argued that the numerous improvements to en-route airspace, while necessary, will

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[12]Even though delay is well understood in its general formulation, a definition has been adopted by the air transport community for consistency in relevant studies and statistical data collection. "*A flight is counted as "on time" if it is operated less than 15 minutes after the scheduled time shown in the carriers' Computerized Reservations Systems (CRS).*" ([293], p. 3)

[13]The evolution of airline networks after the 1978 Airline Deregulation Act [55] has had a major impact in the system capacity and infrastructure requirements for particular regions of the air transportation system, such as hubs.[250]

Figure 3: Airspace sector congestion at 2X demand increase (Source: JPDO [191])
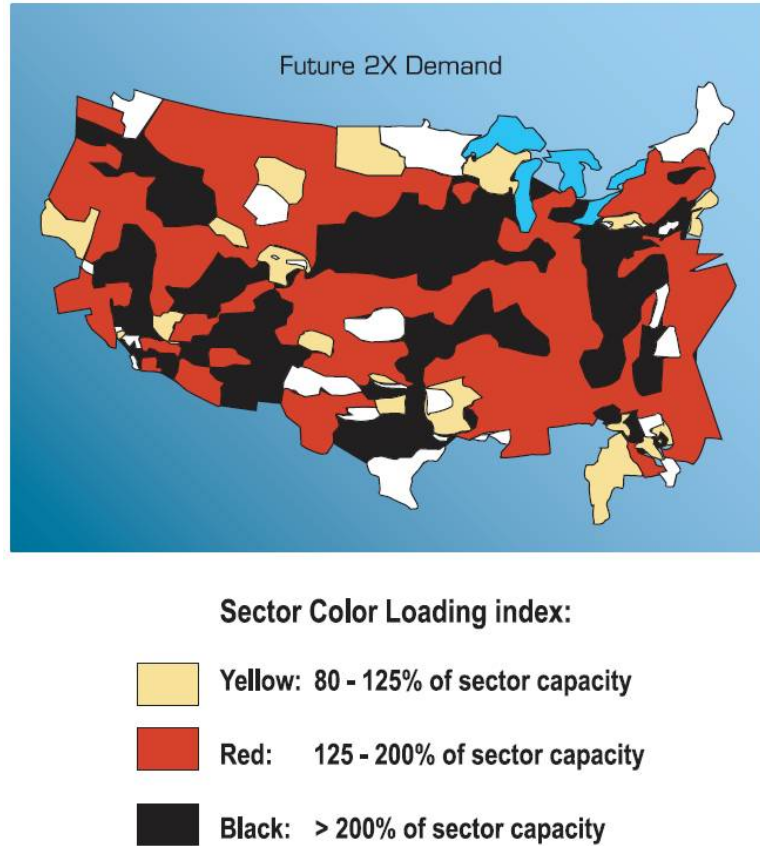
have minimal or no impact if improvements on airports playing a primary role in the NAS network are not realized.([75], pp. 55-64)

It is worth noting that delay and congestion exhibit some interesting features in the air transportation system. Due to the dependencies that arise in the highly networked structure of the system, delay in bottlenecks will propagate to many other parts, even to those where sufficient capacity exists. For instance, high levels of congestion in en-route airspace can limit the number of aircraft taking off, thus causing delay at an airport even if there is no congestion for departure.[116] Another characteristic of delay propagation is its cascade effect. Delay during one operation can propagate to multiple others; each one of those delayed operations can also cause delay in multiple others, and so on. As a result delay does not propagate linearly through the system but rather creates a compounded, or

snowball effect. This is particularly evident in choke points across the nation. For example, in 2004 a flight leaving LaGuardia International Airport (LGA) at 8 a.m. experiencing a five minute delay resulted in all flights at that airport being delayed for fifteen minutes or more during the rest of the day.[161] With these features in mind the it is paramount to note that delay represents a challenging phenomenon and that there is a very well documented history of its growing concern in civil aviation operations.

2.4.3   Economic Effects of Delay

Delay has an important impact on the economic performance of air transport entities. From an operational perspective delay generates economic loss because waiting times have a null contribution to revenue while the stream of direct operating costs continues. Air carriers carry the vast majority of this burden dominated by fuel and labor as key cost drivers. Passenger related costs, resulting from missed connections or cancelations, further increase this figure.[265] According to estimates by the Air Transport Association (ATA) over 308,000 fights were delayed in 1998, costing air carriers about $4.1 billion.[217] The trend has steadily grown and continues to affect the airline industry today. In 2004 more than 1.4 million flights were delayed, costing the airline industry alone over $6.2 billion in direct operating costs. That fiscal year closed with a reported $9 billion in collective losses.[71] The ATA also estimated 94 million minutes in system delay for 2005 leading to $5.9 billion in direct operating costs of which $2.2 billion were on fuel and $1.4 billion were on crew. These figure grew in 2006 with 116.5 million minutes in system delay and %7.7 billion in direct operating costs. It should be noted that while delay minutes increased by 5% between 2005 and 2006, costs increase by %11.[13] Another source of economic loss due to delay, usually more difficult to quantify, stems from indirect and induced costs. For air carriers these are represented, for instance, by ill will and opportunity costs.[265] They also include capital investment incurred to directly address delay. For example in 1999 American Airlines developed a new connecting hub in Nashville due to rising delay and associated costs in its other mayor connection points.[250]

The end users of the air transportation system, passengers and traders, experience economic and immaterial loss as well.[265] The inconvenience produced by excessive flight delays in the summer of 1999, for instance, was enough to prompt congressional hearings where consumers argued for a Passenger Bill of Rights and complained about delay disruptions and poor airline service.[241] Considering that passenger time is valued, on average, at $30.26 per hour [14], simple calculations on the value of time lost due to delay on a yearly basis in the U.S. yield staggering figures. The aggregate economic loss across all users, operators and service providers is therefore gargantuan and often underestimated, reaching surprisingly high levels in system choke points. Atlanta Hartsfield-Jackson International airport, for instance, experienced delays greater than 15 minutes in over 25% of all flights entering the hub during the first half of 2003. The City of Atlanta Department of Aviation (DoA) estimated that these delays costed the airport, its operating airlines, and traveling public just under $1 million per day in fuel, labor, lost passenger time, and business opportunity losses.[24] Expanding the scope to the national level, delay cost estimates for the whole U.S. economy range from $9 billion in 2000 to total gridlock and a projected $30 billion in 2015.[237, 50] By then it is expected that there will be an equivalent of 29 days per year with weather-related delays surpassing the worst day in 2004, not as a result of increased thunderstorm activity but rather due to the magnified effect of bad weather in the context of saturated air traffic operations. This measure of delay will grow to 87 days per year in 2025 for traffic level growth estimates between 1.5 and 3 times that of 2004.[165]

In summary, delays have a very real and tangible effect on the entire air transportation system, creating economic and immaterial losses across all players in its operational context. Due to the important role of air transport as a major driver of the economy, deeply embedded in its fabric and far extending its sphere of influence, delay losses quickly spill onto neighboring economic sectors and eventually to the entire economy. Supported by documented facts such as those presented in the previous sections, a strong argument exists for (ideally) eliminating delay or in the least reducing it as much as is economically feasible.[15]

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[14]This value has been derived from the FAA recommended values as adjusted for Bureau of Labor Statistics (U.S. Department of Labor) employment costs. [38]

[15]Measures to reduce delay have an associated cost which is justified by comparing it to the monetized

2.4.4 Congestion, Safety and Efficiency

Another important effect that the supply-demand mismatch has on the air transportation system is the degradation of operational safety and efficiency. The matter of safety and efficiency is charged, primarily, to the air traffic control system whose stated goal "*is to accomplish the safe, efficient flow of traffic from origin to destination.*"([298], p. 21) It follows that the success of the air traffic control system relies on striking a balance between efficiency and safety which are inherently conflicting goals. Safety is achieved mostly by implementing separation minima between aircraft in the vertical, lateral, and longitudinal directions, thus creating a volume around the vessel that should not be entered by any other aircraft. The factors affecting these separation minima are explained in detail in Appendix A. Understanding that this volume serves as a safety margin in terms of aircraft-to-aircraft proximity it is logical to reason that greater separation minima result in greater safety. However, greater separation between aircraft compromises capacity, and operational efficiency, because it constrains the number of aircraft moving through a given airspace; in other words, greater separation results in fewer aircraft sharing the same airspace.[298]

It is important to pause momentarily and clarify what is meant by *operational efficiency* in this context. Efficiency is directly related to capacity, or throughput, in that it provides a measure of the number of aircraft (or air traffic operations) that an element of the air traffic control system can process in a period of time. For instance, terminal area ATC is more efficient when it services a larger number of aircraft per unit time, managing their individual progress between the terminal area boundary and the gates. For larger separation minima aircraft are required to fly farther apart and thus ATC serves a smaller number of aircraft in a period of time. Thus the air traffic control challenge in balancing safety and efficiency: separating aircraft enough so as to provide adequate safety margins, but keeping the separation small enough so that all aircraft can operate and flow efficiently. This balancing challenge becomes particularly evident when the number air transport operations taking

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cost of delay.([41], p. 61),

place is large enough that the aircraft simply can not fit in a given airspace without violating separation minima. At this point air traffic control can maintain safety by enforcing separation minima, but at the expense of efficiency and throughput. Conversely efficiency can be improved but at the expense of safety (violating separation minima). At this point ATC has reached its capacity limit, and the tradeoff between safety and efficiency that ensues follows the principles of a Pareto frontier where improvement on one goal cannot be achieved without degrading the other. This tradeoff between efficiency and safety has been widely recognized, and has even been characterized through hypothetical inverse relations ([77], pp. 4, 5).

It should be evident that the challenges of the safety-efficiency tradeoff are particularly exacerbated in regions of the airspace system where aircraft inevitably have to fly close to each other. The terminal area around an airport is a prime example that also illustrates clearly the concepts of congestion and bottlenecks as explained in an earlier section. Congestion occurs when enough flow units compete for, or require, the same resource. In the terminal area air traffic converges into the airspace where all aircraft require ATC services and the opportunity to land while flying at a safe distance from one another. Given that a bottleneck is the location in the flow where congestion occurs, terminal areas are nodes of the NAS that most experience congestion and become said bottlenecks. It logically follows that a growing number of operations (such as that predicted by the forecasts introduced in earlier sections) increases congestion, which in turn degrades safety and efficiency. Evidence of this relationship between congestion, capacity, safety and efficiency in the terminal area can be found in air traffic accident surveys which indicate that 95% of air traffic accidents occur in the approach area and active runways where congestion is highest, whereas the remaining 5% occurs in enroute segments.[22] Other studies have also shown that safety is compromised when traffic demand approach or exceeds system capacity, preventing air traffic controllers to maintain separation minima as they attempt to accommodate all aircraft queued for final vectoring and landing.[207, 152]

Thus far the U.S. air traffic control system has given priority to safety over (and at the expense of) efficiency. Its safety record has been mostly due to the very conservative

separation minima and overall design of air traffic operations inherited from past decades. These safety margins come from a time characterized by demand levels much lower than current ones, and by ATC and navigation capabilities with considerably lower accuracy. Current air traffic demand not only requires efficiency levels that inevitably make traditional ATC procedures obsolete, but most importantly drive the ATC system to its capacity limit. Because safety cannot be compromised the result is, as expected, a significant degradation of efficiency.

Past efforts to improve system capacity and efficiency from the ATC perspective have had significant opposition because solutions are limited to a short term horizon and inevitably have an impact in safety, degrading it in the context of the safety-efficiency trade-off. For instance in 1999 the Airline Pilots Association (APA) strongly opposed an FAA initiative to expand the use of Land and Hold Short Operations (LaHSO) which was aimed at increasing airport and terminal area capacity. The FAA had opted for this alternative after facing strong political and community resistance to airport expansions as well as large infrastructure capital investment amounts. The APA argued that "*Capacity is being built on the backs of controllers and pilots*"[218][16], noting that runway incursion incidents had risen by 11% between 1997 and 1998. [218]

The reduction in aircraft-to-aircraft separation via improved navigational accuracy has been clearly identified as a key for enhancing ATC capacity and efficiency without compromising safety.[162] Moreover these improvements are expected to significantly reduce delay. Studies as early as 1998 indicated that cutting aircraft spacing in half could flatten out traffic delays for the next 25 years, even with the anticipated growth levels in demand.[237] In recent years the accuracy of ATC aids and onboard instrumentation has increased substantially, begging a reconsideration of the large separation minima reflecting the equally large error margins inherited from previous generations. Today, CNS performance accuracy is quantifiable, has engineering meaning and statistical significance, but is still to be implemented at a relevant scale. [163, 162]

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[16]Quote originally stated by Capt. Paul McCarthy, executive air safety chairman for the Air Line Pilots Association, on a hearing at the union's annul safety forum in Washington, D.C., July 20th 1999.[218]

2.4.5   Motivation for Supply-Demand Matching

The impact that supply-demand mismatch has on the economic health of the aviation sector, on the quality of the services that it provides, and on its ability to operate safely and efficiently, provide a very strong incentive to correct the mismatch promptly and to ensure that its chances of resurfacing in the in the future are reduced as much as possible. This motivation is strongly supported by the associated impact that society as a whole experiences due to its reliance on civil aviation as an economic and social driver, as a catalyst for growth, and an enabler of the way of life. Clearly, the current state of the system cannot handle current levels of activity in a satisfactory manner, which strongly suggests that it cannot sustain continuous growth in the immediate future either. The motivation for addressing the supply-demand mismatch in civil aviation is clear and self evident, providing one of the fundamental concepts at the basis of this thesis.

2.5   Environmental Impact of the Civil Aviation

2.5.1   Environmental Impact - Preliminary Remarks

Arguments presented thus far refer to the role of the air transportation system in modern society, the benefits that it provides, and the incentive to promote its continuing growth and development. It has also been argued that the system and its development are shaped by forces of demand and supply, and that a mismatch between the two has resulted in quality losses, economic losses, and degradations of efficiency and safety. Thus there is an evident incentive to correct this mismatch so as to increase and fully capitalize on the benefits provided by air transportation. There is however another critical element shaping the development of the air transportation system and comprising a crucial part of the motivation for this thesis: environmental impact. This issue represented little or no concern in the early years of civil aviation but came to the attention of the public eye in a rather accelerated way during the 1960's. This emergence of environmental concerns was due in part to the the sudden increase of public awareness on general environmental issues, and in part due to the alarming decay in local environmental quality around airports resulting from the sharp increase of aviation activity.([22], p. 476) Today the issue of environmental impact is just

as critical a driving force as any of the operational challenges described previously. Divided into its two main components, namely emissions and noise, aviation environmental impact has consequently become an entire field of study in its own right. The next few sections briefly explain why environmental impact is so relevant, how it is inherently interlinked with issues of air transport growth, and thus how it shapes its development.

Before proceeding with arguments on aircraft emissions, a crucial caveat must be stated. Much debate has spurred from claims by researchers around the world arguing for and against the link between emissions and climate change at a global scale, particularly global warming. Some of this debate has inevitably become politically charged. This thesis does not attempt to enter this debate by making claims or providing evidence in favor or against the different propositions of the debate. It is recognized that in the spirit of true scientific reasoning, research must be conducted on a continuing basis with the objective of producing conclusive evidence in support of either side of the argument. However the issue of air transportation environmental impact is hereby approached on the basis of the following fundamental premises (elaborated upon in the next sections): 1) Emissions resulting from air transportation, as well as their effects on human health, are measurable and have been sufficiently documented. Climatic effects however are not fully understood. 2) Some of the sources referenced in this thesis for purposes of constructing the argument of environmental impact support the idea of climate change due to anthropogenic sources. These sources have been carefully selected based on their credibility, reputation and rigor in the scientific approach taken. 3) Public opinion is a very real force currently affecting the expansion and development of the air transportation system. Today's political and community resistance is based on arguments of environmental impact and must be recognized as such even if future research conclusively disproves the hypothesis of climate change and its link to anthropogenic sources.

2.5.2 Aviation Emissions and Human Health

Human activities involving the generation, transformation or usage of energy are known to have an impact on the environment, particularly in terms of gaseous pollutant emissions

directly resulting from the burning of fossil fuels.[290] A primary activity in modern society, transportation has historically fallen into this category and consequently has been characterized as one of the main sources of atmospheric pollution.[70] Aircraft are responsible for the emission of a variety of components throughout the troposphere and lower stratosphere. In a 1999 special report on aviation and its impact to the atmosphere the Intergovernmental Panel on Climate Change (IPCC) states that the primary emissions of aircraft are carbon dioxide (CO_2) and water vapor (both of which act as greenhouse gases), carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO_2) (collectively termed NO_X), sulfur oxides (SO_X), and soot.[243][17] Other emissions include Volatile Organic Compounds (VOC), unburned hydrocarbons (HC), and Particulate Matter (PM) [18].[297] The relative concentration of these pollutants is highly dependent on the power setting at which aircraft engines operate.[291] This dependency in turn affects how emissions particularly impact human health and alter the composition of the atmosphere. The measurement of fuel consumption and consequent emission of these pollutants is currently mature and well understood. Similarly the direct health effects on humans have been studied extensively and are sufficiently documented.[243]

Nitrogen oxide emissions are known to increase with combustion temperature. As a result the highest NO_X levels are emitted during operations at high power levels such as takeoff and climb out. These emissions close to ground level have particularly strong effects on human health.[291] Nitrogen dioxide has been linked to degradation of pulmonary functions both in healthy individuals and in those with preexisting conditions. Additionally NO_X emissions deposited throughout the troposphere during climb out are the main cause of acid rain which affects terrestrial and aquatic ecosystems in a variety of ways.[287] Other pollutants, namely VOC and carbon monoxide, are observed in their highest concentrations during low power operations such as approach, idling, and taxiing, all of which take place in close proximity or at ground level.[291] Carbon monoxide has a significant impact in human

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[17]This special report was produced as per requests by the International Civil Aviation Organization (ICAO), was authored by 107 subject matter experts, and reviewed by over 150 experts from industry, academia and government.[243]

[18]"Particular matter is the general term used for a mixture of solid particles and liquid droplets found in the air"([288], p. 32)

health, particularly in children, the elderly, and people with heart disease. This compound reduces the amount of oxygen in the bloodstream thus impairing exercise, visual perception, manual dexterity, and the performance of complex tasks. Likewise, exposure to VOC has been shown to cause irritation in eye and respiratory tract tissues, as well as some cerebral disfunctions such as headaches, dizziness, visual disorders, and memory impairment.[287] Other aircraft emissions are also produced close to or at ground level but in smaller relative concentrations. Sulfur dioxide is a known respiratory irritant that exacerbates pulmonary conditions. Particulate matter has been linked to premature mortality, degradation of cardiovascular functions as well as a variety of changes in pulmonary structures and functions.

Beyond direct health and ecological effects some of these emissions also act as precursors of other toxic substances not produced by aircraft. Ozone, for instance, is not directly emitted by the burning of fossil fuels, but rather results from chemical reactions involving nitrogen oxides and some types of unburnt hydrocarbons.[291] Naturally occurring ozone is formed in the upper stratosphere (thus the name *stratospheric ozone*) when ultraviolet rays react with oxygen. The region where this reaction is commonplace and where ozone is particularly abundant is known as the ozone layer. Here, the sunlight's shorter wavelengths, harmful to most forms of life, are filtered out. Stratospheric ozone is also a greenhouse gas and thus contributes to the regulation of the planet's temperature in naturally occurring concentrations. In general stratospheric ozone is not considered to be a pollutant but rather an important component in the composition of the upper atmosphere. However, ground-level ozone, also referred to as *tropospheric ozone*, or smog, has harmful effects on humans and animals, and is recognized as a pollutant by organizations such as the World Health Organization (WHO) and the U.S. Environmental Protection Agency (EPA).[291] Tropospheric ozone reduces pulmonary function and causes respiratory inflammation in healthy individuals. It also aggravates existing pulmonary conditions such as asthma and bronchitis.[287]

2.5.3 Aviation Emissions and Climate Change

As mentioned earlier the climatic impact of emissions is not fully understood though the measurement of the emissions is considered to be a technologically mature practice. It is none the less recognized that these emission alter the composition of the atmosphere which in turn have the potential of inducing climatic change.[243] A current hypothesis among researchers is that greenhouse gases, which receive their name from the heat-trapping greenhouse effect they produce in the atmosphere, are responsible for increases in temperature across the globe and for generalized changes in weather patterns. Examples of naturally occurring greenhouse gases *"include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3)."*([289], p. ES-2)

In understanding how aviation affects the environment, particularly in terms of climate change, it is helpful looking at its relative contribution of greenhouse gas emissions. Carbon dioxide, for instance, is the primary emission from aircraft and it is known to survive in the upper atmosphere for about 100 years.[291] During the late 1990's between 2% and 3% of global carbon dioxide emissions were attributed to aviation-related activity. This fraction is comparable to that of some industrialized countries such as Canada and the Untied Kingdom during the same time period.[290] However studies have shown that other aviation-related sources, mainly motor vehicles providing access to airports, account for an important portion of carbon dioxide and other greenhouse gases, in some instances by more than 50%.[291]

According to EPA estimates for the 1990-2005 period, the transportation sector was the second largest contributor of greenhouse gas emissions in the United States, accounting for about 27% of total emissions.([289], pp. 2-23) However, aircraft emissions constitute a truly minuscule fraction within the transportation sector. A separate EPA study on air quality shows that for the year 2000 aircraft were responsible for 0.48% of CO, 0.63% of NOx, 0.35% of VOC, 0.71% of PM_{10}, 0.66% of $PM_{2.5}$ and 0.44% of SO_2, relative to all transportation sources.[19] The percentages relative to *total* emissions in the country are obviously smaller:

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[19]PM_{10} refers to particulate matter less than 10μm, while $PM_{2.5}$ refers to particulate matter less than 2.5μm. For comparison purposes the reader can note that a human hair is approximately 70μm in diameter.

0.33% of CO, 0.34% of NO_X, 0.14% of VOC, 0.17% of PM_{10}, 0.05% of $PM_{2.5}$ and 0.04% of SO_2.[288]

Given that aviation's relative contribution to greenhouse gases is so small it may seem intuitive to infer that any potential climate changes associated with aviation activity are negligible. However aviation atmospheric impact is subject to particular attention from researchers of climate change. In fact aviation is the first industrial sector whose impact on the atmosphere and global climactic system has been subject to an international assessment by the IPCC.[290] In order to reconcile these seemingly contradictory observations it is therefore necessary to identify the environmental impact features that so dramatically differentiate aviation emissions from those by other sources. The IPCC has suggested that this key difference lies in the fact that aircraft produce emissions across the range of altitudes in which they operate whereas all other sources are confined to the ground level. As a result, aircraft emissions are directly deposited into the mid and upper atmospheric levels, making aviation the largest emission source of this kind.[243] *"Some experts believe that aviation's emissions are potentially significant, in part because some aircraft emissions deposited directly into the upper atmosphere are thought to have a greater warming effect than the same volume of emissions generated at ground level."*([290], p. 9)

For instance, depletion of stratospheric ozone results from the combination of NO_X, water vapor, and sulfates produced during cruise and deposited directly in the mid and upper stratosphere. On the other hand NO_X emissions in the troposphere and lower stratosphere increase tropospheric ozone which acts both as a greenhouse gas and a pollutant for human health. Water vapor emitted in the troposphere also acts as a greenhouse gas. The primary emission of aircraft engines, carbon dioxide, is a greenhouse gas directly emitted into the upper atmosphere during cruise. Both NO_X and carbon dioxide, in conjunction with particulate matter, lead to the formation of condensation trails, or *contrails*, which are believed to contribute to climate change.[291]

It is evident that relative emission contributions are not a good indicator of climate change due to aviation activity, and rather that the manner in which the aforementioned

pollutants are emitted is a more significant factor. In order to allow for such considerations across all emission sources the IPCC has adopted *Radiative Forcing (RF)* as a measurement for climate change. "*Radiative forcing is a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system.*"([303], p. 2) It follows that this concept also serves as a quantitative index for comparisons between different factors affecting climate change. Positive values of RF, in units of W/m^2, are indicative of warming while negative values indicate cooling.[303] The 1999 IPCC study on aviation indicated that global aircraft emissions accounted for 3.5% of radiative forcing by anthropogenic sources, and estimated that expected growth in aviation activity could increase this percentage to 5% by 2050.[166, 243]

In brief, the harmful effects that aircraft emissions have on human health and ecosystems are well understood and have been sufficiently documented. In particular those emissions produced close to or at ground level during different modes of operation have a particularly important effect on local air quality and community health. The relationship between aviation emissions and climate change is not fully understood but ongoing research has revealed important insight. The fact that aircraft deposit pollutants directly into the upper layers of the atmosphere has been identified as a key issue by the IPCC, and is suspected to exacerbate climatological greenhouse effects. Use of RF as a measurement scheme has allowed for direct comparison between sources showing that the relative impact of aviation activity to climate change is not negligible and is expected to grow in the future.

2.5.4 Aviation Noise and Human Health

According to the WHO, transportation is the main source of community noise[20]. Aircraft are a significant source, particularly dominant in areas surrounding airports. Thus aircraft noise is widely recognized, as in this thesis, as one of the two primary aspects of aviation environmental impact.[29] From a physical standpoint there is no distinction between *sound*

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[20]The WHO defines *community noise* as "*noise emitted from all sources except noise at the industrial workplace.*" Other commonly used terms for community noise are *environmental noise, residential noise ,and domestic noise.*([29], p. vii)

and *noise.* Both refer to the same physical phenomena and sensory perception of disturbances in air pressure. However they are readily distinguishable based on the subjective criteria of desirability; noise is therefore simply defined as "*unwanted sound*".([268] p. 41, [29] p. vii) Noise is known to have negative effects in human health and wildlife, as well as in socio-cultural and economic aspects of community life.[29] As a result there is a strong incentive to minimize community noise and all of its adverse effects. Because there is no direct relationship between sound energy and community noise effects, this minimization requires a sufficient understanding of the characteristics of the physical phenomenon that adversely affect human response and the environment.[249] It is also important to identify and study the different sources of noise so as to focus efforts in mitigating their impact.

This section does not attempt to provide an exhaustive review of human sound perception or aircraft noise. However, it suffices to note that aircraft noise "*is generated whenever the passage of air over the aircraft structure or through its power-plants causes fluctuating pressure disturbances that propagate to an observer[...]*"([268], p. 41) Within the aircraft system the "*sources [...] most responsible for for community and ground crew effects are the high-velocity jet exhausts, fans, internal turbomachinery, propellers, rotors, internal combustion engine exhausts, and, for supersonic aircraft, sonic booms.*"([249], p. 1) The noise produced by these different sources can be measured and characterized in terms of various metrics. The most important are intensity, measured in deciBel (dB), and frequency, measured in Hertz (Hz). Human auditory perception is limited to a range of values for these metrics, resulting in variations of human response for different levels of intensity and frequency. In a similar fashion wildlife and structures respond differently over ranges of intensity and frequency.

In order to capture human response to noise beyond the pure physical phenomenon, alternative metrics have been constructed. For single events a popular metric is *Loudness Level (LL)* which quantifies perceived intensity with corrections for frequency sensitivity, summation of multiple frequency components, and sound level. The most commonly used loudness model is the A-weighted filter, which applies a weight-based filter to the different

frequencies of noise depending on human sensitivity. *Perceived Noise Level (PNL)* is a popular measure of the noisiness of a sound. *Noisiness*, in turn, refers to "*the characteristic of a sound which makes it unwanted, unacceptable, disturbing, objectionable, or annoying, and which may be distinguishable from loudness.*"([249], p. 7) This measure accounts for frequency and intensity sensitivity, as well as for temporal summation of noise, and was specifically developed to report the annoying quality of jet aircraft noise. Based on these metrics various methods have been developed to calculate total noise exposure for multiple or time-varying events. The A-weighted filter is used in indices such as the *Equivalent Continuous Sound Level (LEQ)*, whereas the *Noise Exposure Forecast (NEF)* is an index based on *Effective Perceived Noise Level (EPNL)* used in the assessment of airport community noise.[249]

Aided by these measures, researchers have studied, quantified, and extensively documented the negative effects of environmental noise. Many of these negative impacts have secondary or indirect effects that are more difficult to assess, but that have none the less been shown to exist. For instance, noise has been linked to hearing loss, a severe social handicap, particularly in developing countries where environmental noise is a significant risk factor.[29] Noise also acts as an interference factor in speech communication and has been actively researched in the context of hearing-critical occupational environments with non-injurious noise levels such as airports, airport vicinity businesses, and Coast Guard vessels.[132] Noise speech interference is known to cause degradations of work performance, uncertainty in communication, and a series of stress reactions.[29]

Recent research on populations living around airports has also shown that community noise acts as an environmental stressor, causing temporary and permanent non-auditory physiological effects particularly on the cardiovascular system (e.g. hypertension, increased heart rate, vasoconstriction) and on children.[132, 29] The relationship between environmental noise exposure and mental health has also been studied extensively. Early studies, which have since been strongly criticized, showed only a weak correlation between aircraft noise and admissions to psychiatric institutions. Other studies showed similar results by observing alternative indicators such as psychiatric symptoms or use of tranquilizers.

Though noise is not believed to be a cause of mental illness, these studies suggest that it can contribute in accelerating or intensifying the development of latent conditions.[29] Environmental noise, in conjunction with a variety of other non-auditory factors, has also been linked to negative social behavior impacts. These effects are generally considered to be indirect, more subtle and more complex than others. In communities near airports aircraft noise interferes with rest and recreation, leading to particular tendencies such as keeping windows closed or avoiding the use of balconies and public social areas.[29]

Sleep disturbance is considered the "*most deleterious effect of noise*,"[133] particularly for residents in close proximity to transportation infrastructure such as railway tracks or airports. Aviation activity has received particular attention in this regard, spurring a variety of aircraft-related sleep disturbance studies around major airports, specially in Europe, which have provided guidance in the development of noise policies. The primary effects include difficulty in falling asleep, awakening, and alteration of sleep depth and sleep cycles. The immediate physiological effects are increased blood pressure, heart rate, and vasoconstriction. The secondary effects, observed during the following day, are the most obvious and critical, and are generally related to fatigue and overall degradation of performance.[133, 29]

The adverse impact of noise on the performance of cognitive tasks has been vastly documented, primarily for occupational noise, and more recently for environmental noise. In general, studies show that critical cognitive capabilities such as attention, reading, problem solving, and memory are particularly degraded. Based on this body of knowledge emphasis has been placed on working and learning populations near airports, particularly schoolchildren. It has been shown that the unpredictability of noise occurrence is the dominating characteristic for cognitive performance and that the effort required by individuals to maintain certain levels of performance are conducive to elevated blood pressure and stress hormone production. The effect on children has been shown to be analogous but greater in magnitude.[29] Numerous studies show that schoolchildren exposed to aircraft noise present degradations on the development of basic cognitive skills such as reading comprehension and long term memory, as well as elevated psycho-physiological indicators of stress and arousal such as blood pressure and stress hormones.[132] For instance a 1980 study showed that

schoolchildren in the vicinity of Los Angeles International Airport were deficient in basic proofreading skills and prolonged focus on challenging problem solving tasks. Other studies indicate that reading acquisition and motivational capabilities are seemingly marred on children with pronounced exposure to aircraft noise during early childhood, a greater damage observed for longer exposure.[29] Preliminary results of a 2003 European study further indicated that that "*reading comprehension, recognition memory, cued recall, and prospective memory are impaired in those exposed to aircraft noise but not impaired by traffic noise.*"[132]

In brief, noise has multiple negative impacts on human health that have been studied and documented extensively. The argument for aircraft noise as a measurable factor that negatively affects neighboring communities is strongly supported by a plethora of evidence such as that introduced in this section. Beyond health matters, aircraft noise is a driver for other issues faced by communities near airports. For instance, noise exposure in areas has made them unattractive for residential purposes, thus devaluating housing and leading to economic loss by owners.

2.5.5 Motivation for Environmental Impact Mitigation

The incentive to tackle factors that degrade the quality of life of any segment of society is obvious and appeals to the most basic concepts of preservation and social responsibility. The effects that aircraft emissions and noise have on human health are well understood, and continue to be studied. Collectively this body of knowledge presents itself as self-evident motivation for the reduction of aircraft emissions and noise exposure. Though much debate still exists regarding climate change, and the climatic effect of anthropogenic sources such as aircraft emissions is still not well understood, evidence about the impact of aviation activity on the atmospheric composition further supports the incentive for environmental impact mitigation.

Several research and policy making organizations have proposed a series of environmental impact mitigation goals. In the U.S. the JPDO has generated a set of system-wide goals [122, 215], whereas NASA has developed analogous performance targets at the vehicle level for

Table 2: Environmental goals for North America and Europe

	ACARE			JPDO/FAA			NASA SFW Vehicles			
	Metric	Baseline	Goal by 2020	Metric	Baseline	Goal by 2025	Metric	Baseline	Goal by 2015	Goal by 2020
Fuel Consumption/ CO_2		2000	-50%	Tg/Billion km	2002-2012	1%/year	Aircraft Fuelburn	737/CFM56 777/GE90	-33%	-40%
Noise		2000	-50%	# people exposed to 65DNL	2002-2007 / 2008-2012	1%/year / 4%/year	cumulative dB	Stage 3	-42dB	-52db
NOx		2000	-80%	part of Fuel			LTO NOx	CAEP/2	-70%	-80%

relevant projects of the *Fundamental Aeronautics Program* such as the *Subsonic Fixed Wing (SFW)*. In Europe, impact mitigation goals have been developed by the *Advisory Council for Aeronautics Research in Europe (ACARE)*, which simply express reductions on a relative percent basis.[8] These goals are summarized and presented in Table 2. However, they are not easily comparable because each of them uses different baselines, metrics, aviation environmental modeling tools, and assumptions. Additionally, although goals are stated in a somewhat consistent fashion in terms of fuel burn, noise, and emissions species of interest such as NOx, they are formulated for a diverse range of abstraction levels, ranging from vehicle level performance to fleet level aggregate performance.

2.6 The Motivation for a Joint Operational-Environmental Solution

Having presented the problems of supply-demand mismatch and environmental impact of air transportation, as well as the profound negative effects that they generate, the motivation to address these immense challenges is not only reasonable and logical, but inherently intuitive and natural to modern society. Yet, while recognizing this powerful incentive, it is easy (and perhaps bewildering) to realize that these problems still exist today and that they will likely

worsen in the future, at lest in the absence of a new approach. Such an observation strongly suggests that not enough has been done, and/or that solutions that have been attempted thus far have had limited success. It is therefore natural to ask: why does the current status quo still feature operational supply-demand mismatch and environmental impact as two of the primary latent problems? What is stopping the different actors and stakeholders from formulating and implementing successful solutions? What forces at play impede progress in these two fronts? There are numerous reasons answering these questions, several of which are treated in this research. Chief among them is the the fact that the operational and environmental issues in question are intimately related, bound to each other in a tug-war, making them two deeply interrelated aspects of a single grand challenge. This interaction inevitably augments the complexity and difficulty of what will be from here on referred to as the *operational-environmental tradeoff*.

From an economic development perspective, social conglomerates such as large cities have the incentive of promoting growth of commercial aviation activity in their area. The underlying idea is that increased access to the region 'brings business', and that growth in air transport operations translates to local economic growth to the sector and to all adjacent industries. However, the environmental impact of aviation is also proportional to its operational activity level, that is, "*increased environmental impact can be expected to accompany [the] increased economic activity [of air transportation].*"([290], p. 6) The incentive to mitigate environmental impact is also very strong, and thus communities are also inclined to oppose increases in air transport operations. This public opposition has acquired strong political and legal support, and has thus come to be recognized as a major force constraining the expansion of aviation operations. This reveals the dilemma at the crux of the operational-environmental tradeoff, and begins to answer some of the questions regarding the absence of successful solutions to either of its aspects.

The current state of affairs thus represents a sub-optimal balance between two forces, where one attempts to meet demand and generate growth, while the other attempts to tackle factors that are negatively affecting the quality of life of local communities. Moreover, it may be argued that the economic and social benefits of increased commercial aviation activity

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extend across a scope significantly larger than that of the communities where environmental impact is most critically experienced. The result is a "Not In My Back Yard" (NIMBY) phenomenon where citizens will approve of commercial aviation growth as long as it does not affect their immediate community. Individuals within the same city will consequently have opposing views about the issue of air transport operations growth, and will stand against each other when facing decisions about expanding or constraining its activity level.

But the relationship between operational and environmental elements is far more complex than a compromise decision about increases in aviation activity. Issues of efficiency (and losses) shape this problem in a unique way such that degradations in its operational aspect are usually accompanied by degradations in its environmental counterpart. For instance, it has been recognized that ATC inefficiencies have led to increases in emissions, and that air traffic management improvements would significantly reduce them [290]. This observation reveals additional degrees of freedom in the problem formulation that further accrue its complexity. It also shows that the relationship between the two main parts of the operational-environmental *problem* extends to its potential *solutions* as well. More specifically, measures that directly address the operational challenges of the system have the potential of affecting environmental impact as well.

For now it is paramount to observe the remarkable significance of this operational-environmental effect, and that it cannot, by any means, remain unacknowledged if research efforts are to attain truly successful solutions. Until very recently the paradigm featured a disjoint view of the problem where the vast majority of proposed solutions focused either on its operational or its environmental constituent, but rarely on both. As a result even the best of efforts yield improvements in one area that are quickly outweighed by the effects of its counterpart. For example, turbofan engine technologies introduced since the 1960's have certainly led to progressive improvements in engine noise which have in turn allowed aircraft to become quieter. However these improvements have not been sufficient to offset the effect that growing aviation activity has on increasing noise exposure levels.[268] The same has been observed with engine and airframe technological improvements aimed at reducing fuel consumption and emissions.[291, 243] In the presence of growing demand (met

by growing air transport operations), solutions at the vehicle level that focus only on environmental performance become necessary but insufficient in isolation. Conversely, solutions aimed exclusively at increasing system capacity (supply) in the face of growing demand, for example a new runway at an airport, will allow for a greater number of operations to take place. However the accompanying result is, as has been discussed already, an increase in the environmental impact.

Attempting to solve these two challenges separately, particularly in with the prospect of a growing air transport industry in the future, will not yield results any different than those of very limited success seen thus far. There is solid motivation, not just to tackle the issues of supply-demand mismatch and environmental impact in air transportation, but more importantly to address the operational-environmental tradeoff as such: a single grand challenge characterized by its complexity, by its numerous degrees of freedom and driving factors, and by the operational-environmental relationship at its epicenter. This realization, along with all the arguments presented in this chapter, also provide a context for the research embodied in this thesis and sets the stage for a treatment on how the problem will be characterized and subsequently addressed, as will discussed in the following chapter.

2.7 Summary

Air transportation is vital in modern society, serving as an economic driver and enabler of the way of life through freedom of mobility. Though commercial aviation has been observed to grow at an accelerated pace in the last few decades, forecasts that predict its continuing expansion continue to do so based on assumptions about the air transport system capacity that misinform key stakeholders and decision-makers about the needs to expand and modernize its infrastructure. The mismatch between the demand for operational capacity and services and the system's ability to provide them is very real, and is particularly exacerbated by the dynamism and variability of demand that contrasts with the notable rigidity of supply. Moreover, supply-demand mismatch in commercial aviation operations leads to massive losses to society, generally observed through inefficiencies, delay, impacts

on safety, and economic loss among others. As a result there is a strong incentive to address the supply-demand mismatch to capitalize on the benefits that air transportation offers to modern society, and to augment its efficiency so that infrastructure investment is economically justifiable.

The air transportation system also produces an impact on the environment, embodied by emissions and noise exposure. Said emissions have been linked to negative effects on human health, and continue to be studied as a source of climate change. Similarly noise has been shown to negatively affect human health in a number of ways. Due to the local nature of this environmental impact, communities in close proximity to airports have posed strong opposition to growth in aviation activity, thus threatening the acceptance of any measures aimed at increasing system capacity. The inherent link between the system's operational capacity and its impact on the environment sits at the crux of the operational-environmental tradeoff and has a very strong bearing on just how much growth in air transportation will take place. Moreover, until very recently, the paradigm involved disjoint efforts addressing operational and environmental issues whose benefits were quickly washed out by increases in activity. The motivation behind this thesis is to address both aspects of the problem jointly so that solutions can be considered in the context of affecting both interrelated constituents.

CHAPTER III

CHARACTERIZATION AND FOCUS OF THE
OPERATIONAL-ENVIRONMENTAL PROBLEM

3.1 Introduction

As is customary in any problem-solving situation, an adequate assessment of the problem
is essential for the creation of a cognitive context in which solutions are to be developed.
It is generally accepted that a good problem definition is necessary in generating good
solutions, and in many cases a more complete characterization of the problem yields better
solutions altogether. The previous chapter articulated the motivation driving this thesis
in terms of the operational-environmental tradeoff, and in doing so provided some vital
background information about the problem at hand while directing the initial focus of the
thesis towards a handful of its key features. In this chapter, additional information about
the operational-environmental tradeoff

related to past and current solution efforts is reviewed, thus complementing the back-
ground included in the motivation and further characterizing the operational-environmental
tradeoff. This body of information is one of the most valuable pieces in the definition of
a problem. In performing this review the determination of what has been attempted be-
fore and with what measure of success is relatively straightforward, thus justifying new
approaches and avoiding the "reinvention of the wheel". It also reveals the identity of key
players and stakeholders that have shaped the problem and its solutions in the past, in turn
pointing at the likely stakeholders of the present and future. When viewed from a histor-
ical perspective, past efforts also tell story of the problem's evolution, not only in terms
of how its different factors have changed over time, but also in terms of how researchers'
understanding of the problem has evolved. Consequently, this information suggests what
the state of the art is and provides a benchmark relative to which new solutions potentially
equate to improvements.

3.2 Thematic Focus

A series of arguments presented in the last chapter constitute the initial focus from the general topic treated in this thesis. Clearly, additional thematic focusing is necessary. This thesis uses a series of *focus items* to document and relate the different focus areas in a structured and transparent manner. The thematic focus areas argued thus far are briefly reviewed and recast as focus items.

3.2.1 A Focus on the Operational-Environmental Tradeoff

Due to the important role that the air transportation system plays as an enabler of modern quality of life and economic driver, there is a strong incentive to promote its continuing growth. However growth is threatened by operational challenges represented by the supply-demand mismatch, and by environmental impact challenges. The issue of addressing these challenges is further exacerbated by the strong relationship linking both parts. This relationship spans from the symptoms of poor air transportation system performance to consideration of joint solutions. Thus there is solid motivation to address both aspects of the problem jointly and allowing additional related aspects to be incorporated in a more indirect way.

Focus Item 1: This thesis focuses on the operational-environmental tradeoff and in its integrated solution, placing special attention on the relationship between both parts and considerations of their interaction for the formulation of solutions.

3.2.2 A Focus on the Terminal Area

As mentioned in the last chapter one of the symptoms of supply-demand mismatch is congestion, which leads to delay and a number of associated losses. It has been noted that congestion is most commonly observed in bottlenecks where many aircraft converge and compete in close proximity for the same system resources. Airports and their immediate terminal airspace, particularly large and medium hubs in key catchment areas, have been identified as such operational bottlenecks. The efficiency-safety tradeoff of air traffic operations was also noted to be particulary exacerbated in these high density areas. On the other

hand, operations in these heavy nodes place aircraft on the ground or on close proximity to it during approach and departure phases. As a result the environmental impact of noise and emissions due to aviation activity is particularly critical in the terminal area. While congestion and emissions are observed in the enroute portions of air transport operations, and should not be ignored in the greater scope, the relatively higher stringency of operational and environmental challenges in the terminal area support the argument for focusing on it.

Focus Item 2: This thesis focuses on the operational-environmental tradeoff at terminal areas, which constitute bottleneck airports and their terminal airspace.

3.2.3 A Focus on the Operational Domain for Supply and Demand

The issue of defining supply and demand depends primarily on the vantage point from which observations are made. It was shown in the last chapter that from a traveler's perspective demand for air travel begins with the ultimate customers, that is, passengers and cargo traders, and that supply was embodied by airlines and carriers. The matter of terminal area congestion and environmental impact is none the less more intimately related with an operational view of the air transportation system. In the latter, demand comes from airlines whose aircraft require access to various resources and services that comprise the air transportation system infrastructure, such as air traffic control and runways for takeoff and landings. Supply of such resources is enabled by entities and operators who generate resources and offer services.

Focus Item 3: This thesis focuses on the operational perspective of supply and demand, recognizing that other perspectives are also important and help shape the behavior of supply-demand dynamics at the operational level.

3.3   Operational-Environmental Solution Types

3.3.1   A Focus on Long-Term Terminal Area Solutions

The difficulty of supply-demand matching in air transportation operations stems from the variability of demand over time with respect to the relatively rigid capacity of the system. Variations in demand are easily observed throughout a day, particularly since the

Airline Deregulation Act of 1978 which allowed carriers to create and adjust their operations schedule.[55] In an attempt to capture markets and maximize profit, airline schedules have become market-driven constructs, leading to an uneven distribution of operations throughout the day as airlines seek to accommodate passenger preferences in terms of flight times (and locations). Moreover, the hub-and-spoke system that emerged since the 1978 Deregulation Act has led to the evolution of some airports into major transfer hubs where airlines are forced to implement schedule banking, causing "strongly periodic and highly peaked"[207] operations schedules which further exacerbate demand levels at specific times. As mentioned in the last chapter, supply-demand mismatches translate to losses in the system, particularly for businesses with high fixed costs and variable demand, and thus are highly undesirable. Insufficient supply in peak periods translates to unmet demand and lost opportunities for revenues, whereas supply levels to serve peak demand lead to vastly underutilized capacity when demand levels are low.[284]

There are two main approaches to supply-demand matching, namely demand management and capacity enhancement. As indicated by their names, demand management implements measures on the demand side, whereas capacity enhancement does so in the supply side. In the context of air transport operations, demand management refers to "the collection of strategic, administrative, and economic policies designed to ensure that demand for access to some element of the Air Traffic Management (ATM) system is kept at a manageable level".[84] Demand management measures can help address these variations in demand and thus reduce mismatch-related losses. Additionally, there are some attractive features relative to capacity enhancement alternatives, such as shorter implementation times and seemingly lower upfront costs.[205] A review of demand management methods is presented in Appendix B

However, the formulation of the operational-environmental tradeoff is best presented in the context of a long term horizon, strongly suggesting that demand management is a necessary approach but insufficient if not properly complemented with capacity enhancement. Moreover, the incentive articulated in the previous chapter is to meet growing demand with

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necessary capacity, not to cap it. This thesis adopts a long-term perspective of the problem and its potential solutions, and consequently focuses on capacity enhancement. While demand management measures will not be explicitly addressed, it is recognized that those which have proven to be most effective and feasible in their implementation will continue to be used in the future to address short-term demand variability. It is also recognized that short- and long-term measures, as well as demand- and supply-side solutions, are complementary and should be concurrently considered in the greater scope of the problem. An emphasis on one or the other, as has been adopted in this thesis, serves to scope and focus the problem to a manageable state, as well as to point out how different solutions cannot be generally applied without contextual considerations of their adequacy.

Focus Item 4: This thesis focuses on supply-side solutions aimed at enhancing the air-transportation system's capacity over a long-term time horizon.

3.3.2 Solution Types for Operational and Environmental Performance

There is a variety of different solutions that have been proposed, and that are actively being pursued, for terminal area capacity enhancement and mitigation of environmental impact. Many of the key entities in charge of the formulation, Research and Development (R&D), and implementation of these solutions are summarized in Appendix C. Though there are some important differences across the gamut of solutions, they can be organized according to their general approach into distinct solution types.

One solution type pertains to additions or modifications to *airport infrastructure*, particularly in regards to the airport's surface and general layout. New runways are constructed to provide an additional departure and/or arrival queue to augment the overall throughput of the airport. The magnitude of the additional throughput provided by an additional runway depends strongly on its specific layout with respect to existing ones, its length, its orientation, and the way that departure and arrival procedures for the new runway can potentially interfere or interact with traffic using procedures attached to existing runways.([200], Ch. 6) Existing runways can be extended to accommodate operations of larger aircraft, to enable certain surface traffic flow patterns that reduce runway crossings or improve taxiway

throughput, or to decouple certain takeoff and landing operations between dependent runways, among other operational reasons. The construction of new taxiways provides access to new areas on the airport surface, enables improvements on surface traffic flow efficiency, and can help reduce taxi time. Sometimes, staging areas are built near a terminal to provide a physical space for waiting aircraft that does not compromise gate availability, gate access, or traffic density on the ramp. Staging areas are also sometimes constructed near a departure runway head so that controllers can increase capacity by appropriately adjusting aircraft sequencing. High-speed exits are angled taxiways used primarily by landing aircraft to exit the runway earlier in the landing roll, enabling a reduction in Runway Occupancy Time (ROT) which can be exploited for closely separated arrivals.[126, 98, 104, 93, 95]

Another solution type pertains to operational, or procedural, improvements. Operational improvements are enabled systems and technologies located in aircraft, as well as by a variety of ground-based and space-based assets and systems. In general, operational improvements enhance situational awareness for pilots and controllers, improve the accuracy of navigation and surveillance functions, and help manage the workload for operators by facilitating decision making. Most operational improvements focus on mitigating the effect that poor weather conditions have on airspace and airport capacity, resulting form the increase in safety margins and separation minima implemented during Instrument Meteorological Conditions (IMC).[1] Most notably, operational improvements seek to reduce separation standards to enable visual separation during Marginal Meteorological Conditions (MMC), reduced in-trail separation for arrivals during IMC, and reduce arrival-departure separation for same runway use or for closely separated runways.[112, 119] These operational improvements are enabled by systems such as the Automatic Dependent Surveillance - Broadcast (ADS-B) or the Local Area Augmentation System (LAAS), which can be used with Cockpit Display of Traffic Information (CDTI) systems on board to provide the pilot with the location of other aircraft and enable more precise in-trail separation. Similarly, the use of Area Navigation (RNAV) capitalizes on Global Positioning System (GPS) infrastructure to increase the accuracy of flight trajectories, which can be used to help mitigate noise

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[1]Appendix A presents details on the NAS operational architecture and the separation of aircraft.

exposure impact. Additionally, RNAV is used in conjunction with the Flight Management System (FMS) onboard an aircraft to realize tightly orchestrated ATC and ATM strategies, allowing for instance a more consistent flow of traffic to arrival runways regardless of weather conditions.[102, 111, 126] Another notable example of an operational improvements geared towards reductions in environmental impact and reduced fuel consumption is the concept of Continuous Descent Arrival (CDA), where the FMS is used to implement optimal arrival profiles with cutback engine power in a continuous profile rather than the stepped/staged descent profile commonly used.[47] Considerations for aircraft wake turbulence have a strong bearing on aircraft separation, as illustrated in Section A.3.2 of Appendix A, and thus have a major impact on terminal area throughput, particularly for consecutive arrivals and/or departures on the same runway or on closely separated runways. Reductions in wake vortex separations are being actively researched and implemented through wake vortex detection systems like NASA's Aircraft VOrtex Spacing System (AVOSS), the Wake Vortex Advisory System (WVAS), the Automated Vortex Sensing System (AVOS), or the Wake Turbulence Mitigation for Departures (WTMD) concept.[238, 212] Other operational solutions enable the simultaneous / independent use of multiple runways that would otherwise be dependent, particularly under IMC, due to close proximity or intersecting flight paths. Dependent operations are known to yield lower throughput than simultaneous ones. These improvements are enabled by systems such as the Precision Runway Monitor (PRM), a high update radar system that allows simultaneous instrument approaches to parallel runways that are up to 3000 feet apart. This system also enables other simultaneous runway usage concepts such as the Simultaneous Offset Instrument Approach (SOIA) system.[102, 111, 126]

A third solution type identified corresponds to advanced aircraft concepts, systems and technologies. Clearly, this type of solutions is not associated with terminal areas in particular, but rather addresses improvements in aircraft performance resulting in fuel consumption, emissions, and nose reductions. These fleet level improvements are contingent on a variety of factors that characterize fleet composition from an operational perspective, such as the introduction rate of new aircraft, the utilization of new and existing aircraft, and the survival/retirement rates of the existing aircraft. New aircraft can be classified being part

of the anticipated industry response or as next generation advanced concepts. Anticipated industry response vehicles are new aircraft models that are currently in production or will soon enter production. Notable examples include the Boeing 787, Boeing 747-8, Airbus 380, Airbus 350, and all of their respective variants. On the other hand, next generation aircraft concepts are defined by leading aeronautical research entities such as NASA to study performance tradeoffs, assess design requirements and goals, identify promising configurations and technologies, and identify key technological gaps. Although advanced aircraft concepts are based on relevant market needs and are framed within projected time scopes, the research associated with these concepts is primarily geared to guide future technology R&D and assess the realizable improvements on the entire air transportation system. A number of advanced vehicle concepts have been proposed by NASAs Fundamental Aeronautics Mission Directorate and are geared towards improved performance with aggressive environmental goals in mind. A spiral approach has been adopted where different types of vehicles are identified for performance improvements during specific time frames with increasingly more aggressive goals, so as to produce an incremental approach in technology development and vehicle design. These different spirals are referred to as *N+1*, *N+2*, and *N+3*, whose corresponding initial operating capability or entry into service dates are 2015, 2020, and 2030-2035.[233]

3.3.3 Solution Types as Strategic Alternatives

It is evident that all the aforementioned solutions cover a wide range of approaches to enhance operational and environmental performance of terminal areas. For this reason it may be difficult to conduct side-by-side comparative assessment with many of these alternatives because it may not be perceived as an 'apples-to-apples' comparison. However, all solution types share a couple of important features.

First, there is a considerable development time period for each of these solutions. For instance, an airport runway project requires about 2 years for planning and preliminary assessments, 2-3 years for environmental impact assessment, 3-5 years for negotiations between supporting and opposing parties, 1-2 years for the actual design, and 2-3 years for

construction. Thus, the approximate total runway project time is 10-15 years.[83] A new runway project also has a considerable capital investment amount associated with it. For instance, the project for runway 10/28 at Atlanta's Hartsfield-Jackson International Airport (ATL), which began operations in 2006, had a total duration of over 10 years and costs that exceeded $1.3 billion.[134] Other infrastructure projects have equally prolonged time frames, and capital costs highly sensitive to concrete and steel market fluctuations. For example, projects for Atlanta's new south terminal for domestic flights and the new international terminal have a current estimated cost of $9 billion.[252]

The realization of operational improvements also have a prolonged time frame associated with it. This is because because they are directly dependent on enabling systems and technologies whose R&D, certification, implementation, and widespread adoption, are time-intensive phases particularly sensitive to to lack of consensus among stakeholder on a wide variety of issues.[51] Moreover, a 2006 independent cost forecasting study conducted by the Research Engineering Development Advisory Committee estimated that the cost of developing and implementing next-generation air transportation systems for operational improvements is $15.5 billion a year for 20 years.[164]

R&D programs for advanced aircraft concepts and technology development are also known to extend for prolonged periods of time and to require vast budget allocations. In the U.S. these programs are primarily conducted and managed by NASA, who submits and justifies funding budgets to the U.S. Office of Management and Budget (OMB). Thus, the duration and funding allocation for said advanced aircraft concept programs is highly sensitive to national priorities and budgetary constraints. The High Speed Research (HSR) program is an illustrative example of such aircraft research efforts. This program was initiated in 1990 with a projected $4.9 billion cost, and was phased out in (fiscal year) 1999 due to budgetary constraints.([60], Ch 7.)

Once aircraft technologies reach an appropriate level of maturity, they are usually transferred to industry for further development and full-scale implementation. It is worth noting that the production of new aircraft is driven by the time periods associated with multiple phases of design, testing, certification, and production ramp-up. Each of these phases is

in turn sensitive to economic conditions, continuity of the workforce, availability of suppliers, and global collaboration in integration efforts.[158] For this reason, aircraft systems manufacturers and integrators incur in significant capital costs whenever embarking on a new aircraft project. For instance, it is well known that the capital investment required for the original Boeing 747 project was so massive that its failure would have likely caused the bankruptcy and demise of The Boeing Co.[182]

Given the characteristically long development cycles and massive capital costs for these types of solution families, it is clear that any decision relevant to the selection of a specific solution needs ample consideration. On one hand, the considerable magnitude of the investment associated with any of these solutions attaches an equally important consequence to the potential success or failure of the project. On the other hand, the extended development time frames in question cause a chronological divide between the identification of a need, or problem, and the implementation of a solution. For instance, the need for additional airport capacity can be identified today, but a solution such as a new runway will not be realized until 10 to 15 years in the future. This condition makes the decision making process significantly more difficult because the selection of a solution must account for the needs observed in the present as well as those that may occur in the future. Such a consideration would not be problematic if future conditions were fully known. However, it goes without saying that there is inherent uncertainty about how the future may evolve. If this uncertainty and the potential for change is ignored, by the time a solution has been fully implemented the problem that warranted its implementation in the first place may have grown, diminished, or otherwise changed significantly, rendering the vast investment of resources utterly useless. This specific situation has been readily observed in the procurement of a number of military assets, for which the need and design requirements evolved significantly before the asset could be completed, resulting in very costly project failures [247].

The decision making problem pertaining to terminal area solutions can therefore be viewed as one with a high degree of *risk*. In its traditional systems engineering formulation, risk is comprised of an *uncertainty* component and a *consequence* component. The risk associated with an endeavor is higher if the consequences are greater. Similarly, risk is higher

Figure 4: Graphical Depiction of Uncertainty and Consequence as Components of Risk and Opportunity
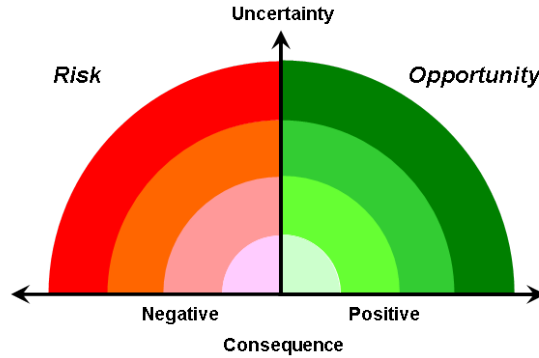
when the uncertainty about relevant outcomes is higher. It follows that the greatest risk occurs with conditions of high uncertainty and greater consequences. It is worth noting that the concept of consequence was commonly interpreted to be negative, and thus risk had an inherently negative connotation. This view has changed in recent years to account for the possibility that consequences can be positive, and thus that the combination of positive consequences with uncertainty leads to *opportunity*. The concept of risk and opportunity resulting from consequences and uncertainty is illustrated in Figure 4.([177] §7.3, [227] §6.4) In this sense, the selection of terminal area solutions is a problem with significant risk, but also one of many opportunities. Thus, it is necessary to adopt an adequate planning framework specifically geared towards the mitigation of risk and the realization of opportunities. Systems engineering offers a variety of tools for risk and opportunity management, many of which are synergistically combined in a framework for *strategic planning*.

3.4   The Strategic Planning Framework

3.4.1   Fundamental Definitions for Strategic Planning

To illustrate what is *strategic planning*, it is important to recognize that terminology tends to be ambiguous and often times confusing, and that the term 'strategy' can have somewhat different interpretations depending on who is using it and in what situation. Despite this ambiguity in terminology, "the notion remains that it [strategy] is about the most important of management responsibilities, capable of the most profound impacts on corporate

development and success."([242] p 19) The concept of strategy and its connection with management is further revealed by recognizing that "*strategic management involves making those decisions that define the organization's mission and objectives, determine the organization's most effective utilization of resources, and seek to assure the effectiveness of the organization within its environment.*"([39] p. 4)

It follows that, in general terms, *strategy* refers to the actions and steps an organization sets to execute in order to achieve its objectives and mission.([39] pp. 18, 92) The purpose of a strategy is to define the direction of an organization and guide the concentration of efforts and resources, in a manner that is consistent and adaptable to changes, to meet said objectives.([242] Ch. 1) In other words, an organization's objectives can be thought of as the '*what*', whereas a strategy is the '*how*'.[36]

In this context, *strategic planning* is the actual framework, formalized through a strategic planning process and a variety of enabling tools and techniques, by which strategic management is realized.

3.4.2 The Strategic Planning Process

The strategic planning process is divided into two main phases. The first phase deals with the identification of the organization's mission and general philosophy, the definition of objectives across the range of short and long term horizons conducive to achieving the organization's mission, and the selection of a strategy to be implemented. To do so, the strategic planning begins with an analysis of the organization's environment. For private sector or corporate applications it is common to conduct some sort of market analysis where the customer base is characterized and potential competitors are identified.([39] Ch. 2, [20] Ch. 1)

Otherwise, the organization environment is examined to identify key contextual factors of interest, relevant to the organization's performance but beyond its control. Typical aspects of interest include political, economic, legal, regulatory, social, and demographic. Related factors often considered include competitors, labor, technology, key physical resources, suppliers, distributors, transportation, and energy, among others. Based on the

identification of these factors, the next step is to characterize how the organization's environment will evolve and how it will look like sometime in the future. In the classical formulation of strategic planning this characterization captured by forecasts. Since forecasts are heavily reliant on subject matter expert opinion, planners implement methods to structure the elicitation of information, moderate iterations, and synthesize the information that is collected. Noteworthy examples of this type of tools are the Delphi method and Nominal Group Technique. Other forms of qualitative data collected and used for forecasts include customer evaluations, anticipatory surveys, and assessments from sales managers that can be used to compose a Sales Force Composite Forecast. Forecasts can also be generated quantitatively by using empirical data and applying mathematical methods to generate expected behavior patterns in the future as an extrapolation. Typical examples of these methods include time-series forecasting, regression modeling, and econometric modeling. The body of tools and methods used to identify contextual factors and generate forecasts is commonly referred to as *environmental scanning*. Although the use of forecasts is considered common practice in strategic planning, many have recognized that they are inadequate for some industries where contextual conditions can change abruptly, too rapidly, or are altogether too uncertain. ([39] Ch. 2, [20] Ch. 1-4, [242])

The next step of strategic planning is and internal organizational analysis, which is an introspective assessment to determine strengths that ought to be capitalized on and weaknesses that need to be mitigated. Often times opportunities and threats are included to produce a SWOT analysis. Relevant aspects examined in the internal organizational analysis include financial position, general capabilities, organizational structure, as well as the gamut of resources such as personnel, products and services, operations, and physical facilities. This step leverages on workshops, interviews, focus groups, and surveys to elicit the necessary information, and often makes use of the incorporates product/service analysis, financial analysis. The next step defines organizational objectives, which are formulated so that they are align with organizational culture, minimize threats, mitigate weaknesses, leverage on strengths, and exploit opportunities.([39] Ch. 3, [20] Ch. 7, [242])

In the next step, a pool of strategies is formulated from which a subset will be chosen.

Once strategic alternatives have been laid out, a decision-making process must take place to choose a course of action. Information about the organization, its environment, and the anticipated impact of a strategy, are used for the selection. General types of strategies have been identified for private sector and corporate applications, such as stable growth, vertical integration, horizontal diversification, endgame, merging, and sell out. Additionally, a number of business portfolio analysis techniques exist for business applications, whereby objectives such as profitability and favorable market position are assumed, business units are classified into categories based on the internal and environmental analyses, and strategies are recommended based on this classification.([39] Ch. 4,5) Examples include the Growth-Share matrix [155], Industry Attractiveness - Business Strength matrix [219], the Life-Cycle approach [149] and Hofer's Product-Market Evolution Matrix ([201], p. 257). For other applications, the selection of a strategy is based on the organizational objectives identified in previous steps. In some form or another, strategies are evaluated relative to each other by means of several descriptors. The most fundamental one is a measure of how each strategy enables the organization to meet its objectives and mission. Other factors may include the cost associated with deploying that strategy, or the inherent risks brought forth by it. Formalized methods such as the competitive strategy analysis assesses the adequacy of each strategy based on the degree of consistency between the objectives that the strategy aims to attain as well as the organization's policies and philosophy [248].

The remainder of the steps in strategic planning correspond to the second phase, which involves strategy deployment, implementation, and monitoring. These steps incorporate the use artifacts such as budgets or motivational systems that support resource allocation, Gant charts or PERT charts to schedule and monitor tasks, and roadmaps or decision trees to define key decisions and actions.([20], Ch. 10-14)

In summary, strategic planning can characterized by a number of broadly accepted key features [20]:

1. It recognizes the environment or context, defined by the collective of externalities outside the organization, and incorporates it in the planning process.

2. It has a long term time focus, ranging from a handful of years to multiple decades depending on the application.

3. It is conducted at the top of an organizational structure.

4. It involves decision-making that commits large amounts of resources.

5. It sets the directions for the organization by focusing its role in the changing environment.

3.4.3   Strategic Planning for Airports

Although a significant portion of strategic planning work is associated with an *organization* and is geared towards business and corporate applications, the strategic planning process is also formulated for a *system* and is actively used in operations-centric applications. For example, long-term facility capacity planning in POM incorporates an estimate of how much long-term capacity is needed, when it will be needed, and where within the system it will be needed, so that the massive capital investments necessary can be decided upon and adequately planned with sufficient lead time. These decisions are crucial because they are strategic in nature and reflect the general direction defined at the highest operational level, shaping decisions at the tactical level.([138]Ch 7.)

In a similar fashion, the *strategic systems planning process* has been applied to airports, and has been tailored and refined for this application throughout the years. During the early years of civil aviation airport planning occurred in an ad hoc fashion and was primarily driven by airlines. With the dramatic growth of aviation, particularly after the second world war, considerations for land use as well as the need for consistency and standards in airport development became evident. In turn, *master planning* was adopted by individual airports as a mechanism to justify major investments and land use.[2] After the Civil Aeronautics Authority was established by the Civil Aeronautics Act of 1939, efforts to identify the

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[2]Currently, the *master plan* for individual airports is a comprehensive planning document that informs the public about the phased development of all airfield and airspace components so that affected entities can participate in the planning process. The master plan also provides provisions for compatibility with economic and transportation development plans at all government levels, economic planning of capital investments, capacity assessments, and aviation activity projections.([41] pp. 6-8)

airport needs at a national level were undertaken. This marked the transition of airport planning to an integrated and more strategically oriented approach that covered the entire domestic airport system. Although the first federal grant programs were established later in 1946 to fund airport development, no formal planning requirements had been defined at the time. In 1967 state-level aviation officials expressed the intent of developing state airport system plans, and later formed a working group with FAA representatives to develop a formalized airport planning process to guide the generation of said state system plans. This process, discussed next, has since experienced very few changes. A number of federally funded programs have been developed since then to provide additional guidance on planning processes, identify specific needs for individual airports, and fund development projects at the state and metropolitan level.([41] pp. 6-8)

It is evident that strategic planning is conducted for airport systems at different levels (federal, state, regional/metropolitan) and for individual airports. Consequently, there are different time scopes, guidance documents, planning documents, and funding mechanisms associated with each of these levels. This information is illustrated and summarized in Table 3.[83]

Table 3: Airport Planning at Different Levels

Level	Planning Document	FAA Document	Duration
Federal	National Plan of Integrated Airport Systems (NPIAS)	ORDER5090.3C	5 year plan, updated every 2 years
State/ Regional/ Metropolitan	Airport System Plan	Advisory Circular (AC) 150/5070-7	Varies, updated periodically
Local	Airport Master Plan	AC 150/5070-6B	20 year plan or ultimante buildout, updated periodically
Project Specific	Airport Capital Improvement Plan	ORDER5100.38C	2-5 year program, updated annually

Despite these differences, the general process for strategic airport (or airport systems) planning can be described through the following steps ([41] pp. 46, 169-179):

1. *Step 1* - Entities affected by, or involved in, airport development are identified as the set of stakeholders. Representatives from the different groups collectively define the issues, goals, and objectives of the planning effort.[3]

2. *Step 2* - The current state of the airport is assessed, usually through an inventory of facilities, and an evaluation of the airport's performance under current conditions.[4]

3. *Step 3* - The contextual factors defining the airport's environment are examined. These factors usually include traffic and passenger volumes, which capture different aspects of demand and airport usage. Unconstrained forecasts are developed in terms of these factors to identify the potential for growth.[5]

4. *Step 4* - System deficiencies are identified for the airport's current state and/or for the conditions described by the forecast. In this sense, the assessment of the airport in its current state and the demand projections serve as reference points to determine the extent to which the airport must be developed.

5. *Step 5* - A pool of solution alternatives, covering a range of different approaches and solution types, is identified. It is common to include a no-action alternative to provide a reference strategy against which alternatives can be comparatively evaluated.

6. *Step 6* - Solution alternatives are evaluated based on criteria that usually incorporate improvements and degradations on different metrics of performance, as well as different forms of cost.

7. *Step 7* - Solution alternatives are comparatively assessed, ranked, and selected based on how they meet planning objectives.

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[3]A list of key entities and stakeholders of for strategic airport planning is presented in Appendix C.

[4]The strategic systems planning process implicitly incorporates the classical systems perspective whereby: 1) the the system is composed of interrelated elements, 2) the system exists within an environment that can also be characterized as having interrelated elements, and 3) the elements of the system interact with elements of its environment.[177]In this step, the assessment of the airport prescribes an assessment of the system's elements

[5]In accordance to the systems view, this step prescribes the assessment of the system's environment in terms of its elements and interactions.

3.5 Methodological Challenges of Strategic Airport Planning

3.5.1 Strategic Airport Planning and Decision-Making

It is critical to recognize once again that strategic planning is inherently a decision-making process where a wealth of information is collected, generated, and synthesized to support the selection of a strategic alternative. Cognitive sciences research on decision-making note that there are two distinct parts in making a choice. The first one pertains to a *situational assessment* that identifies alternatives and values, and characterizes the context in which the decision is being made. The second part pertains to the *decision event* itself, which implements logical and mathematical mechanisms by which alternatives are comparatively assessed. This body of work also recognizes that attention is commonly placed on the decision event, for which over 70 qualitative and quantitative techniques exist [258], but that the contextual assessment prior to the decision event is equally or more important.[59, 157, 240]

The importance of situational assessment in decision-making, and its relevance to the present problem, is further supported by the fact that the decision event occurs in the last step of the strategic airport planning process (*Step 7*), whereas the situational assessment is realized in all previous steps (*Steps 1-6*). Thus, to successfully conduct a strategic airport planning process, it is paramount to attain a thorough understanding of the different aspects of the problem with *Steps 1-6*. However, doing so presents a number of key methodological challenges for strategic airport planning, particularly one that focuses on operational-environmental performance. These challenges are discussed next.

3.5.2 System Complexity and Performance Characterization

It is well known that air transportation constitutes a *complex system*.[102, 72] Although there is no universal definition for *complexity*, it is generally accepted that a system exhibits increasingly complex behavior as the number of elements and interactions between its elements grows, resulting in an aggregate or *emergent behavior* that is ever less intuitive and harder to understand [63, 64]. The numerous external and internal factors defining an airport and its terminal airspace are heavily interrelated, particularly for the current

problem where the interaction between operational and environmental elements is explicitly addressed. The air transportation system, or even a single example of an airport and its terminal area, can also be considered to be a *large system* from the *axiomatic design* perspective because it satisfies multiple and different sets of functional requirements throughout the systems lifetime. More particularly, an airport is a *flexible large system* because it has functional requirements defined at the top level of abstraction in the systemic hierarchy structure, and must satisfy these changing requirements at different points in the life cycle, thus requiring a level of flexibility and reconfigurability to do so. Under the axiomatic design paradigm, systemic complexity is hence associated with the degree of uncertainty associated with the satisfaction of functional requirements in the system's design.([273], Ch. 4, 9) An airport is therefore, without question, a complex system in its own right.

The implication of an airport's systemic complexity for this problem is that, in order to gain the necessary level of understanding and realize a pre-decisional situational assessment, planners are required to characterize airport operational-environmental performance that is inherently complex. Given its complex behavior, performance characterization can take certain forms that provide particularly meaningful information.

Interactions - As noted above, interaction among system elements is one of the root causes and defining features of complex behavior. It follows logically that interactions should be quantitatively and explicitly characterized.

There are three distinct types of interactions: those between endogenous elements, those between exogenous elements, and those between endogenous and exogenous element. For example, runways and taxiways are elements endogenous to the airport. These elements interact if a taxiway crosses a runway, because the movement of aircraft on the taxiway is interacting with the movement of aircraft on runway, and viceversa. An aircraft using the taxiway cannot cross the runway if it is active, that is, if a landing or a takeoff is taking place. Conversely, an aircraft waiting to depart is not cleared for takeoff until all crossing aircraft have exited the runway. The specific traffic flows used and the procedural rules implemented will define how operations on a runway and its intersecting runway will interact, which in turn will have an impact on performance metrics such as throughput (e.g. takeoffs/landings

per hour), taxi time, and runway crossing delay. Procedural logic pertaining to endogenous elements is described by *factors* such as runway assignment, prioritization of different types of movements, or sequencing of runway crossings and takeoff/landing operations. In this sense, these factors are also endogenous, and interact with each other.

Similarly, exogenous elements interact with each other, and by virtue of the previous argument, exogenous *factors* will interact as well. For example, operational demand is an exogenous element that can be described by factors which are known to interact such as time-of-day distribution, usage of arrival or departure headings, or fleet mix. Consider for instance the distribution of arrivals over time-of-day and over airspace arrival routes. The clustering or even distribution of operations according to these two factors will have an impact on performance metrics such as airborne delay, fuel burn, and emissions. More specifically, if operations counts are higher for a given arrival route and have sharp time-of-day peaks, then there will be very high demand levels associated with the prescribed arrival route during peak times. As explained Chapter 2, this will result in system inefficiencies that will be observable as increases in delay, fuel burn, and emissions. Conversely, if operations are approximately evenly distributed over all arrival routes and throughout the entire day, then the system will be able to consistently provide system resources without experiencing inefficiencies or degradations in performance metrics.

Lastly, exogenous elements interact with endogenous ones, and as can be expected, exogenous *factors* interact with endogenous ones. For example, fleet mix is an exogenous factor used to describe operational demand. Aircraft sequencing for arrivals and departures is an endogenous factor describing the internal procedural logic used by airport operators. Because aircraft separation depends on the aircraft size class, the mix and sequence of aircraft conducting takeoffs and arrival approaches will have a bearing on how separation is implemented, and consequently will have an impact on performance metrics such as throughput and delay.[6] If, for example, the vast majority of operations are performed by the same size class aircraft, then sequencing schemes executed by controllers will have

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[6]The size of each aircraft in a sequence of takeoffs or arrivals is a dominant factor in the in-trail separation between them. Appropriate sequencing can enhance capacity by accommodating a greater number of aircraft within a given airspace. Section A.3 in Appendix A explains the fundamental principles of aircraft separation.

negligible impact on performance. However, if the fleet mix exhibits comparable numbers of aircraft for all size classes, then the implementation of controller sequencing strategies will have a significant impact.

Sensitivities - The previous discussion on interactions alludes to the impact that certain factors have on performance metrics, particularly as factor settings, or values, change. Sensitivity refers to the variability that a performance metric is observed to experience with the change of factor settings. Sensitivity information is relevant because it identifies 'big-hitters' and negligible factors for a given metric, and can be used to determine how to effectively alter system performance and provide more value.

It is important to recognize that the sensitivity that a metric has to a given factor is not necessarily constant, and that it will change if there are interactions with other factors. Recall the previous example that illustrated the interaction between fleet mix and controller sequencing. If the fleet mix is mostly limited to the same aircraft size class, then the implementation of different controller sequencing schemes has minimal impact on performance. However, if the fleet mix is relatively well distributed over all aircraft size classes, the impact of varying among different controller sequencing schemes will be significant.

Thus, sensitivity information characterizes how the impact that a factor has on a given metric changes with the settings of all other factors.

Tradeoffs - It has been established that changes in factor settings have an impact on performance metrics. The impact that a certain factor has on a metric will be, for the vast majority of practical applications, different from the impact that it has on other metrics. This has important implication because changing the settings of a factor to effect an improvement on one performance metric can result in a degradation on another performance metric. This condition of opposing factor effects imply a conflict between performance objectives. Thus, a tradeoff is revealed whereby a given performance improvement prescribes a different performance degradation associated with it.

The most relevant and obvious example of a performance tradeoff for the problem addressed in this thesis is that between operational capacity and environmental impact, discussed at length in Chapter 2. Increasing airport capacity to accommodate larger traffic operation volumes exacerbates the environmental impact of aviation activity. Performance objectives of increased throughput and reduced environmental footprint are in conflict, and represent a tradeoff.

It is important to recognize that interactions, sensitivities, and tradeoffs, are simply different ways of examining the same complex behavior in airport performance. Therefore, they individually procure different information that must examined collectively and synthesized.

There are two major components of the strategic airport planning process where performance characterization is required. The first one is the evaluation of the airport in its current state, prior to the evaluation, selection, and implementation of terminal area solutions. This task takes place in *Step 2* with the inventory of facilities and the reference performance assessment, but could also be conducted jointly with *Step 4* where performance deficiencies are identified for current and projected conditions. This characterization pertains to the complex behavior of operational and environmental performance metrics of interest with respect to endogenous and exogenous factors.

The second component of strategic airport planning that requires performance characterization is the evaluation of strategic solution alternatives, conducted in *Step 6*. The implementation of solutions will have a varying impacts on performance metrics for which sensitivities must be identified, particularly when considering that interactions among solutions are likely to occur whenever they are implemented in combination. Moreover, solutions may induce performance improvements and degradations that comprise tradeoffs between them. In this sense, This characterization pertains to the complex behavior of operational and environmental performance metrics of interest with respect to airport solutions, which behave like factors whose settings are 'Yes' and 'No' to denote whether or not a solution is implemented.

As will be shown in Section 3.6, a review of past and current strategic airport planning

efforts reveals that these forms of performance characterization are notably absent, both for current state performance assessment and for airport solution evaluation.

3.5.3   The Scenario-Based Alternative to Forecasting

The development of forecasts as a means to describe demand and the future conditions in which a system or organization can be expected to operate is a basic component in strategic planning. Air transportation applications such as airport planning make use of unconstrained demand forecasts, which provide a measure of how much aviation operations can potentially grow, granted that the system has sufficient capacity to accommodate it. The development of aviation activity forecasts for airports has been documented extensively and is a standard practice in strategic airport planning.[272] The development of these forecasts in *Step 3* of the strategic airport planning process constitute fundamental component of pre-decisional situational assessment.

However, as mentioned earlier in Section 3.4.2, many in the strategic planning community have recognized that forecasts are inadequate for industries where contextual conditions can change abruptly, too rapidly, or are altogether too uncertain.[39] Similar arguments have been made by the futures studies community, who deem forecasts inadequate even for moderate levels of uncertainty about the operating environment, or for environments that are notably dynamic.[140, 264] These characteristics are certainly prevalent in air transportation, and thus the use of forecasts for strategic airport planning should be revised.

As an alternative to forecasts, a scenario-based approach proposes the use of not one, but multiple depictions of the future. Whereas the purpose of forecasting is to correctly predict future conditions based on projections of historical trends, scenario development provides a number of distinct and relevant possibilities for future conditions. With this approach, planners evaluate and select strategies based on the impact that they have across the gamut of scenarios. In other words, rather than selecting an optimal strategy based on a forecast, planner select a robust strategy that offers a sufficiently good outcomes across multiple scenarios and hedges uncertainty.

In this respect, the JPDO Futures Working Group (FWG) comments on the shortcomings of forecasts and the advantages of scenarios as follows:

"*Because extrapolation treats only a single extremely thin thread of possibilities, it is a high-risk approach for forecasting future conditions. Like water running down a hill, the future finds its own way. The future has little regard for the past except as a point of departure. Discontinuous events happen and change the course of the future. While there are discontinuities that no amount of planning will ever predict, there is value in considering a broad set of plausible conditions and exploring their potential consequences on the enterprise of interest.*"([197] p. 21)

There is a wealth of formulations for the development of scenario sets, which vary widely depending the application.[49] However, the general observation is that said formulations are predominantly qualitative in nature, and lack methodological rigor commensurate with the strategic airport planning process. As will be shown in Section 3.6, a review of past forecasts developed for air transportation supports arguments about their inadequacy for strategic airport planning. Additionally, a survey of the few scenario-based planning efforts that have been conducted to date reveal that a formal quantitative method for the generation, evaluation, and selection of scenarios is notably lacking.

3.6   Benchmarking of Operational-Environmental Improvement Efforts
3.6.1   Characterization of Operational-Environmental Performance

It goes without saying that a vast amount of strategic airport planning efforts have been conducted to date, and that many of them have been documented. The purpose of the survey presented in this section is not to exhaustively cover all these documented efforts, but rather to present the most relevant and representative ones. As noted earlier, airport planning can be conducted at the federal, regional, or metropolitan level, or on the basis of individual airports in the case of master planning. In the interest of the breadth of these levels, the sources reviewed focus on efforts conducted by the FAA and the JPDO for individual airports and for the domestic airport system. However, there are many other key entities and stakeholders in the strategic planning of airports which must be recognized.

This task is beyond the immediate scope of this chapter, but is provided in Appendix C.

The FAA Airport Capacity Program Office, later superseded by the Office of System Capacity (ASC), was created in 1985 as a response to the record delay levels observed in the early 1980's and the realization that a centralized entity was necessary for the coordination of activities. Efforts were conducted by Airport Capacity Design Teams which were placed at specific airports to interact with key representatives, propose and evaluate multiple alternatives that could enhance existing airport and terminal airspace resources, and perform the necessary studies. These teams were composed of representatives from the FAA, airport operators, local DoT and port authorities, and the airline industry. In each study, which focused on a single airport, much of the effort was dedicated to gathering and validating appropriate data, agreeing on suitable assumptions, and interpreting the results of simulation experiments. Over 50 such studies had been completed or were still in progress in the year 2000. As part of this program a series of *Airport Capacity Enhancement Plans* were generated and released to the general public, describing the different solutions that were analyzed at each airport as well as the findings that resulted.

One of the first earliest studies made available by the FAA was the 1996 *Portland International Airport (PDX) Capacity Enhancement Plan*, which focused on this airport as one of the fastest growing nodes in the NAS during the mid 1990's. The study made use of 1994 traffic levels as a benchmark, namely 281,000 yearly aircraft operations, to assess capacity levels for the reference case, and assessed the value of a number of capacity enhancing measures for two notional future traffic levels labeled Future 1 (386,000 yearly operations) and Future 2 (491,000 yearly operations). Each of these futures included fleet mix and scheduling (peaking) assumptions generated from Official Airline Guide (OAG)[7] data and Capacity Team inputs. Two types of improvements were considered for Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) operations: airfield improvements and operational improvements. Airfield improvements included the construction of new

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[7]The Official Airline Guide (OAG) is firm with worldwide operations dedicated to flight information data management and solutions. Its aviation solutions sector focuses on the collection of airline information, leveraging its airline schedules distribution services. Given its breadth and accuracy, the OAG is often used by government and private research entities.[239]

exit taxiways to reduce runway occupancy times, construction of taxiways connecting the ends of parallel runways 10R/28L and 10L/28R to reduce arrival and departure taxi times, construction of penalty boxes where late arrivals wait for gate assignment without congesting apron surface, and construction of departure pads at runway ends to allow passing in takeoff queues so that departing aircraft can be better sequenced by air traffic controllers.[86]

Operational improvements included the installation of Instrument Landing System (ILS) category (CAT) I equipment on runways 10L and 28L for dependent staggered CAT I approaches, simultaneous independent CAT I arrivals to all parallel runways via equipment acquisition and rule change,[8] addition of a noise abatement immediate north divergent turn for turbo prop aircraft to complement existing immediate south divergent turns, immediate divergent turns for all aircraft departures, and use of runway 3 for small cargo aircraft during peak periods. The performance assessment of all operational improvements was performed through computer simulations using the FAA Airport and Airspace Simulation Model (SIMMOD), which captured the characteristics of the operational demand for the two futures and the different enhancement alternatives considered. For each improvement, and for a few selected combinations of improvements, benefits were reported in terms of appropriate metrics such as reductions in ROT for the construction of new taxiways, or annualized delay reductions with equivalent monetized values for CAT I approach enhancements. Results of this study revealed varying levels of improvement based on monetized annual delay savings. For Future 1 the 1.5 NM staggered approach using CAT I ILS on runways 10 and 28 (east flow) proved the most beneficial with over $20 million in delay savings. In the high density case (Future 2) the combined effect of immediate north divergent turn for all aircraft, staggered approaches for east and west flow, and parallel runway end connections, yielded a dramatic $179 million annual saving in delay.[86]

In 1997 an Airport Capacity Enhancement Plan update was released for Memphis International Airport (MEM). The original 1988 plan for MEM was updated in lieu of the

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[8]A complete description of the ILS, ILS categories, and dependent/independent parallel runway operations is provided in Section A.2 of Appendix A.

commission for construction of a new runway in 1996 and the anticipated closing of existing runways for reconstruction. The plan aimed to update existing models, provide inputs to the MEM master plan, and examine additional measures of capacity enhancement. As with the plan for PDX released the previous year, baseline values of aviation activity were set as reference for two notional futures representative of moderate and high increases in operations. Airfield improvements included runway extensions to reduce ground congestion and delay, high speed runway exits to reduce ROT and support longitudinal separation reduction in IFR arrivals, and departure staging areas which allow Air Traffic Control Tower (ATCT) to reconfigure the departure queue to increase capacity. Facility and equipment improvements included CAT IIIc approaches to runways 36R and 36L allowing simultaneous independent approaches in cases of extremely reduced visibility, use of PRM/Final Monitors/Aids (FMA)[9] for simultaneous independent use of closely-spaced parallel runways 18R/36L and 18C/36C, and acquisition of the WVAS for reduced aircraft separation. Operational improvements included the reduction of in-trail separation to 2.5 NM for similar class aircraft within 10 NM of the runway threshold, and double and triple simultaneous departures assuming immediate track divergence removing noise abatement procedures. Additionally, a variety of runway operation configurations were examined for the reconstruction period of the airport.[90]

A number of similar *Airport Capacity Enhancement Plans* were conducted in the following years, including Miami International Airport (MIA) in 1997 [91], Newark International Airport (EWR) in 2000 [98], Tampa International Airport (TPA) in 2000 [99], and a second one in PDX in 2001 that explored the option of a third parallel runway in combination with reduced noise restrictions [104]. The different types of improvements, estimated costs and calculated delay savings for these airports are summarized in Table 4. Delay savings are annualized and shown in hours and equivalent monetized values. Both delay savings and improvement project cost values (where available) are given in current dollars[10]. Airport diagrams from the aforementioned studies are also included for convenience, and shown in

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[9]Complete descriptions of PRM and FMA are presented in detail in Section A.2 of Appendix A.

[10]For example, the 1996 study of PDX uses 1996 dollars whereas the 2001 study of PDX uses 2001 dollars.

Figure 5: Airport diagrams from selected FAA Airport Capacity Enhancement Plan studies. (Source: FAA [86, 90, 91, 98, 99, 104])
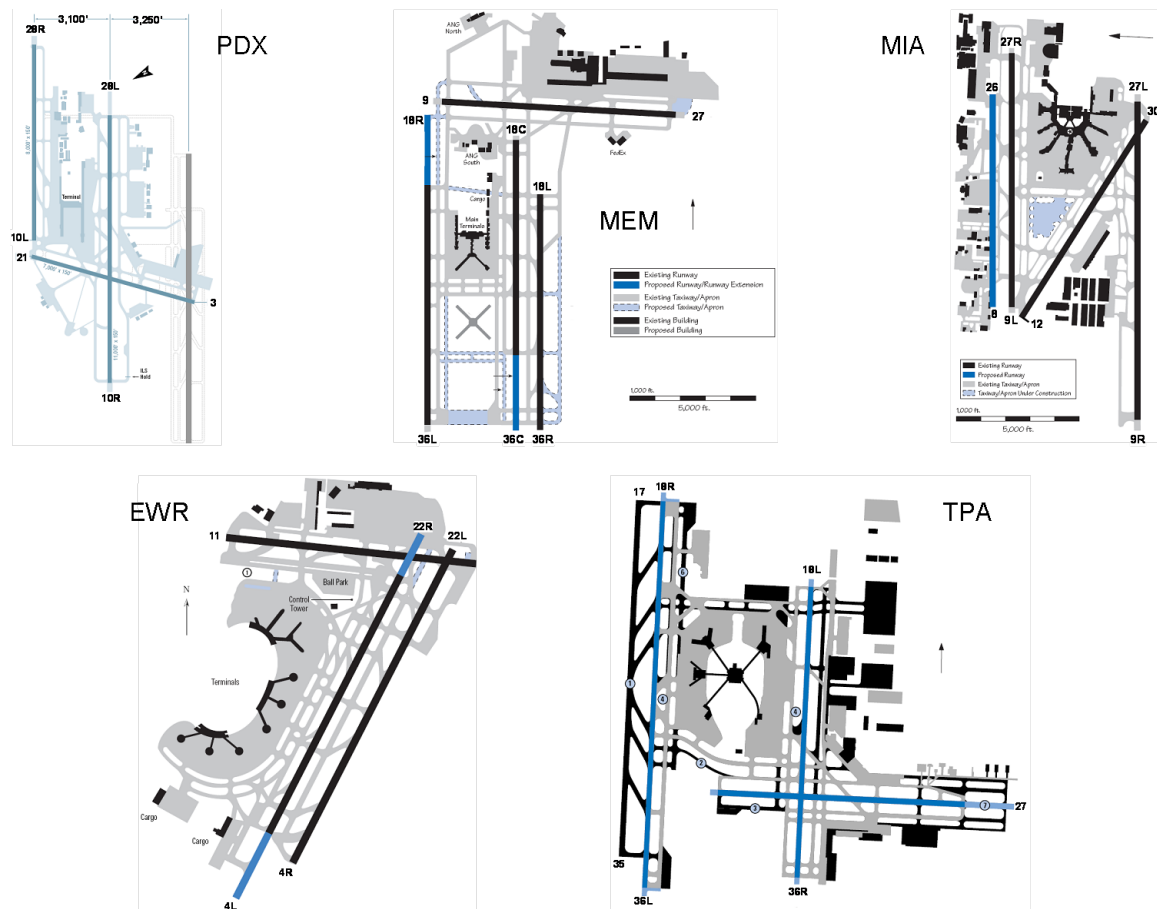
Figure 5.

Overall, these capacity enhancement plans demonstrate how improvements to each airfield provide measurable results for varying levels of operational activity. Moreover, they illustrate how operational improvements require the necessary facilities and equipment, and how they can leverage airfield improvements such as an extended or a new runway. The importance of a sufficient and well designed taxiway network that enables ready access to runways and gates is also highlighted, recognizing that surface traffic is a major component of terminal congestion and delay. The notable focus on independent/simultaneous and dependent operations on parallel runway configurations, as well as the reported delay savings figures, strongly suggests that this type of improvement is particularly promising.

It is worth noting that some of these plans included policy-type measures. The plan for EWR, for instance, considered the use of vertiport and tiltrotor vehicles, within the hour de-peaking, and updated fleet mix composition. Similarly, the 2001 study for PDX considered varying levels of reductions in noise restrictions. While recognizing their analytical value, such measures fall outside the scope of interest of this thesis and thus have not been included in Table 4.

There are however some notable shortcomings that can be generally attributed to all these *Airport Capacity Enhancement* plans. The extent to which the performance of each airport is characterized in its reference state is limited to very few illustrative empirical figures on delay. Despite the availability of numerous experts, a wealth of empirical data, and terminal area simulation models, the characterization of the airport's complex systemic behavior is altogether absent. Similarly, while quantitatively assessing the impact of individual solutions, and the aggregate impact of selected combinations, the sensitivity of relevant performance metrics to this solutions was not fully characterized, particularly since the interactions between solutions is not explicitly quantified either. These plan also fail to account for environmental, socioeconomic, or political issues, but recognize the importance of these considerations by providing recommendations for additional studies to address these matters.

Not all Airport Capacity Enhancement Plans were as general in nature as the six that were just explained. Rather than providing airfield, operational, and equipment type improvements, special focus studies were conducted at selected airports. An *Airport Capacity Enhancement Plan* was published in 1996 for Los Angeles International Airport (LAX) that focused on a purely tactical initiative where commuter airline gates were relocated to reduce airport traffic congestion and delay. Four proposed commuter gate configurations were investigated in combination with the alternative of an additional taxiway . The study concluded that given acceptable levels of modeling error there was no significant improvement in delay from any of the gate configurations considered.[89] Two other plans investigated the re-design of terminal airspace: the 1996 *Airport Capacity Enhancement Terminal Airspace Study* for Minneapolis-Saint Paul International Airport (MSP) [88], and

Table 4: FAA Airport Capacity Enhancement Plan studies summary

Improvement Type	Improvement	Annual Delay Savings		Improvement Costs (millions)*
		Baseline	High Density	
Portland International Airport (1996)				
Airfield	Extend existing exit taxiways	ROT < 50 sec.		$0.7 - $1
	Build new exit taxiways	ROT < 50 sec.		$2.3 - $3.8
	Build new taxiway connecting east end of runways 10R/28L and 10L 28R (Dep. Sequencing)	684 - $0.8	45,200 - $54.2	$56
	Build departure pads for 10R/28L, 28R runway ends (Dep. Sequencing)			$2.3 - $3.2
Operational	1.5 NM staggered approach ILS Runway 10L (east flow)	1,111 / $1.3	65,457 / 78.52	
	1.5 NM staggered approach ILS Runway 28L (west flow)	530 / $0.6	32,273 / $38.7	
	Simultaneous CAT I approaches to all runways	1,753 / $2.1	98,647 / $118.4	
	Immediate divergent turn for all aircraft (IFR Dep. Separation)	684 / $0.8	35,089 / $42.1	
Memphis International Airport (1997)				
Airfield	Extend existing exit taxiways	830/$1.9	8,210/$29	$25
	Extend runways (accommodate long range flights)			$69 - $100
	High speed exits on all runways - all directions (reduced ROT and longitudinal spacing)	210/$0.5	2,550/$9	$7
	Departure staging areas on all runway ends (Sequencing)			$5 - $12.5
Facilities	Precision Runway Monitor, Final Monitors/Aids	1,410/$3.4	6,230/$22	$7
	Wake Vortex Advisory System (WVAS) (assumed 100% detection)	450/$1	6,390/$22.6	
Operational	Reduced longitudinal in-trail spacing to 2.5 NM in IFR	790/$1.9	4,940/$17.5	
	Simultaneous IFR parallel departures for runways 18R and 18C (assume immediate divergence)	60/$0.6	300/$1	
	Triple simultaneous parallel departures 18R,C,L, with RWY 27 (no noise abatement)	310/$0.8	2,310/$8.2	
Miami International Airport (1997)				
Airfield	New non-precision runway 8/26 (8,600' air carrier runway)	17,420/$36.9	397,840/$843.8	$180
Facilities	CAT II/III ILS on runway 9R			$3
	Instrument precision approach equipment (glideslope and middle marker) on runway 30			$2
	WVAS for triple simultaneous parallel departures (assumes runway 8/26)	400 / $0.9	2,570/$5.4	
	WVAS for triple simultaneous parallel departures and arrivals (assumes runway 8/26)	2,110/$4.5	15,050/$31.9	
Operational	Dependent non-precision approach to new runway 8/26 (relative to runway 9L/27R)	120/$0.3	840/$1.8	
	Optimize runway crossing/taxi paths and flows for runways 8/26, 9L/27R and terminal area	580/$1.2	1,010/$2.1	
	Reduced IFR arrival in-trail separation to 2 NM (assumes reduced ROT)	470/$1	400/$0.9	
	Establish 3rd departure heading for jet takeoffs in west flow conditions (day operations)	1,540/$3.3	22,900/$48.6	
Newark International Airport (2000)				
Airfield	New taxiways	1,049/$2.3	1,541/$3.4	
	New runway for independent arrivals in all weather conditions	83,059/$182.7	278,880/$613.5	
Operational	Alternate departure queuing scheme for extended runway 4L/22R			
	Parallel dual visual approaches for runways 4L/22R and 4R/22L	3,856/$8.5	10,404/$22.9	
	Localizer Directional Aid (LDA) offset approach to 4L/22R for light aircraft	6,432/$14.2	15,582/$34.3	
	Simultaneous Offset Instrument Approaches (SOIA) for runways 4L/22R and 4R/22L	9,008/$19.8	20,759/$45.7	
	Dependent Converging Instrument Approaches (DCIA)–SW flow	3,371/$7.4	3,846/$8.5	
	Simultaneous Converging Instrument Approaches (DCIA)–NE flow	6,530/$14.4	9,718/$21.4	
	Reduce minimum in-trail IFR separations to 2 NM between similar class non-heavy aircraft	2,101/$4.6	4,955/$10.9	
	Immediate divergent turns for turboprop/prop aircraft (reduce Dep-to-Dep time, to 1 min)	9,560/$21.0	28,608/$62.9	
Tampa International Airport (2000)				
Airfield	New runway 17/35, parallel to 18R/36L and 18L/36R		9,690/$15.6	$70
	Extend taxiways		3,390/$5.5 (x2)	$15
	High speed exits on runways 18L and 18R (IFR arrival in-trail spacing reduction to 2.5 NM)	380/$0.5	1,070/$1.7	$3
	Holding pads on all runway ends (Dep. Sequencing)			$5.1
	Extend runway 9/27 to allow (DCIA) on runways 27 and 35		3,900/$6.3	
	Extend runway 18L north (allow use of high speed exits)			
Facilities	Install glideslope or WAAS GPS on runway 36R for simultaneous independent approaches	130/$0.2	4,710/$7.6	$0.2
	Install CAT II/III ILS or LAAS GPS on runway 18L for south flow operations with low visibility			$2.4
Operational	DICA to runways 27 and 35 using CRDA	150/$0.2	6,180/$10	
	Relaxation of noise restrictions on runway 18L/36R		3,040/$4.9	
	Triple parallel arrivals using LDA approaches (including new runway 17/35)			
	Independent precision instrument approaches to existing runways 36L and 36R, or 18R and 18L	180/$0.2	5,240/$8.5	
	Reduce IFR arrival in-trail spacing to 2.5 NM	210/$0.3	6,980/$11.3	
Portland International Airport (2001)				
Airfield	New runway parallel to 28R/10L and 28L/10R (assumes N-S taxiway and no noise restrictions)		388,954/$645.7	
	North-south taxiway connecting east ends of existing runways and new runway			
Operational	Simultaneous CAT I approaches to existing parallel runways (assumes N-S taxiway and no noise restrictions)		359,718/$597.1	

*Cost of improvements is provided in year dollars corresponding to the year of each Airport Capacity Enhancement Plan study

the 2001 *Anchorage (ANC) Area Airspace Study* [103]. The study for MSP was commissioned by by the Metropolitan Airports Commission of the Minnesota Legislature after the 2010 Long Term Comprehensive Plan for the airport was approved. The plan included the creation of runway 17/35, as shown in Figure 6, which required the corresponding investigation of terminal airspace. The study had three main objectives: 1) to determine whether the terminal airspace could be reconfigured to accommodate inbound and outbound traffic of runway 17/35, 2) to investigate the potential benefits of additional airspace modifications such as a a new arrival stream, and 3) to examine the impact that MSP terminal airspace modification would have on the 13 or so nearby airports. The study in fact determined that an airspace reconfiguration for runway 17/35 was possible, and that the inclusion of a new jet arrival fix, as shown in Figure 6 would further help reduce delay. However the Class B airspace of the airport would require an increase in radius, from 20 to 30 NM, and a general aviation operations between satellite airports would no longer be able to take a direct route but rather circumvent the restricted airspace adding 10 to 30 miles to their trajectory. Most importantly, the study recognized that any changes to the airspace are subject to an Environmental Impact Study (EIS), and that despite its importance in realizing airspace improvements, any environmental considerations were beyond its immediate scope. While it is understandable that airport planning studies cannot always incorporate all relevant aspects, this plan is another representative example of how operational and environmental aspects have been treated disjointly in the past.

In the case of the ANC area airspace study the objective was to identify and evaluate various measures aimed at increasing airspace capacity, improving efficiency and reducing airspace-related delays. Due to their close proximity the study also included 3 additional airports: Elmendorf Air Force Base (EDF), Merrill Field (MRI), and Lake Hood (LHD), as shown in Figure 7. The study explored a large number of runway use configurations for all included airports, and examined the airspace interactions between them, particularly in the case of ANC and EDF. As a result, the solution alternatives considered in this study were not only aimed at increasing capacity for each airport but more importantly at increasing capacity in a safe and efficient way with the entire group of airports in mind and with the

Figure 6: Airport diagram and new airspace configuration for MSP, 1996 Airport Capacity Enhancement Plan. (Source: FAA [88])
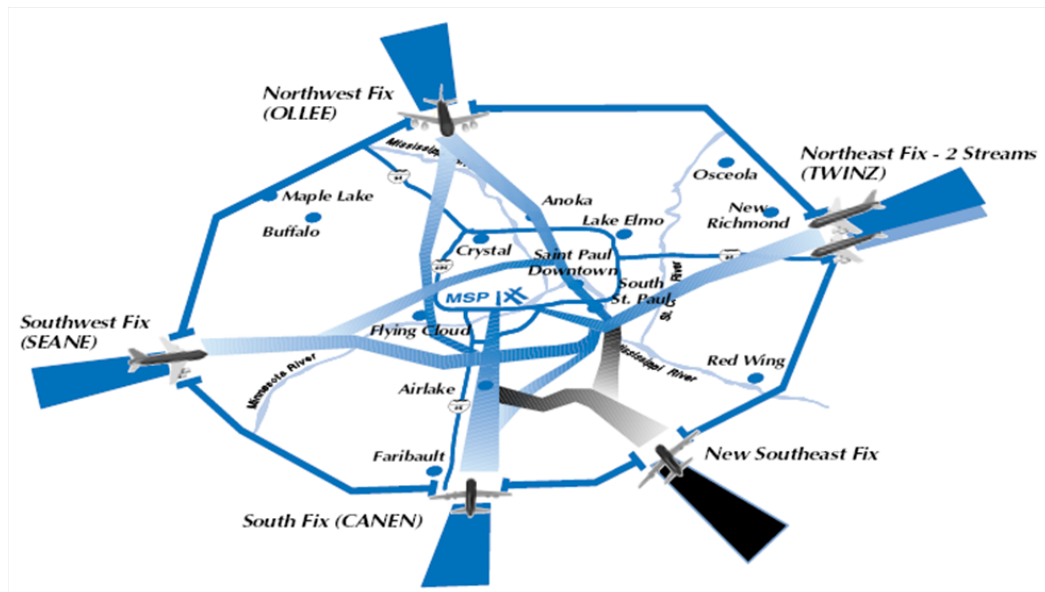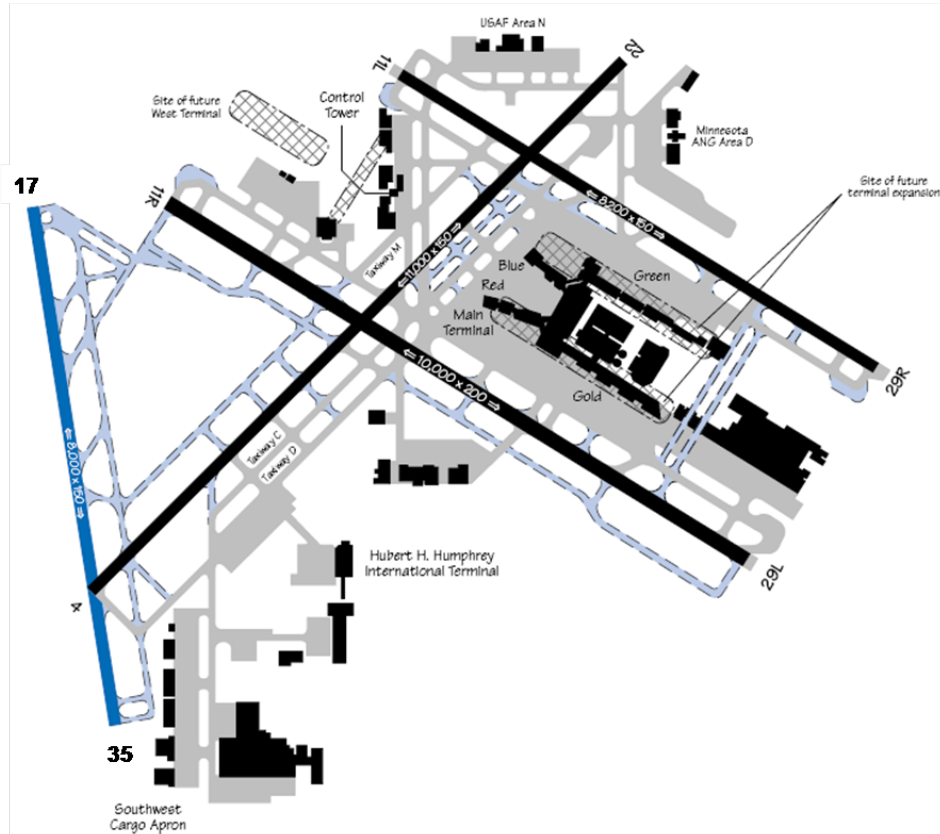
Figure 7: Airspace diagram and representative solutions, 2001 Anchorage Area Airspace Study. (Source: FAA [103])
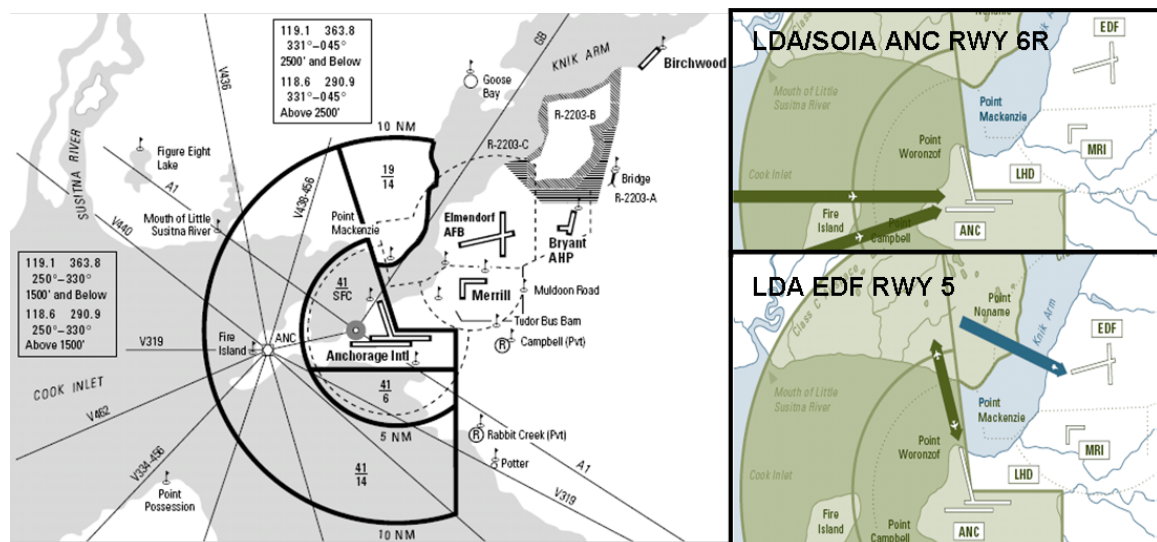
interaction between them as a primary focus. Said set of solutions included use of Localizer type Directional Aid (LDA) and SOIA on runway 6R at ANC, LDA on Runway 5 at EDF, and Dependent Converging Instrument Approaches (DCIA) on runways 14 and 6R at ANC among others, as shown in Figure 7.[103] The airspace study of ANC is slightly different from others of its kind because it incorporated considerations for capacity and safety as interdependent goals more explicitly. However, as in other *Airport Capacity Enhancement Plans*, it did not provide a characterization of performance for the system of airports in the Anchorage area other than the qualitative assessments documented therein. Additionally, the study did not explicitly quantify the interactions between proposed solutions, nor their combined impact in a sensitivities assessment.

Though the FAA continued with Airport Capacity Enhancement Plans through 2001, in 1998 its Office of System Capacity (ASC) began publishing the *Aviation Capacity Enhancement Plan* describing all major initiatives geared towards expanding NAS capacity and improving its performance and efficiency, as well documenting major milestones and accomplishments. This plan built upon the *Airport Capacity Plans* that had been conducted thus far, but extended the concept from the airport and surrounding terminal area

to to the entire airspace system. Each yearly publication, discontinued after 2003, explored a variety of different solutions and approaches which included the construction or expansion of runways and other airport surfaces, airspace re-design, arrival and departure procedure re-design, and capacity enhancing technologies.[109]

The first Aviation Capacity Enhancement Plan (1998)[93] introduced the paradigm that would be used for the next decade in terms of how the capacity problem was approached. First, it provided an overview of the NAS and pointed at four key aspects that the FAA would use to measure its performance: delay, which simply refers to the differen between scheduled and actual operations, flexibility, which relates to the extent to which different users of the NAS can alter and optimize their operations, predictability of the ATM functions, and access to all NAS resources. Secondly, it defined strategies that specifically address problems in each of these four aspects. Third, it explicitly identified a set of problematic airports that were experiencing major operational capacity shortfalls and were responsible for marked system-wide inefficiencies. Lastly, it explained major capacity initiatives such as *Free Flight* and *Safe Flight 21*, and the modernization of NAS functions like CNS and weather monitoring. Additionally it detailed developments in four main fronts:

1. *Airport Development* - Construction of new airports, expansion of existing airports, impact of next-generation aircraft on airport development, and ongoing airport capacity studies, as were illustrated in the Airport Capacity Plan studies.

2. *Airspace Development* - New entities responsible for airspace management and development, and ongoing airspace studies, as illustrated in the airspace studies for ANC and MSP.

3. *New Operational Procedures* - En route procedures (e.g. National Route Program (NRP), RNAV), oceanic en route procedures (e.g. Reduced Vertical Separation Minima (RVSM) and Reduced Horizontal Separation Minima (RHSM)), and terminal area and approach procedures (e.g. Simultaneous Converging Instrument Approaches (SCIA) and SOIA).

4. *Capacity Enhancing Technologies* - CNS, weather monitoring, and ATM technologies.

The 1999 Aviation Capacity Enhancement Plan followed a similar structure as its predecessor, but was instrumental in introducing the concept of ATM from a historical perspective, illustrating the transition from a purely tactical ATC infrastructure to a more strategically oriented one that leveraged on collaborative decision making in the national coordination of traffic flow. It continued to focus on problematic airports such as Atlanta (ATL), Chicago O'Hare (ORD), Dallas-Fort Worth (DFW), Los Angeles (LAX), noting that these and others alike were the busiest airports in terms of operations. Continuing with system performance based on delay, flexibility, predictability and access measures, this document presented developments for the modernization of the NAS with capacity enhancing systems like CNS technologies, weather data integration, and decision support systems. Programs previously introduced such as Free Flight and Safe Flight 21 were updated. Finally, the plan provides updates and reports of new initiatives for airport development, airspace redesign and new operational procedures.[95] The 2000 Plan furthered ongoing efforts and focused on the emergence of regional jets as a crucial element reshaping the operational behavior of the air transportation system.[97]

Though the aviation industry was facing great capacity challenges at that time, as well as undergoing major changes in the way the said challenges were viewed, the the terrorist attacks of September 11th had a profound impact on all NAS initiatives. At the time it was clear that these events would have a dramatic impact in the air transportation system and that the immediate effect would be a sharp decline in air transportation demand. How big that decline would be was still very uncertain, which made all industry and government growth forecasts obsolete. Moreover, the transformation of the air transportation system would shift from a safety and efficiency focus to one that greatly incorporates security as fundamental pilar of change. There were serious implications regarding the allocation of government resources to commercial aviation. Funds that were once destined to the modernization of the NAS and improvements at various airports would likely diminish in order to quickly ramp up government mandated security capabilities. None the less, starting in 2001 the FAA launched a series of coordinated efforts that closed the era of the Airport Capacity Enhancement Plans and introduced a new paradigm in the formulation of capacity

solutions. This included the continuation of the Aviation Capacity Enhancement Plan, the NPIAS, the Airport Capacity Benchmark Report studies, and the OEP.

The *2001 Aviation Capacity Enhancement Plan* followed the structure of previous reports in presenting NAS modernization efforts, and airport and airspace improvements. Solutions continued to focus on the construction of taxiways to reduce airport surface congestion and delay, construction of new terminals and gates, new or expanded runways, and airport equipment to facilitate high yield operations such as dependent/independent approaches in parallel runways, particularly in IFR conditions. It also focused, once again, on problematic airports noting that these were the ones with the highest number of present and projected operations, and noting that they had been consistently identified as such in the previous reports. Most of these airports were the focus of the *2001 Airport Capacity Benchmark Report* and the first version of the OEP. In turn, the 2002 and 2003 *Aviation Capacity Plans* incorporated the structure that had been traditionally used thus far, as well as a significant portions of the results of the *2001 Airport Capacity Benchmark* and reported on the ongoing initiatives contained in the OEP V1.0.[101, 106, 109]

The NPIAS is a comprehensive planning document developed by the FAA and used by its management to administer the Airport Improvement Program (AIP). Because the AIP is funded by the Federal government, the plan is submitted to congress and serves as detailed document justifying all investment estimates. Each NPIAS report identifies existing airports considered of significance to the national airport system and eligible for Federal funding through the AIP, as well as an assessment performance in terms of safety, capacity, pavement condition, financial performance, accessibility, and noise. Based on said assessment and on demand projections, the infrastructure needs for each airport under consideration are identified and their cost estimated. NPIASs have been generated since 1980 when the investment estimate was $8.7 billion. Since then, as illustrated in Figure 8, the scope of the plan and the total figures of federal funding for the AIP have grown considerably.[107]

Development efforts for the NPIAS are categorized as follows [107]:

Safety and Security: Refer to all projects required by standards, certification, or Federal

Figure 8: Evolution of National Plan of Integrated Airport Systems (NPIAS) investment estimates. (Source: FAA [128])
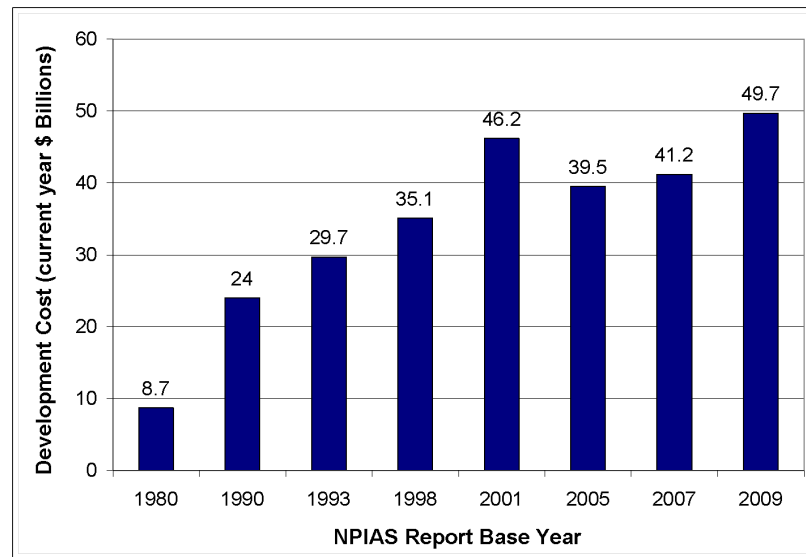
regulation, whose primary purpose is the protection of human life.

Reconstruction: Refer to the replacement or rehabilitation of facilities such as airport surface and lighting systems that have deteriorated over time and cannot be repaired with normal maintenance procedures.

Standards: Refer to all projects whose purpose is to make a facility meet recommended FAA design criteria, such as the relocation of runways and taxiways for clearance reasons.

Environment: Refer to projects aimed at reducing environmental impact to surrounding communities, such as land acquisition for residential relocation.

Terminal Building: Refer to projects exclusively aimed at the construction or expansion of buildings that accommodate passengers, airport service providers and airport tenants.

Surface Access: Refers to projects addressing ground access to the airport.

Airfield Capacity: Refers to projects that effectively increase the volume of operations

at the airport and/or reduces delay.

New Airports: Refers to airport construction in localities where enough demand for air travel exists, and no airport exists or nearby airports cannot be feasibly expanded to accommodate the prescribed demand.

Additionally, the NPIAS classifies airports as general aviation, reliever, commercial service, non-hub, small hub, medium hub, and large hub.[107] The distribution of NPIAS estimates across development types and airport classes for the last four plans is summarized in Table 5.

Table 5: NPIAS estimates and distribution 2001, 2005, 2007, 2009.(Source: FAA [107, 113, 118, 128])

NPIAS	2001-2005	2005-2009	2007-2011	2009-2013
No. of Airports	3364	3344	3431	3356
Safety	3 %	3 %	5 %	4 %
Security		2 %	3 %	2 %
Reconstruction	13 %	13 %	17 %	19 %
Standards	30 %	36 %	27 %	27 %
Environment	4 %	4 %	5 %	5 %
Terminal Building	20 %	16 %	17 %	18 %
Surface Access	10 %	5 %	4 %	4 %
Airfield Capacity	18 %	19 %	21 %	17 %
New Airports	2 %	2 %	2 %	3 %
General Aviation	13 %	17 %	19 %	19 %
Reliever	6 %	7 %	7 %	7 %
Commercial Service	2 %	3 %	2 %	2 %
Nonhub	9 %	10 %	10 %	10 %
Small Hub	7 %	7 %	8 %	8 %
Medium Hub	12 %	14 %	11 %	14 %
Large Hub	53 %	43 %	41 %	36 %
(New Airports)			2 %	3 %
Investment Estimate	$46B	$39.5B	$41.2B	$49.7B

It is important to recognize that the NPIAS has a very broad scope given that it addresses the entire domestic airport system and justifies funding at the federal level. It would be unreasonable to expect exhaustive characterization of each airport's performance, or comprehensive assessments of sensitivities, interactions, and tradeoffs in the implementation of solutions that have been considered in each case. However, this plan is effective

in considering a breadth of performance aspects for airport assessments: safety, capacity, pavement condition, financial performance, accessibility, and noise. Yet, it fails to provide explicit considerations for the tradeoffs that exist across these dimensions of performance, particularly since tradeoffs are manifested with the implementation of the proposed solutions.

The 2001 and 2004 *Airport Capacity Benchmark Reports* presented critical operational information about the nation's 31 most important airports in the NAS. The report highlights the complexity of airport capacity as a measurable quantity, given its dependence on weather conditions, runway configuration, airfield equipment, and aircraft fleet composition. However, the FAA sought to simplify and convey in a straightforward way this complex behavior through capacity benchmarks that could be used to compare airports and identify different general types. For instance, airports most sensitive to weather changes can be identified, allowing for an informed allocation of resources in the long term to correct this condition. This type of information was also found to be of profound value in policy discussions as it conveyed the current and projected future state of each of these key airports. The methodology of this study included current airport configurations and demand levels at the time, projected demand values procured by the FAA Terminal Area Forecast (TAF), and anticipated improvements where applicable. The improvements included in this study focused on new or extended runway construction plans that were fairly mature, as well as procedural technologies such as ADS-B and CDTI with LAAS for precise aircraft tracking and separation, or PRM for simultaneous instrument landings to closely separated parallel runways. These capacity benchmarks did not consider delay due to surface traffic, cause for instance by construction or taxiway congestion. Simulations were performed with "*the FAAs widely accepted airfield capacity computer model*"[11][102] for optimum and reduced visibility rates, which were later confirmed with actual data reported by acATC personnel

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[11]The 2001 and 2004 Airport Capacity Benchmark Reports do not specify what tool was used for the simulations, other than stating it is a *widely accepted airfield capacity computer model.* Given that SIMMOD was used by the FAA to conduct the Airport Capacity Enhancement Plan studies published up until 2001, it is very likely that this same tool was used for the capacity benchmark studies.

and historical data, as well as carrier scheduled data from the OAG. The measure of performance for these benchmarking studies is delay, measured for aircraft whose operations were more than 15 minutes later relative to the schedule on the FAA Operations Network (OPSNET) database. The capacity benchmarks demonstrated that problems and potential solutions are very specific to each airport. For example, there is significant variability in the reduction of capacity due to adverse weather among the 31 airports considered, ranging from 2% for Cincinnati to 40% for San Francisco according to the 2001 report. However, general behavioral trends could be observed all across, like the increase in delay close to capacity limits which resulted in reduced levels of operational quality when operating at maximum capacity.[102, 111]

The *Airport Capacity Benchmark Reports* represent the most complete, explicit, and dedicated efforts to airport performance characterization. These studies are noteworthy in that they recognize systemic complexity as a key challenge for this task, and because they tackle the impact of weather conditions on airport capacity head-on, providing a basic form of sensitivity analysis and illustrating how this sensitivity is varies across airports. Although these studies took into consideration airport configuration as a primary endogenous factor affecting capacity and delay, they do not illustrate how these performance metrics change with different airport configurations. Thus, the potential interactions between airport configuration and weather conditions, and the way that this interaction can affect the sensitivity of delay to these metrics, is not explicitly treated. Finally, it is evident that consideration of environmental impact are beyond the scope of *Airport Capacity Benchmark Reports*, illustrating once more the prevalence of a disjoint view of these two aspects of airport performance. Thus they are not really intended to tackle, even in the most basic form, the operational-environmental tradeoff.

It is worth noting that the TAF constitutes demand projections at a local level based upon FAA national forecasts of aviation activity. The TAF database is maintained by the FAA Office of Aviation Policy and Plans (APO) which also updates the forecast on a yearly basis and publishes a summary report that is made available to the general public. Both the TAF database and the yearly reports represent an important resource for the budget

allocation and planning exercises. The yearly forecasts between 1997 and 2000 were system-level reports that procured "*historical aviation data and forecasts for airports receiving FAA and contract tower radar service.*"[92, 94, 96, 100] Starting in 2001 the TAF broadened its scope to all airports in the NPIAS, and placed particular emphasis on the top 31 busiest airports that had been identified in the Aviation Capacity Enhancement Plan and in the Airport Capacity Benchmark Report issued that same year.[105]

Though *Aviation Capacity Enhancement Plans* were procured by the FAA through 2003, the original release of the OEP in June 2001 marked the beginning of a transition to a more integrated paradigm in the FAA's approach to enhancing capacity and efficiency in the NAS. The OEP was created in response system inefficiencies that had been experienced during the 1990's and had peaked with record delays and cancelations in the summer of 2000. The plan serves as a general blueprint for all efforts aimed are addressing these gaps, and works towards a goal to accommodate a 3% (average) annual growth in NAS user demand. Additionally, it identifies key problems and establishes general solution strategies such as minimizing congestion at high altitudes and increasing airport arrival rates under all weather conditions. To coordinate efforts in these areas the OEP has been structured into four major quadrants: ATM flow efficiency, en route congestion, terminal area congestion, and airport surface. The first three quadrants are aligned with the FAA's Air Traffic Organization (ATO), whereas airports surface is aligned with FAA Airports and FAA Regions and Center Operations. ATM flow efficiency projects focus on improved weather information, collaborative coordination of traffic flows, and efficient operation of arrival streams, and depend on the successful implementation of systems, concepts and technologies such as Airport Surface Detection Equipment - Model X (ASDE-X), Traffic Management Advisor (TMA), and CDA. Enroute congestion efforts aim to implement user-preferred routing and RNAV routes, reduced separation, and reduced voice communications, also enabled by relevant technologies. Efforts on terminal area congestion for the OEP build upon those of previous FAA plans, and include the creation of new arrival, approach, and departure procedures, as well as technology-enabled reductions in aircraft separation.Airport surface projects include the construction, extension or relocation of runways, as well as the

construction taxiways and other related surfaces.[111, 129]

While maintaining a system-wide, all-encompassing approach to the NAS, the OEP clearly places particular focus on airports and terminal areas. The top 31 busiest airports referred to in other FAA efforts, were largely responsible for most of the aforementioned delays and cancelations that prompted the creation of the OEP. These airports were also projected to experience severe capacity shortfalls in the absence of a concerted effort, and thus were the object of particular attention in the OEP, consistent with other plans and reports. The set of 31 airports was since then referred to as the *OEP airports.* An updated version of the plan was released in December of 2001, and has since then been updated and published as a new version on a yearly basis.[110, 116] In 2004 the set of OEP airports was increased to a total of 35 as shown in Table 6, which was reflected in the 2004 *Capacity Benchmark Report* released that same year, in all TAF reports published since that year, and in the NPIAS reports since 2005. Moreover, as the different capacity enhancement measures were considered and refined over the years since 2001, all the aforementioned plans and reports reflected these changes consistently.[111, 129]

Table 6: OEP 35 Airports.(Source: FAA [116])

Hartsfield-Jackson Atlanta International	ATL	Memphis International	MEM
Baltimore-Washington International	BWI	Miami International	MIA
Boston Logan International	BOS	Minneapolis-St Paul International	MSP
Charlotte/Douglas International	CLT	New York John F. Kennedy International	JFK
Chicago Midway International	MDW	New York LaGuardia	LGA
Chicago O'Hare International	ORD	Newark Liberty International	EWR
Cincinnati-Northern Kentucky	CVG	Orlando International	MCO
Cleveland-Hopkins International	CLE	Philadelphia International	PHL
Dallas-Fort Worth International	DFW	Phoenix Sky Harbor International	PHX
Denver International	DEN	Portland International	PDX
Detroit Metro Wayne County	DTW	Ronald Reagan Washington National	DCA
Fort Lauderdale-Hollywood International	FLL	Salt Lake City International	SLC
George Bush Intercontinental	IAH	San Diego International Lindbergh	SAN
Pittsburgh International	PIT	San Francisco International	SFO
Honolulu International	HNL	Seattle -Tacoma International	SEA
Lambert St. Louis International	STL	Tampa International	TPA
McCarran International	LAS	Washington Dulles International	IAD
Los Angeles International	LAX		

At the time version 8.0 of the OEP was published, in 2006, success in many key areas had been recognized by industry and congressional leadership. This motivated the expansion of the original plan into the *Operational Evolution Partnership*, which superseded the *Operational Evolution Plan* and overtook its acronym. Version 1.0 of the partnership, published in June 2007, was formulated as the FAA's implementation plan for the transformation to the Next Generation Air Transportation System (NextGen) as envisioned by the JPDO, of which the FAA is a member agency.[121] For the next version of the OEP issued a year later (June 2008), the partnership was appropriately renamed the *FAA NextGen Implementation Plan* to explicitly state its purpose.[126] With this transition, the *FAA NextGen Implementation Plan* currently features a profoundly integrated view of the challenges and proposed solutions across the entire system, and consistent with JPDO planning artifacts such as the Integrated Work Plan [194], the Concept of Operations [192], and the Enterprise Architecture [193].

In parallel to OEP and capacity benchmarking efforts, the FAA also produced a 2004 *Future Airport Capacity Task (FACT)* reports which identified airports that would not meet projected future demand levels on prescribed target years, and examined how selected operational technologies and new runways, outlined in OEP reports, would enhance capacity under different weather conditions.[112] An updated 2007 FACT report broadened its solution portfolio and used updated capacity benchmarks. It also noted the importance of environmental impact assessment to capacity enhancement, primarily in the case of new runways, but the extent of said consideration was limited to basic assumptions about environmental impact constraints.[119] Recent FACT efforts included additional NextGen concepts and show more explicitly that the combined effect of airport solutions can be greater than the sum of its individual contributions. This work emphasizes (albeit implicitly) the existence and importance of interactions among solutions, but does not explicitly quantify those interactions.[135] Moreover, *FACT* studies do not provide a characterization of performance for the airports considered that elucidates the tradeoffs across various performance metrics for the proposed improvements at each of them.

The Joint Planning and Development Office is the executor of the Next Generation Air

Transportation Systems (NGATS) Integrated Plan which proposes a transformation of the current system across multiple objectives such as reduced environmental impact, increased capacity, safety and security among others. Within the JPDO the Interagency Portfolio and System Analysis IPSA) division, formerly known as the Systems Modeling and Analysis Division (SMAD), performs assessment of transformation strategies and reports the key goal tradeoffs to the Offices principals, thus supporting and enabling the prioritization of investments. More specifically, IPSA models Operational Improvements (OI), each of which denotes a given measure or concept contributing towards JPDO capabilities and consequently to national goals. Thus, the performance of the system is evaluated under a variety of scenarios of interest to assess the effect of different OIs and the ability to meet goals relative to a baseline year. The integrated modeling and analysis process implemented by SMAD incorporates basic demand modeling tools that are complimented with airport and airspace queuing models to identify feasible demand levels based on capacity limits. It also incorporates system models at the runway, airport, and NAS level that feed to economics, security and environmental performance tools.[215]. The analyses conducted by IPSA cover a wealth of solutions, captured by OI's, and assess their impact across different performance metrics. In doing so, this work represents the highest level of multidisciplinary analysis integration that is readily conducive to airport performance characterizations discussed thus far. Although much of this work has successfully captured many of the interactions and sensitivities inherent in the realization of OI's, there is still much space for improvement with regards to quantitative characterizations of complex systemic behavior.

The characterization of terminal area performance and comparative evaluation of solution alternatives in terms of tradeoffs, sensitivities, and interactions, is paramount in realizing strategic pre-decisional assessment, but the review efforts presented in this section reveals that it is done only to a limited extent. This survey also depicts how operational and environmental considerations traditionally have been treated disjointly, and that although environmental constraints are recognized to be of significance for capacity enhancement, the emphasis is predominantly found in the operational domain. The assessment of different solution types has also been limited, although efforts by the JPDO represent a major push

towards truly interdisciplinary and integrated assessments. Capacity enhancing plans compare airfield and operational procedure improvements, and in recent years have also included new operational concepts, but the comparison relative to other solutions is less explicit or altogether lacking. While the value of aircraft technologies to reduce fuel consumption, emissions, and noise, cannot be disputed, an assessment of its benefits vis-a-vis terminal area improvements is notably absent. Moreover, it has also been noted that "*within the ATM community, analysis focuses on quantifying the benefits of specific technology investments, and infrequently will assess alternative technologies. Seldom, if ever, are non-technology policies included in the analysis.*"[205] In turn, the combined effect of proposed solutions has been addressed in a very limited fashion, and quantification of interactions among proposed solutions and the sensitivity that key performance metrics will have to them is yet to be explicitly treated.

3.6.2 Forecasts and Scenario Development for Strategic Airport Planning

Although the use of scenarios for strategic planning is not new, it has only adopted for aviation and aerospace applications such as strategic airport planning in recent years. For the most part, the use of forecasts has constituted the predominant practice in the development of projections describing future conditions and levels of aviation activity. As with the previous section, the purpose of here is not to offer an exhaustive review of all forecasting and scenario-based efforts in this field, but rather to illustrate relevant strengths, weaknesses, and gaps in some of the most representative ones.

The strategic planning efforts reviewed in the previous section make use of forecasts or scenarios to describe possible future conditions of interest. The TAF is an unconstrained forecast developed by the FAA to assess the potential growth of aviation activity, that is, assuming that sufficient capacity will be available for the forecasted time frame. Thus, the TAF provides a measure of the potential growth in demand that can be expected, and thus represents a reference for how much the system may have to grow to accommodate those demand levels. Thus, the TAF has been used for all of the FAA's national/federal-level strategic airport planning efforts, such as the *Aviation Capacity Enhancement Plan*, the

Airport Capacity Benchmark, the *NPIAS*, and the *FACT* studies. Whereas the the TAF is updated on a yearly basis, and its use has been FAA standard practice for many years, many argue against the suitability of forecasts for strategic airport planning by pointing at fundamental methodological limitations and flaws.

The inadequacy of using forecasts in the uncertain and dynamic environment of air transportation was most clearly revealed after the terrorist attacks of September 11, 2001, but is certainly not limited to this particular instance. First, the construct and development of forecasts precludes the prediction of low-probability events, such as terrorist attacks of considerable magnitude. Second, the gamut of changes and developments that unfolded from this event were very sharp, highly uncertain, and rapidly changing [101]. Some notable examples include the decline in demand, the funding on NAS improvement initiatives, and changes in standard practices by operators. These conditions made all preexisting industry and government growth forecasts obsolete, and all ongoing/new forecasts grossly inadequate. Given this highly uncertain environment, experts in the futures studies and strategic planning disciplines advocated the use of scenarios in the period following the aforementioned terrorist attacks to manage the impact of such a catastrophic event and conduct planning efforts accordingly.[281]

The use of scenarios to account for a number of possible future conditions is not prevalent in FAA studies, but was employed at a very small scale in the *Airport Capacity Enhancement* plans for individual airports where only two future demand levels were considered for each airport study, one commensurate with available forecasts and another with higher operations count representative of high density volumes. (See for instance Ref. [86].)

NASA has been implementing full-scale scenario-based strategic planning efforts for a number of years. One study was conducted in 1996 by the *Office of Aeronautics* and the National Research Council (NRC) to identify issues and items of key importance to aeronautics, the potential for evolutionary and revolutionary technology developments, and the role that NASA could play to address these issues by adequately allocating its resources on relevant technology development programs. Although this study did not focus on strategic airport planning, it is none the less relevant as it illustrates how scenario development has

been approach for the aeronautics field by a key player of the air transportation system such as NASA. The study defined a time frame of interest spanning 15-25 years into the future. Like most strategic planning and scenario development efforts, this study centered about subject matter experts and conducted a series of workshops to elicit information and reach consensus. The development of scenarios was initiated with the enumeration of a variety of *drivers* based on the collective of expert opinions. These drivers were then distilled into four top-level dimensions, or characteristics, describing possible futures for air transportation. These defining characteristics and their possible alternatives are:

- *U.S. Economic Competitiveness*: Strong vs. Weak

- *Worldwide Demand for Aeronautics Products and Services*: High Growth vs. Low Growth

- *Threats to Global Security and/or Quality of Life*: High vs. Low

- *Global Trend in Government Participation in Society*: High vs. Low

A total of sixteen combinations, each representing a different scenario, are possible based on these four dimensions and the two alternatives defined for each of them. The total list of scenarios is shown in Table 7. From this set, the five scenarios highlighted were selected "*based on the potential challenges or opportunities they may hold for aeronautics.*"([9] p. 11) The study then identified needs and opportunities for each scenario, and then classified all of them as robust, significant, and noteworthy. Robust refers to needs and opportunities that are common to all scenarios, significant refers to those that are less common but vital to some scenarios, and noteworthy are those that are specialized and unique to a given scenario.

The definition of evaluation criteria for scenario selection in this study is ambiguous and subject to much interpretation. It can only be assumed that the selection process was based on expert judgement and on a qualitative basis. Whereas value and importance of expert opinion for this study cannot be disputed, there is a notable lack of methodological rigor and formalism.

Table 7: Scenarios for NASA's Aeronautics Enterprise.(Source: [9])

	U.S. Economic Competitiveness	Worldwide Demand for Aeronautics Products and Services	Threats to Global Security and/or Quality	Global Trend in Government Participation in Society of Life	Scenario Name
1	Strong	High Growth	High	Low	
2	Strong	High Growth	High	High	
3	Strong	High Growth	Low	Low	Pushing the Envelope
4	Strong	High Growth	Low	High	
5	Strong	Low Growth	High	Low	
6	Strong	Low Growth	High	High	Grounded
7	Strong	Low Growth	Low	Low	
8	Strong	Low Growth	Low	High	
9	Weak	High Growth	High	Low	
10	Weak	High Growth	High	High	Regional Tensions
11	Weak	High Growth	Low	Low	Trading Places
12	Weak	High Growth	Low	High	
13	Weak	Low Growth	High	Low	
14	Weak	Low Growth	High	High	Environmentally Challenged
15	Weak	Low Growth	Low	Low	
16	Weak	Low Growth	Low	High	

Another noteworthy scenario-based strategic planning effort was conducted for NASA by the Logistics Management Institute (LMI) in 2003. In contrast with the 1996 study by the *Office of Aeronautics*, this effort focused on characterizing the context in which operational concepts and NAS technologies proposed by NASA would be implemented, thus enabling relevant assessments of their operational and societal benefits. To do so, experts were actively engaged to address the interdependencies between key economic drivers, the role of air transportation and its economic impact, and the impact of ATM solutions for the NAS proposed by NASA. The development process for scenarios is substantially based upon its 1996 predecessor, but introduces some new components. Given the operational focus of this study, a series of *demand* drivers was compiled and distilled to four fundamental ones. Each of these demand drivers was defined to have two possible values as follows:

- *GDP Growth*: High vs. Low

- *Airline Yields*: High vs. Low

- *Limits to Aviation System Growth*: Many vs. Few

- *Substitutes to Commercial Air Travel*: Good vs. Poor

The resulting set of sixteen scenarios were then checked checked for internal consistency among demand driver values, and reduced to a subset of eight plausible scenarios. Experts were then asked to provide estimates of the likelihood associated with each of these eight scenarios, which were documented as probability values. Based on this assessment, three scenarios were determined to be plausible but unlikely, and were discarded to yield a final set of five scenarios shown in Table 8. Note that the eight plausible scenarios have been highlighted, but that only the final five were given scenario names and further developed.

Table 8: Scenarios for NASA's NAS Technology Assessment Study.(Source: [302])

	GDP Growth	Airline Yields	Limits to Aviation System Growth	Substitutes to Commercial Air Travel	Scenario Name	Probability
1	High	High	Few	Good		
2	High	High	Few	Poor		
3	High	High	Many	Good		
4	High	High	Many	Poor	Economic Growth / Airlines Recover	20%
5	High	Low	Few	Good		
6	High	Low	Few	Poor	Economic Growth / Consumer Rules	10%
7	High	Low	Many	Good	Substitutes Take Share	15%
8	High	Low	Many	Poor		
9	Low	High	Few	Good		
10	Low	High	Few	Poor		
11	Low	High	Many	Good		
12	Low	High	Many	Poor	Growth Limits Prevail	15%
13	Low	Low	Few	Good	Low-Cost Carriers Dominate	20%
14	Low	Low	Few	Poor		
15	Low	Low	Many	Good		
16	Low	Low	Many	Poor		
	N/A	N/A	N/A	N/A	All Other Scenarios	20%

To assess the operational, economic, and societal benefits of ATM technologies, aviation activity projections were created for each of the final five scenarios. These representative operational activity levels were intended to be captured in an appropriate modeling and simulation environment where the impact of ATM technologies could be assessed for each scenario. A baseline of aviation activity was defined and used as a reference point upon which growth factors were applied to generate projections accordingly. The determination of appropriate growth factors prescribed the use of economic and demand models that relate the demand drivers characterizing each scenario to said growth factors.[302] In this sense, each scenario was defined according to top-level demand drivers that were translated

to corresponding levels of operational activity through adequate models. The process for scenario evaluation and selection featured in this study represents a a considerable improvement in the degree of methodological formalism relative to the 1996 *Office of Aeronautics* scenario study. In particular, the use of internal consistency and likelihood as downselection criteria provides a more rigorous approach, although it is still entirely based on expert judgement. However, the concept of internal consistency is not sufficiently defined, nor is the mechanism by which the relationship between demand drivers comprising each scenario was assessed. On the other hand the generation of projections for each scenario represents a very interesting approach, of particular relevance to the strategic airport planning process, given that it maps top-level demand drivers to lower level descriptors of operational activity. This capability, as was noted, requires appropriate modeling tools to realize this mapping between drivers and operational activity descriptors.

The use of scenarios has also been fully adopted by the JPDO, whose Futures Working Group (FWG) conducted a study in 2004 to develop a set of five long-term global scenarios, "*with the intent of crafting air transportation strategies that would prove effective across the range of postulated future worlds.*" ([197], p. iii) The development of scenarios and top-level strategies by this group involved interviews of over one hundred experts representing the interests of stakeholders and actors of the air transportation system. A total of five distinct and plausible scenarios were developed for which eleven robust strategies supporting the transformation of the system were articulated. The scenario development process began with the compilation of an exhaustive list of drivers relevant to air transportation over a ten year time frame. This list of drivers contained a variety of entities, trends, actors, technologies, and influencing conditions for the operating environment. Drivers were then aggregated into four top-level dimensions for with two possible alternatives as follows:

- *Strength of the U.S. Economy*: Strong vs. Weak

- *Rate of Globalization*: Increasing vs. Decreasing

- *Global Trend in Transportation Architecture*: Centralized vs. Diffuse

- *Nature of Impediments to Aviation Growth and Development*: Security-Driven vs.

Quality-of-Life-Driven.

A total of sixteen combinations are possible based on these four dimensions and the two alternatives defined for each of them. These are the sixteen scenarios contained in the scenario space, which are shown in Table 9. From this set, the five scenarios highlighted were selected as the final set, and further developed. The rationale used for this selection process is articulated by the JPDO FWG in the following way:

These five scenarios, in the judgment of JPDO, highlight the most compelling challenges that may face the air transportation system over the next two decades, and, as a set, capture the fullest range of plausible futures for planning purposes.

This statement suggests that scenarios were chosen based on their individual relevance to anticipated challenges, and on the extent to which they collectively captured the broadest range of distinct possibilities. Beyond the obvious ambiguity in the definition of these evaluation and selection criteria, the selection process appears to be predominantly qualitative and entirely reliant on the judgement of participants. Although the value of expert opinion and judgement must be recognized in scenario development efforts, the evaluation and selection process lack traceability and methodological formalism.

It is clear that the three representative examples described follow closely the same basic approach for scenario development. Although the 2003 LMI study stands out as a more rigorous and transparent process, the general observation is that the evaluation and selection of a scenario set lacks methodological formalism, and as a result features a notable deficiency in traceability and repeatability. The reliance on subject matter expert opinions for scenario development, and in general for strategic planning efforts, is recognized as a necessary and inevitable condition. However, the insight that can be produced by eliciting expert judgement in this task must be made more explicit and transparent through a properly defined method that is flexible enough not to stifle assessments procured by participants.

3.7 Research Objectives

Given the importance of pre-decisional assessments to support informed decision making in airport strategic planning, it is paramount to adequately characterize airport performance

Table 9: JPDO Futures Working Group Scenarios. (Source: [197])

	U.S. Economy Strength	Pace of Globalization	Global Trend in Transportation Architecture	Impediments to Aviation Growth & Development	Name
1	Strong	Decreasing	Centralized	Quality-of-Life Driven	
2	Strong	Decreasing	Centralized	Security Driven	"Storm Clouds"
3	Strong	Decreasing	Diffused	Quality-of-Life Driven	
4	Strong	Decreasing	Diffused	Security Driven	
5	Strong	Increasing	Centralized	Quality-of-Life Driven	
6	Strong	Increasing	Centralized	Security Driven	
7	Strong	Increasing	Diffused	Quality-of-Life Driven	"Markets Rule"
8	Strong	Increasing	Diffused	Security Driven	
9	Weak	Decreasing	Centralized	Quality-of-Life Driven	"Is It Hot or What"
10	Weak	Decreasing	Centralized	Security Driven	
11	Weak	Decreasing	Diffused	Quality-of-Life Driven	
12	Weak	Decreasing	Diffused	Security Driven	"Terror Uncontained"
13	Weak	Increasing	Centralized	Quality-of-Life Driven	
14	Weak	Increasing	Centralized	Security Driven	
15	Weak	Increasing	Diffused	Quality-of-Life Driven	"Asia's Century"
16	Weak	Increasing	Diffused	Security Driven	

and focus efforts on addressing its inherent systemic complexity by examining interactions, sensitivities, and tradeoffs. This characterization is particularly relevant to the assessment of airport performance under current/reference conditions realized in *Step 2* of the strategic airport planning process presented in Section 3.4.3, as well for the assessment of different terminal area solutions realized in *Step 6*. However, the review of documented airport strategic planning efforts reveals that performance characterization under reference conditions is altogether absent in some cases, or fail to sufficiently account for interactions, sensitivities, and tradeoffs, even in dedicated performance benchmarking studies. Similarly, most evaluations of potential terminal area solutions are generally lacking in the characterization of interactions, sensitivities, and tradeoffs, although the most recent efforts have more exhaustively examined the matter of aggregate impacts by multiple interacting solutions.

Whereas these methodological gaps have been recognized and readily identified a number of existing representative studies, the following objectives are can be stated for this thesis:

Thesis Objective 2: To quantitatively characterize the operational-environmental performance of terminal areas by investigating the interactions between exogenous and/or exogenous factors, the sensitivity operational and environmental performance metrics to different factors, and the tradeoffs and correlations between operational and/or environmental metrics.

Thesis Objective 3: To quantitatively characterize the effect that different solutions, and combinations thereof, have on the operational-environmental behavior of terminal areas, both in terms of solution main effect and their mutual interactions.

An adequate assessment of potential future conditions, realized in *Step 3* of the strategic airport planning process, has also been recognized to be paramount in pre-decisional assessments. Recalling that the use of forecasts for strategic airport planning has been questioned, the development and use of scenarios provides a valuable alternative. However, documented scenario planning efforts reveal that the evaluation and selection of scenarios is notably lacking in transparency, traceability, and methodological formalism.

Whereas these methodological gaps have been recognized and readily identified a number

of existing representative studies, the following objective are can be stated for this thesis:

Thesis Objective 4: To formulate and implement a traceable, repeatable, and rigorous approach for the definition, generation and down-selection of future scenarios in the context of strategic planning.

Based on the observations and arguments presented in this chapter, particularly in terms of methodological gaps identified for the scenario-based strategic airport planning process, and the thesis objectives that have been formulated accordingly, the process can be formulated as shown in Figure 9.

The proposed methodological approach for the characterization of airport performance and assess terminal area solutions in terms of interactions, sensitivities, and tradeoffs, is presented next in Chapter 4. The generation of an appropriate M&S environment enabling the aforementioned assessments, and upon which proposed approach is applied, is discussed in Chapter 5. The implementation of the method for airport performance characterization under reference conditions, and corresponding results, are presented in Chapter 6. Similarly, implementation of the method and accompanying results for the assessment of terminal area solutions are presented in Chapter 7. The issue of scenario construction, evaluation, and selection, is treated separately in Chapter 8, where a more complete background of the problem is presented, and where a scenario evaluation and selection method is proposed and demonstrated.

3.8   Summary

A proper characterization of the operational-environmental tradeoff is extremely important in the formulation of a solution approach that can be properly justified. To do so, the thematic focus of this thesis presented throughout the motivation, in Chapter 2, is recapitulated, further elaborated, and framed in terms of four focus items:

Focus Item 1: This thesis focuses on the operational-environmental tradeoff and in its integrated solution, placing special attention on the relationship between both parts and considerations of their relationship for the formulation of solutions.

Figure 9: Scenario-Based Strategic Airport Planning Process
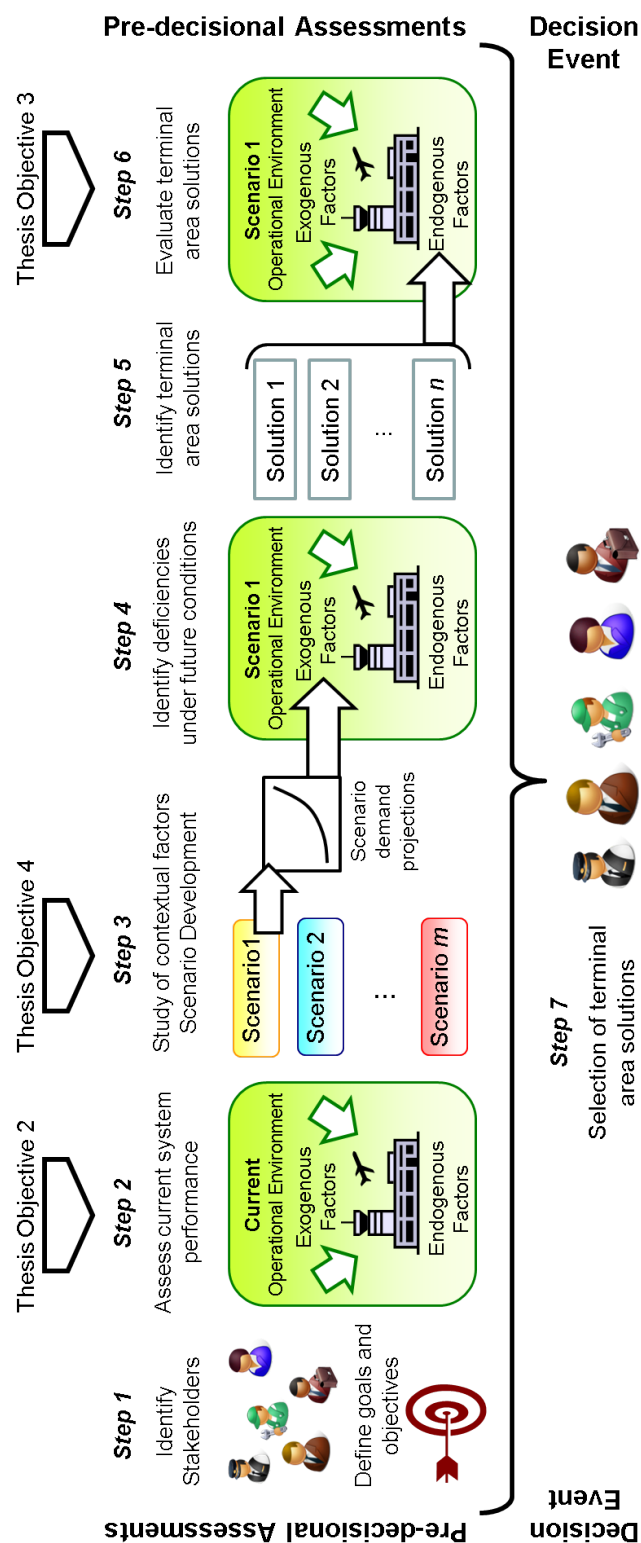
Focus Item 2: This thesis focuses on the operational-environmental tradeoff at terminal areas, which constitute bottleneck airports and their terminal airspace.

Focus Item 3: This thesis focuses on the operational perspective of supply and demand, recognizing that other perspectives are also important and help shape the behavior of supply-demand dynamics at the operational level.

Focus Item 4: This thesis focuses on supply-side solutions aimed at enhancing the air-transportation system's capacity over a long-term time horizon.

Section 3.3.2 lists representative supply-side solutions for capacity enhancement and mitigation of environmental impact, and illustrates how they can be classified into three main solution types, more specifically, airport infrastructure, operational improvements, and advanced aircraft concepts. Despite obvious differences in the general approach of each solution type, long development time frames and significant capital costs are shown to be common features for all of them. Based on this assessment, strategic planning is noted to be an appropriate approach for the selection of terminal area solutions.

The fundamental tenets of strategic planning, discussed in Section 3.4, include considerations for the definition of goals and objectives, examination of an entity's internal composition and its operational environment, projections of future conditions, evaluations of performance under current and future conditions, and finally the generation, evaluation, and selection of strategies. In this context, the process of strategic airport planning is presented.

Strategic planning is recognized as a decision-making effort, and as discussed in Section 3.5.1, is primarily dedicated to the realization of pre-decisional assessments in support of a decision event that culminates the process. The inherent complexity of airport performance represents an important challenge in attaining the necessary level of understanding that yields informed strategic decisions in airport planning. The characterization of this complex behavior take several forms that were described in Section 3.5.2, namely the interactions among system factors, the sensitivities of performance metrics to system factors, and the tradeoffs between performance metrics. This characterization was also shown to

be particularly relevant in specific steps of the strategic airport planning process, more specifically, the assessment of performance under reference conditions and the evaluation of terminal area solutions under future conditions.

In a similar fashion, the definition of future conditions is recognized to be paramount for pre-decisional assessments in strategic decision-making. Section 3.5.3 presents arguments against the use of forecasts to generate projections of future conditions given the natural dynamism and uncertainty of the air transportation industry. The use of scenarios presents an appealing alternative, but prescribes important challenges in the selection of an appropriate scenario set.

A review of past strategic airport planning efforts, presented in Section 3.6.1, reveals that the complex behavior of airport performance is not sufficiently characterized, nor is the evaluation of terminal area solutions sufficiently comprehensive, thus revealing a gap in current practices. Similarly, Section 3.6.2 illustrates how scenario development efforts for the aviation and air transportation sector lack traceability and methodological formalism in the selection and evaluation of scenarios. Based on the development of the research focus, and the identification of relevant methodological gaps in the strategic airport planning process, the following objectives are formulated:

Thesis Objective 2: To quantitatively characterize the operational-environmental performance of terminal areas by investigating the interactions between exogenous and/or exogenous factors, the sensitivity operational and environmental performance metrics to different factors, and the tradeoffs and correlations between operational and/or environmental metrics.

Thesis Objective 3: To quantitatively characterize the effect that different solutions, and combinations thereof, have on the operational-environmental behavior of terminal areas, both in terms of solution main effect and their mutual interactions.

Thesis Objective 4: To formulate and implement a traceable, repeatable, and rigorous approach for the definition, generation and down-selection of future scenarios in the context of strategic planning.

CHAPTER IV

PROPOSED METHODOLOGICAL APPROACH

4.1   Introduction

This chapter presents the proposed methodological approach for the characterization of airport operational and environmental performance. The arguments presented in the previous two chapters with regards to problem definition are used to identify the methodological requirements that enable said characterization and that observe relevant resource limitations. Appropriate techniques, tools, and methods are then presented in the context of an integrated process that is traceable and repeatable.

4.2   Methodological Requirements

The systemic complexity observed in airport performance, and discussed in Chapter 3, requires the *quantitative characterization of tradeoffs between performance metrics, interactions between endogenous and/or exogenous factors, and sensitivities of performance metrics to the different factors.*

Doing so, however, has implications on the M&S capabilities available, a well as on the number of data points that are required. Thus, there are important considerations with respect to the availability and commitment of resources for such an effort. In this spirit, the Interagency Portfolio and Systems Analysis (IPSA) division of the JPDO has recognized that a brute force approach consisting of billions of runs could capture most of the key tradeoffs and relationships of interest. However, due to M&S manual set-up time and simulation run times, generating this vast number of data points is prohibitive, limiting the the number that is realistically attainable in practice to a few hundred with the current state of the art, practices, and budgets.[139] Moreover, with a brute-force approach key relationships are easily obfuscated amidst a plethora of data that overwhelm the decision-makers, degrade the pre-decisional assessment of participants, and ultimately lead to uninformed/misinformed decisions that compromise the results of the entire endeavor.

Thus, the proposed approach must realize the quantitative characterization of performance while observing these computational/ M&S resource limitations. In other words, *tradeoffs, sensitivities, and interactions must be quantified using a reduced number of M&S runs.*

The value of characterizing complex airport performance relationships is only realizable inasmuch as this information can be *explicitly and transparently* communicated to analysts, experts, and other participants of the strategic airport planning effort, by means of adequate data representations and artifacts. The use of interactive visual interfaces has been recognized by the visual analytics community to as a key enabler that that supports analysts and decision-makers to synthesize information and accrue insight from complex and massive data. In this sense, interactive visualization facilitates the detection of expected behavior patterns and the discovery of unexpected ones, thus providing "*timely, defensible, and understandable assessments.*"([282], p. 4) Thus, it is highly desirable that the proposed methodology produce data constructs that are already *amenable to interactive visualization representations.*

4.3 Methodological Approach

With the aforementioned methodological requirements in mind, this research proposes the use of well established statistical techniques that can be used to guide the allocation of modeling and simulation resources, and mathematically characterize the interactions and sensitivities of interest. First, an intelligent selection of modeling runs is conducted by using a *Design of Experiments (DoE)*, which specifies the settings of independent/input factors that will produce corresponding values of a given dependent/response variable. In general, more information is usually attainable with more data points. In turn, DoEs are constructed to produce the most information possible with a minimal number of experimental runs. There is a wide variety of DoE types, which tailor to the type of information that is being sought and the availability of resources used to generate or acquire the data set prescribed in the DoE. For instance, a main effects DoE is used to conduct a screening test, which requires a very small number of data points and can be used to identify dominant factors for further evaluation based on their relative contribution to the variability of the response.

Other types of DoE are tailored to sample the corners or edges of an n-dimensional space to enable interpolations, whereas others enable a systematic sampling of the interior of the space. In this fashion, DoE can be used to quantitatively characterize the interaction effect between independent variables, as well as the sensitivity of response variables to independent variables.([224], Ch 1) An in-depth review of DoE theory and practical applications is beyond the scope of this chapter, but can be found in the published literature (see for instance [224, 206, 28]).

The characterization of the behavior of a given response is realized by the implementation of *regression analysis*, which uses the data set from the DoE and the M&S runs to produce an expression of known mathematical form describing the behavior of the response in terms of independent input parameters, referred to as *regressor variables*. In the formulation of linear regression this expression is a polynomial function that relates the response to a sum of first order terms that correspond to the *main effects* of independent factors, cross products corresponding to the *interaction effects* between independent factors, *quadratic effects*, and other higher order terms that may be required. This function describes an n-dimensional hyper-surface, and thus is referred to as a *Response Surface Equation (RSE)*. The RSE is thus expressed as follows:

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{(i,i)} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{(i,j)} x_i x_j + \epsilon \tag{1}$$

where y is the response and x_i are the regressor variables, namely the independent factors against which the the response y is regressed. The regression parameters β are the constat coefficients associated with each distinct effect contained in the RSE. β_0 is the intercept, β_i is the coefficient for the main effect $\beta_i x_i$, $\beta_{i,i}$ is the coefficient for the quadratic effect $\beta_{(i,i)} x_i^2$, and $\beta_{i,j}$ is the coefficient for the interaction effect $\beta_{(i,j)} x_i x_j$. Because this RSE is an approximation of an underlying behavior, it has error associated with it. That error is represented by the term ϵ. As shown in Appendix D, the notation $\hat{\beta}$ is used to refer to the *estimate* of the parameter, and to distinguish it from the unknown theoretical β.

Leveraging on the definition of an RSE, it is possible to quantitatively assess the impact that main effects, interaction, effects, and higher order effects have on the response. This

quantitative assessment is conducted primarily through tests of *statistical significance of regression*, such the regressor parameter estimates test, also known as the *t-test*, and the Analysis of Variance (ANOVA). These tests, described in detail in Sections D.5 and D.6 of Appendix D, combine measures of the magnitude of regression effects and the error associated with them into properly defined statistics that can be used to determine whether or not effect are significant for a response. More over, a key advantage of these tests is that they are based on the concept of *statistical hypothesis testing*, which is well suited for the development of relevant and testable hypotheses in this thesis, and is discussed in Section D.4. [224, 153]

The aforementioned analyses and statistical tests are part of a large collection of statistical analysis techniques called *Response Surface Methodology (RSM)*. A detailed discussion regarding theoretical principles and practical applications of RSM and regression analysis is beyond the scope of this chapter, and is presented in Sections D.2 and D.3 respectively. Additionally, these topics have been vastly documented in published literature (see for instance [224, 202, 34]).

There are some notable advantages in the generation and use of RSE's, particularly for the application in this thesis. First, the mathematical expression of the RSE is in itself a quantitative representation of systemic behavior, relating a given response variable to a prescribed set of potentially interacting factors. Second, for all practical cases the evaluation of an RSE requires computational resources that are orders of magnitude smaller relative to the original M&S environment used to produced the regression data set. For this reason an RSE enables a variety of applications that leverage on its almost instantaneous evaluation, such as interactive visualization environments and Monte Carlo simulations. Third, given the polynomial construct of an RSE, sensitivities can be analytically determined by estimating local gradient values from partial derivatives, for which closed form solutions are readily obtainable and thus eliminate the need for numerical methods. Fourth, the analytical definition of partial derivatives leverages a variety of visualization schemes, where different two-dimensional 'slices' of the n-dimensional space can be visualized. Lastly, the interactive visualization mechanisms enabled by RSE's for a number of response variables

can be used to readily identify tradeoffs between these responses.[184, 188]

Because an RSE effectively emulates the mapping between independent factors and a response produced by M&S capabilities, it is often referred to as a *surrogate model.* However, RSE's are not the only type of surrogate models. Other popular forms include artificial neural networks [151, 32], Gaussian processes [253], and Spline models [295]. Each of them features unique mathematical characteristics that renders them particularly well suited for the characterization of some forms of response behavior, but also present particular model regression or training data requirement that may be prohibitive. Thus, the choice of these surrogate alternatives is dependent on the known or anticipated nature of the response behavior, and the number of data points needed for the regression of the surrogate. In this regard, RSE's generally require a smaller number of data points compared to alternative surrogate model types, but are still able to capture moderately complex response behaviors. In some instances when RSE accuracy is insufficient, functional transformations can be applied to the response prior to the regression process to mitigate, but properly capture, a dominant mathematical effect beyond the functional definition of the RSE. Common examples include logarithmic and exponential transformations.

Beyond methodological considerations, the implementation of the proposed approach is is supported from a practical perspective by the availability of statistical analysis commercial-off-the-shelf software such as *JMP*®, which offers a variety of capabilities such as DoE generation, model fitting and regression analysis, statistical analysis of regression results such as ANOVA and parameter estimates test, as well as a wealth of interactive visualization schemes. In this way, it is possible to implement all components of the proposed approach within a single software application from which interactive visualization tools can be constructed and deployed.

4.4   *Application of the Proposed Approach*

For the characterization and benchmarking of airport performance under reference conditions, metrics of interest relevant to capacity and environmental impact can be studied with respect to a variety of model parameters that capture exogenous and endogenous factors. As

mentioned in Chapter 3, exogenous factors can be used to characterize operational demand, among other contextual elements, whereas endogenous factors include internal procedural logic such as airport configuration, runway assignment, airfield traffic flow control, gate holding, and queuing strategies. Thus, exogenous and endogenous factors are handled as independent regressor variables, whereas operational and environmental metrics of interest are handled as dependent response variables.

To implement the proposed approach, a selection of relevant exogenous and endogenous factors must be made first. An appropriate DoE can then be constructed based on the number of simulation runs that can be afforded, the number of effects that are to be characterized (i.e. interaction effects, quadratic effects, higher order effects), and the allowable levels of error inherent in the DoE. The tradeoff between these considerations may require various iterations where the choice of factors and the modeled effects is revised until the required number of data points and the inherent level of DoE error are acceptable.

Once the DoE is chosen, the runs are executed in the M&S environment. Data from the DoE detailing factor settings and accompanying M&S results for operational and environmental metrics are used to conduct regression analysis, from which an RSE is produced for each metric. The ANOVA test conducted on the data set provides a measure of how much variability in the data is collectively captured by all the factors in question. If ANOVA shows favorable results, effects estimates can be tested to determine the statistical significance of regression for each of them, thus assessing how the main, interaction, quadratic, and potentially higher order effects of the different factors contribute to the behavior of the prescribed performance metric. These results readily reveal the statistical significance of interactions, which are of particular interest.

The manipulation and visualization of the regression model provide further mechanisms to assess and represent tradeoffs, sensitivities, and interactions under examination. However, the accuracy of the RSE must be assessed first, for example through the coefficient of multiple determination R^2, as discussed in Section D.5.

With these arguments in mind, it is possible to formulate a methodological hypothesis regarding the adequacy of the proposed approach and the feasibility of its implementation

to the characterization of airport performance under reference conditions. As discussed in Section 1.3, this type of hypothesis cannot be directly tested in the formal framework of scientific reasoning. Rather, it is supported by demonstrating the proposed methodological approach, and by testing more detailed (testable) hypotheses that can be derived thereof. The methodological hypothesis is hence stated as follows:

- *Methodological Hypothesis 1:* A quantitative characterization of interactions, sensitivities, and tradeoffs for airport operational-environmental performance metrics with respect to *endogenous and exogenous factors* is realized through regression analysis, statistical testing techniques, and interactive visualization of RSE's.

In a similar fashion, the impact of different environmental and capacity enhancing solutions on airport performance can be quantitatively characterized in terms of interactions, sensitivities, and tradeoffs. For this application of the proposed approach, each terminal area solution is handled as an independent *categorical* variable, where 'Yes' and 'No' values can be used to represent whether or not a given M&S run models the implementation of that terminal area solution. This is in contrast with many exogenous and endogenous factors which are represented by continuous variables. Regression analysis and related statistical tests are none the less applicable to categorical variables. Operational and environmental performance metrics of interest are handles as response variables.

For this application a DoE specifies what combinations of solutions should be modeled in individual experimental runs. The M&S results of this DoE can be used to generate appropriate categorical RSE's that characterize the impact of terminal area solutions, and upon which statistical test for significance of regression can be applied. Explicitly capturing interaction effects reveals the extent to which the aggregate effect of a given solution combination is greater or smaller than the sum of its individual components, hence identifying those with diminishing returns or high payoff, and thus revealing sensitivity information. This insight can be further augmented by considering how individual solutions have beneficial and deleterious effects on across operational and environmental metrics of interest,

which characterizes the tradeoffs of the solution portfolio. The visualization of the categorical RSE through interactive visualization mechanisms further illustrate and represent interactions, sensitivities, and tradeoffs.

Based on these arguments, a methodological hypothesis can be stated in regards to the use of the proposed approach and the feasibility of its implementation to the characterization of terminal area solutions on airport performance, as follows:

- *Methodological Hypothesis 2:* A quantitative characterization of interactions, sensitivities, and tradeoffs for airport operational-environmental performance metrics with respect to *terminal area solutions* is realized through regression analysis, statistical testing techniques, and interactive visualization of categorical RSE's.

4.5 Definition of Sample Problem

Given that the two methodological hypotheses cannot be directly tested within the formalized framework of the scientific method, the demonstration of the proposed approach is the primary mechanism to support said hypotheses. Consequently, the selection of a realistic and relevant sample problem on which the proposed approach is demonstrated is of critical importance. Even if there is true value in the proposed approach, its implementation on a sample problem lacking in relevance, significance, and realism results in weaker support for the methodological hypotheses. Moreover, the implementation of the approach represents in itself a fundamental research contribution of this thesis.

With these arguments in mind, the following thesis objective is stated as follows:

Thesis Objective 5 : To demonstrate the synergistic and integrated implementation of the proposed methodological approach in a relevant and realistic sample problem.

To address this objective, the implementation of the proposed approach is illustrated in detail using Atlanta's Hartsfield Jackson International Airport (ATL) as a representative and relevant sample problem. This choice is driven by the important role that this airport plays in the national airport system and in the NAS. ATL serves as a major domestic transfer hub, as an international gateway into the U.S., and as the only commercial service

Table 10: World ranking by yearly traffic movements. (Source: [16])

Year	Ranking 1	2	3	4	5
2000	ATL 915 454	ORD 908 989	DFW 837 779	LAX 783 433	PHX 637 779
2001	ORD 911 917	ATL 890 494	DFW 783 546	LAX 738 114	PHX 553 310
2002	ORD 922 817	ATL 889 966	DFW 765 109	LAX 645 424	PHX 545 771
2003	ORD 928 691	ATL 911 723	DFW 765 296	LAX 622 378	PHX 541 771
2004	ORD 992 427	ATL 964 858	DFW 804 865	LAX 655 097	DEN 560 198
2005	ATL 980 386	ORD 972 248	DFW 711 878	LAX 650 629	LAS 605 046
2006	ATL 976 447	ORD 958 643	DFW 699 344	LAX 656 842	LAS 619 486
2007	ATL 994 346	ORD 926 973	DFW 685 491	LAX 680 954	DEN 614 065
2008	ATL 978 824	ORD 881 566	DFW 656 310	LAX 622 506	DEN 619 503

ATLANTA (ATL)
CHICAGO (ORD)
DALLAS/FT WORTH (DFW)
LOS ANGELES (LAX)
PHOENIX (PHX)
DENVER, COLORADO (DEN)

airport for the Atlanta metropolitan area. For many years ATL has handled more operations than any other airport in the world, second only to Chicago O'Hare (ORD) for a handful of years. Yearly traffic movements statistics by the ACI are shown in Table 10 for the world's top five airports during the 2000-2008 period.[16] Data for ATL is highlighted in this table. The sustained growth of operations at this facility is reflected in the capacity enhancements that have been adopted recently; most importantly however, additional capacity enhancements have been identified for its mid and long-term growth projections, along with the need to comply with ever more stringent environmental compatibility goals.[112, 119]

CHAPTER V

MODELING AND SIMULATION ENVIRONMENT

5.1 Introduction

This chapter presents details regarding the composition and integration of M&S capabilities for operational and environmental airport performance assessments. First, the thematic scope of this thesis is used to narrow down requirements M&S requirements to ensure that proper capabilities are selected. Next, a survey of modeling tools for terminal area operations and environmental impact is presented, and used to evaluate alternatives and make a final selection. The M&S environment is then discussed in terms of its three major components: the generator of schedules of operations, the model of terminal area operations, and the model of terminal area environmental impact. Modeling limitations and noteworthy modifications of key modeling components are also described.

5.2 Modeling & Simulation Capability Requirements

The selection of appropriate Modeling and Simulation (M&S) tools is a crucial consideration for the generation of relevant data as well as for the management of resources in the overall research effort. Modeling capabilities must adequately meet requirements of scope, fidelity, and resolution without exceeding constraints on computational/experimental resources.

Given the scope and thematic focus definition presented in Chapter 3, modeling tools must capture *terminal area* performance in terms of two major components:

1. *Operational* - The aircraft operations taking place within the terminal area

2. *Environmental* - The environmental impact of aircraft operating in the terminal area

In this sense, *aircraft operations* refers to the movement of aircraft throughout the terminal area, namely, on the *airport surface* and in the *terminal airspace*, ranging between the gates and the terminal airspace boundary. Conversely, *environmental impact* is that resulting from realization and execution of said aircraft operations.

The scope and level of detail with which aircraft operations ought to be captured is directly driven by the degree to which terminal area operations must be characterized both operationally and environmentally, and should take special consideration to how environmental performance is driven by its operational counterpart. Moreover, the definition of scope and resolution is also driven by the types of terminal area solutions that would be explored in a strategic airport planning effort, and how their direct and indirect effects are realized in the operations themselves, as well as in the way said effects are modeled accordingly within analytical tools. Thus, modeling resolution should be high enough to enable the differentiation between operational-environmental performance under reference conditions, under notional future conditions with no terminal area solutions implemented, and under conditions where specific solutions have been implemented.

With this in mind, it is paramount to recognize once again that terminal area solutions under consideration involve the addition or modification of airport infrastructure such as terminals, runways, and taxiways, as well as resulting changes in the structure of terminal airspace procedures, arrival routes, and departure routes. A second type of solutions involves operational and procedural improvements that determine the constraints and rules defining aircraft movements, such as separation minima for takeoffs and all airborne movements, or ATC tactical logic with which traffic flows are managed. Finally, the third type of solutions involves the characterization of aircraft-level performance of distinct aircraft models pertaining the existing and anticipated fleet. Thus, scope and resolution must encapsulate detailed movements and waiting periods of aircraft throughout the airport and its terminal airspace and must be associated with the performance and environmental impact characteristics of each aircraft conducting them. Modeling of aircraft performance must therefore provide sufficient differentiation between distinct aircraft models, and similarly, modeling resolution of operations must explicitly account for infrastructure and procedural differences that would exist between reference conditions and those where terminal area solutions have been implemented.

The scope and detail of terminal area operations are thus stated as follows to define M&S requirements: Departure operations must include boarding times at the gate, waiting

Figure 10: Depiction of aircraft operations modeling requirements
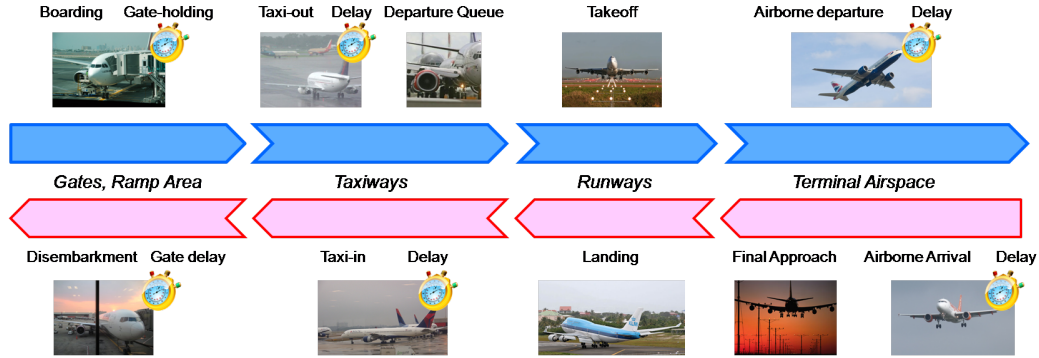
time at the gate (gate holding) resulting from the aggregate effect of airfield and airspace congestion, push-back, all taxi-out movements and associated taxi-out delays resulting from phenomena such as taxiway congestion and runway crossings, progress through the departure queue and the associated waiting times, waiting time prior to takeoff due to consecutive departure separation, takeoff, airborne departure movements (climbout), and any departure airborne delay that may result due to airspace congestion or airborne aircraft separation. Similarly, arrival operations include airborne arrival, airborne delay due to holding or path vectoring during transition to final approach, final approach, landing, taxi-in movements and associated delays resulting from surface traffic phenomena such as taxiway congestion or runway crossings, waiting periods for available gates, and gate de-boarding. These aircraft operations are illustrated in Figure 10. This diagram also illustrates the areas of the airport surface that must be explicitly modeled in order to capture the corresponding aircraft movements and potential delays/waiting periods.

Accordingly, M&S capabilities should model these aircraft movements following prescribed airport procedural logic, capacity limitations, and the characterization of operational demand captured by overall number of operations, fleet composition, and operation counts associated with specific components of the terminal area such as distinct arrival and departure routes. The operational logic must capture ATC guidelines, practices, rules, and regulations that dictate how aircraft conduct operations. Examples include prioritization logic for different operations, separation and timing rules, and mapping/allocation of flights

to gates, runways, and routes among other components.

Commensurate with this scope and resolution, operational performance must be expressed through appropriate output metrics of throughput, usage of terminal area components and resources, and various forms of delay, which result directly from the modeling of aircraft operations.

On the other hand, environmental impact modeling tools should be able to provide values for properly defined metrics of fuel burn, different pollutant emission species, and noise. Because airport environmental performance directly results from the aggregation of aircraft environmental performance for prescribed operations, airport level environmental metrics should be produced with a sufficiently detailed representation of aircraft performance for different aircraft models as well as from a representation of terminal area movements by these aircraft. The modeling resolution of the environmental component should be such that it allows for the representation of a variety of aircraft models, including new anticipated industry response aircraft models and notional advanced aircraft concepts.

5.3 Survey and Selection of Modeling Tools

5.3.1 Airport Surface and Terminal Airspace Operations

There is a variety of M&S tools that provide a range of modeling capabilities for terminal area operations. As will be illustrated in this section, these tools can be classified into two major categories. One category corresponds to those that focus on the terminal area, and the other corresponds to those that cover the entire NAS, or large parts of it. As can be expected, there is a tradeoff between breadth and depth, or modeling scope and resolution. Thus, tools that focus on the terminal area will, in general, provide higher resolution modeling and results, but may represent particularly intensive data and set-up requirements due to the level of detail. On the other hand, tools that span a larger scope will usually provide lower resolution models for airports and terminal airspace which may be deemed sufficient, and will be less demanding in terms of data requirements and model definition. Though the review of available tools presented in this section does not cover all existing alternatives, it none the less addresses the most well known and noteworthy.

The Aviation System Analysis Capability (ASAC) Airport Capacity Model (ACM) and Airport Delay Model were developed for NASA in 1997 to support the analysis and evaluation of various operational technologies geared to increase capacity and reduce delay at airports. The capacity model focuses on two major elements of terminal area operations that drive capacity, namely Arrival Runway Occupancy Time (AROT)[1] and aircraft in-trail separation. This tool provides comparative assessments of airport throughput using known or representative AROT aircraft separation figures vis-a-vis notional ones that capture technology implementation. The effect of technologies is emulated by adjusting modeling parameters such as aircraft separation matrices. Capacity estimates are generated from arrival-departure curves for varying levels of technology implementation and weather conditions at a specific airport. Surface movements, known to be a key constraint to airport capacity and a noteworthy source of airport delay, are not captured in this model except for arrival capacity reductions due to active runway crossings. Gate usage time, and thus gate delay, are not captured either. Throughput estimates are hence considered to be *unimpeded capacity*. The delay model is primarily based on capacity figures and makes use of a queuing module. Delays due to airline practices such as schedule peaking and major schedule disruptions such as cancelations resulting from severe weather are not captured. It is worth noting that the level of detail of ASAC models was consciously chosen to avoid replication of capabilities that were already offered by detailed airport modeling tools available at the time.[210] The ACM was updated to the Enhanced Airfield Capacity Model (E-ACM) by the MITRE Corporation for use in the 2007 *FACT* study [119].

The SIMMOD is a discrete-event simulation model originally developed by the FAA that has been used extensively in a number of airport studies (e.g. [204]) including the FAA *Airport Capacity Plans* (e.g. [91, 98, 99]). As a discrete event simulation model, SIMMOD follows the movement of individual aircraft on the airport surface and the airspace. The events describing aircraft operations pertain primarily to a variety of movements and waiting times, as well as as to other ancillary events such as boarding and disembarkment. SIMMOD

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[1]Arrival Runway Occupancy Time (AROT) is the window of time between the instant an arriving aircraft crosses the runway threshold to that when the aircraft has completely exited the runway.[210]

makes use of three critical data constructs that prescribe the particular way in which aircraft movements are simulated. The first one is a network, appropriately defined by links and nodes, which defines the paths that aircraft can use to conduct operations. Although links and nodes for airspace and airport surface are treated differently in many respects, they collectively embody the topology of the airfield and the terminal airspace. Surface links and nodes can be defined to have special roles such as high-speed runway exits, departure queues, gates, staging areas, and de-icing areas. Certain properties can be defined for surface links in order to capture part of the operational logic governing aircraft movements. For instance, links have a given capacity, can be defined to have directionality, and can be defined to allow only arrivals or departures. These properties limit the number of aircraft occupying parts of the surface at any given time and are used to tailor surface traffic flow patterns.[131, 108]

For airspace, groups of nodes and links are used to define departure and arrival routes, and can be used to define airspace sectors to which capacity limits may be imposed to simulate ATC workload constraints. Capacity is also defined for each airspace link and node, which has a very important bearing on how traffic is controlled whenever nodes or links downstream have reached capacity limits, or whenever in-trail separation minima, discussed next, prohibit release of aircraft downstream. To simulate ATC functions, airspace links incorporate rules for aircraft movement, such as the option to allow or deny passing. Conversely, aircraft movement control strategies are specified at airspace nodes to determine the logic with which the flow of aircraft is processed. For instance, a node can be specified to use a First In First Out (FIFO) strategy. The manner in which SIMMOD implements logic and control of airspace traffic is of key importance because, contrary to surface movements, airspace movements must account for the fact that airborne aircraft must continue flying within allowable speed limits and cannot be made to stop and wait. To address airspace congestion and process aircraft movements without violating separation rules or capacity limits, SIMMOD implements the concept of 'path stretching'. In this modeling technique an airspace link is artificially stretched so that the aircraft can be made to spend a longer time flying between the initial and final nodes of the prescribed link. This mechanism effectively

captures ATC vectoring functions which are implemented in real terminal airspace operations, usually during the transition from an arrival route to the final approach procedure, to elongate arrival trajectories and accommodate larger traffic volumes.[131, 108]

The second fundamental SIMMOD data construct comprises the definition of aircraft which includes the enumeration of individual aircraft models, aircraft size classifications for airspace separation and access to airport surface areas such as taxiways and gates, takeoff and landing distance distributions, and the definition of basic aircraft performance values such as ranges for airborne speed and values for taxiing speed. The third data construct is comprised of a variety of logical rules with which operating procedures and some ATC functions are simulated. Chief among them are rules for access to specific areas of the airport, in-trail separation rules for airborne aircraft according to size class, time intervals for consecutive same-runway takeoffs, separation and time intervals for arrivals and departures in dependent runways, and the definition of plans which specify groupings of values and settings for all the aforementioned rules. SIMMOD does not model weather conditions directly, but rather provides a mechanism to capture its potential effect by modifying values for the aforementioned parameters and rules. A crucial data set required for the simulation of airport operations in SIMMOD is a schedule of operations. The schedule specifies information pertinent to each operation such as type (departure or arrival), arrival/departure route to be used, airline, flight number, aircraft model, simulation injection time, and several optional parameters such as assignment of concourse or runways. The definition of airlines is used in conjunction with the definition of gates to control gate access. The aforementioned data constructs define the logic and capacity limitations that govern aircraft operations. When the simulation is run, a history file is produced with all the discrete events. This raw data is internally processed to generate a wealth of aggregated and per-flight statistics for relevant operational metrics of interest such as operation counts (throughput), delay, unimpeded movement times, and usage of airport real estate such as gates or runways. Additionally, the definition of the surface and airspace network can be used in conjunction with the simulation history file to produce visual animations of aircraft movements. [131, 108]

One of the major shortcomings of SIMMOD is that the input and output data is exists

in the form of text files, or 'flat files', for which very specific formatting and syntax exists. This presents a challenge since the definition of the physical/geographical architecture is naturally a visual task that is not facilitated by the coding of raw data in text form. Documenting and managing the considerable amount of data necessary for a model, even if only moderately large, is therefore inherently difficult. Moreover, data in separate input records must be consistent so that the SIMMOD engine can be run successfully. For instance, data records enumerating all airfield and airspace links and the nodes they connect must be consistent with records enumerating and defining nodes. Another example is the definition and enumeration of airlines which must be consistent with records of gates where airlines using each gate are specified. Attempting to generate and consistently modify input files is hence problematic. However, visual interface environments with embedded relational databases have been created so that the network of nodes and links can be visually constructed, and so that all model data can be conveniently stored in interrelated tables. These environments conveniently generate the necessary input files using the data in the database which checks for internal consistency, and invoke the SIMMOD simulation engine executable with these input files, vastly facilitating the generation, modification, and review of models. Additionally, these environments also retrieve the output files generated by SIMMOD, which are also text files, and provide a number of data exploration and movements visualization schemes. Two major visual interface alternatives exist: 1) *Visual SIMMOD*, created by *AirportTools*, which uses the publicly available and free version of SIMMOD maintained by the FAA[17, 18], and 2) *SIMMOD Pro!*©by the *ATAC Corporation*, which maintains a separate version of SIMMOD different form that maintained by the FAA, and is not free of cost[2].

The Total Airspace and Airport Modeler (TAAM) is a gate-to-gate airspace and airport simulator used worldwide by civil aviation authorities, airlines, airport operators, and other civil aerospace entities for a wealth of planning efforts and assessment analyses. Considered to be an industry standard for airport and air traffic simulation, it provides the flexibility to customize modeled airspace and airfields to assess performance under a variety of operating conditions.[304] TAAM is has been successfully utilized to assess future traffic

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volume levels and estimate the impact of various types of CNS and ATM technologies, procedural improvements, schedule management techniques, and the introduction of new aircraft. Because of its modeling capabilities, scope, and uses for modeling and planning efforts, TAAM can be most closely compared with the FAA's SIMMOD. Though it is recognized that TAAM has more features and a more modern script architecture, its acquisition cost is significant and requires "a considerable amount of training and data preparation to operate."[74] Furthermore, its internal structure is mostly sequential in nature, resulting in very long run times that significantly limit its use and have prompted efforts geared towards parallelizing several of its internal processes to increase its speed.[271]

Other M&S tools focusing on the airport and its terminal airspace have been developed, but have not been widely adopted. Examples include the Virginia Tech Airport Simulation model (VTASim) [283], Total AirportSim [208], MACAD, PowerSim [309], and a number of agent-based formulations (eg. [304]).

5.3.2 System-wide Operations

The M&S tools discussed next feature a broader modeling scope relative to dedicated airport modeling tools previously discussed.

The Airspace Concept Evaluation System (ACES) is a non-real-time gate-to-gate simulation framework for aircraft operations at a local, regional, and national level. The development of ACES began in 2002 as part of NASA's Virtual Airspace Modeling and Simulation (VAMS) program, a five year R&Deffort that sought to "*evaluate the costs and benefits of new operational paradigms early in the development process*"[274] in response to growing aviation demand and insufficient air transportation system capacity.[21, 274] The broad range of operational concepts to be captured by ACES extends from technologies applied to specific segments/phases of flight, such as automation or warning systems for taxiing movements, to system-wide operations management schemes such as a shift towards point-to-point carrier network architecture. Thus ACES modeling requirements included aspects of operational performance, economic impact, dynamics of inter-agent interactions, and infrastructure constraints, as well as a flexible and extensible modeling architecture.[21]

A multi-year phased approach has been adopted for the development and validation of ACES beginning with the identification of architectural requirements and the development of a proof-of-concept, followed a baseline modeling capability, continuous improvements in model fidelity, and validation of ACES simulation output.[274] Build 1 of ACES, delivered to NASA in March of 2003 [221], was the first working version where the collective assembly of an agent-based framework had been emphasized over the fidelity of individual agent models. Notably absent in Build 1 were models relevant to terminal area operations, namely separation constraints and arrival delay for terminal airspace and surface, as well as some enroute functionalities including sector capacity limits and altitude/speed changes. This first build was used for an initial assessment of system-wide airspace delay. This study considered four levels of demand growth and nine different weather-driven airport capacity conditions, for a total 36 NAS scenarios. This study concluded that delay grows quadratically with demand but suggested that additional non-linearities can be associated with more complex factors such as regional clustering of airports.[305] After Build 2 and Build 3 were delivered in October 2003 and July 2004 respectively [221], ACES would be used to evaluate the system-wide impact of the Surface Operation Automation Research (SOAR) concept [43], and underwent a new validation exercise that used real world data for its demand schedule and weather inputs as well as a reference for comparison of its output operational metrics of capacity and delay statistics. This study used Aviation System Performance Metrics (ASPM) data to generate capacity estimates for the top 53 continental U.S. airports and assigned generic capacities to the rest.[307] Build 4 was delivered in July 2005 [221]; its validation effort extended previous studies and included four actual days of operations that span high and low levels of traffic volumes and en route weather, the latter modeled with reduced sector capacities.[306]

There are three main types of models in ACES: agent models represent different types of operators such as air traffic service providers (en route, terminal, tower, and ramp) and airlines; environment models represent contextual constructs such as weather, airports, or airspace definitions; infrastructure models capture interactions between agents or between agents and the environment, such as CNS or weather prediction functionalities.[274] Models

in ACES Build 4 include 4-D flight performance, airspace configurations, airport models accounting for runway and surface configurations as well as arrival-departure rates, terminal and en route weather, and flight demand scheduling. Interactions between air traffic operation entities are captured through communications between them, which are supported at the software level by its agent-based framework. Build 4 uses a pure agent-based framework that replaced the High Level Architecture (HLA) federated agent-based approach used in earlier versions due to performance and memory deficiencies. ACES models flights by instantiating a variety of models representing the different phases of flight as well as the hierarchical control structure of air traffic operations. The sequence of phases begin with gate push back, and continue through taxi out in the airport surface taxi system, takeoff using the airport runway system, terminal airspace departure to a departure fix, a series of en-route airspace sectors, and an arrival sequence using terminal airspace, arrival runway, taxi in, and gate arrival. At the top of the hierarchical structure an Air Traffic Control System Command Center (ATCSCC) agent provides centralized control of operations for all phases, communicates with Traffic Flow Management (TFM) agents in each of the flight phases, and receives flight plan modification whenever they occur by each individual flight. At the next level, airport, Terminal Radar Approach Control (TRACON)[2], and Air-Route Traffic Control Center (ARTCC) TFM agents provide strategic trajectory planning by assessing projected demand and issuing traffic restrictions to ATC agents. ATC agents, located at a lower level, are also instantiated in each flight phase, and control aircraft movements at the tactical level by applying procedural rules while observing TFM restrictions. Aircraft at the lowest level of the structure comply with instructions issued by agents, conduct movements accordingly, and communicate with ATCSCC when flight plans are modified.[221]

In the tradeoff between breadth and depth, or scope and resolution, the NAS-wide operational scope of ACES comes at the expense of M&S resolution for terminal area operations. Thus, ACES provides lower resolution in terminal area operations compared with modeling environments dedicated to airport and terminal airspace operations such as SIMMOD. The

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[2]The Terminal Radar Approach Control (TRACON) is an ATC facility that provides *Approach Control* and *Departure Control* services to all arriving and departing IFR aircraft and participating VFR aircraft while airborne in the *Terminal Radar Service Area.*[127, 25]

terminal airspace is modeled generically in ACES as a 40 nmi radius circular area about the airport, with four arrival fixes and four departure fixes evenly spaced along its circumference. However, Build 3 introduced the option of modeling selected terminal airspace sectors with greater detail, allowing for multiple airports in a given TRACON, as well as any number of fixes, and their location about the TRACON boundary, to be specified. The airport TFM agent uses the flight schedule for the airport to project takeoff and landing volumes and determine departure/arrival rates based on capacity parameters and operating conditions. This agent passes planned acceptance rates to airport ATC and projected landing times to TRACON TFM. In turn, TRACON TFM restrictions for departures are relayed by airport TFM to airport ATC. Airport capacity is determined from arrival-departure Pareto fronts which were generated for the top 53 continental U.S. ASPM provided airports, and assigns generic airport state capacities for the approximately 200 additional airports included in the model based on similarity of runway configuration [307]. Taxi-in and taxi-out times are derived from historical data for the top 49 airports, and are assigned default 10-minute or 5-minute values for all others. The TRACON transit time is calculated as a representative value based on user-defined or default flight distance and speed data. This flight distance is estimated as the distance between the departure/arrival fix on the TRACON boundary and the designated runway fix. Similarly, the length of the final approach segment is estimated as representative distance between the designated runway fix and the final approach fix. Runway system models can be explicit, requiring user-defined time spacing between wake vortex aircraft classes for all combinations of arrival/departure operations. The operational interaction constraints between runways, such as those observed for intersecting, closely separated parallel, or closely separated converging runways, can also be specified though it is not compulsory. The definition of a basic airport layout and TRACON waypoints is supported by a graphical user interface called the Terminal Area Editor.[221]

Because of the breadth of its scope, ACES has considerable data requirements. In particular, it requires the definition of a schedule of operations for all flights in the model simulation. The level of resolution of a simulation run can be augmented but requires more detailed flight plan data in the schedule of operations. It may also require the definition

or revision of system definitions such as airport and sector capacities and their variability with weather. In turn, the output of an ACES simulation can vary dramatically in size, depending on the number of operations, airports, and enroute sectors modeled.[306, 221]

The MIT Extensible Air Network Simulation (MEANS) is an event simulation framework that captures aspects of air traffic control and flow management, airspace congestion and delay, airline operations scheduling, and delay disruptions to passengers, crews, and aircraft. Its ability to concurrently capture these various elements of air transport operations is a distinguishing feature of MEANS, whose modular and extensible architecture also provide the user with the flexibility to manage the level of detail and fidelity with which they are treated. The airline module simulates airlines' centralized decisions and operations scheduling in response to disruptions, such as flight cancelations or aircraft swaps, and keeps track of passengers to assess the impact that these decisions have on their itineraries. A gate module implements airline operations at an airport involving the turnaround of aircraft as well as any delay that may be associated with it, for instance as a result of mechanical failure. The taxi module generates taxi-in and taxi-out time estimates in one of three basic modes: 1) through constant, user-provided time estimates for each airport, 2) from a historical distribution of values unique to each airport, and 3) using an unimpeded taxi time model that incorporates delay estimates resulting from aircraft passing. The tower/TRACON module is one of the most important ones in MEANS as it simulates airport air traffic control functions that drive departures and arrivals. The service times that aircraft must experience in the departure and arrival queues at each airport are determined from arrival-departure rates unique to each airport that vary with the impact that weather conditions have on each of them. MEANS implements one of four tower modes for this purpose: 1) an empirical data approach that directly applies user-provided hourly rates data observed for a specific day, airport, and airport configuration; 2) a second empirical approach that uses hourly rates to generate historical arrival-departure rate Pareto frontiers; 3) a simulation-based approach that uses a Monte Carlo simulation rather than historical data to generate the arrival-departure Pareto frontier for a specific airport, airport configuration, weather conditions, and fleet mix; and 4) a controller agent based approach where each operation

is handled individually using the event-sequencing and the spacing rules used to generate the simulated Pareto frontiers, thus providing more accurate airport capacity estimates but at greater computational expense. A centralized traffic flow management functionality is simulated via an ATCSCC module that manages ground delay programs based on predicted demand and capacity estimates generated within the simulation. However, en route movements are only captured via an en route flight time estimate for a give origin-destination pair, and thus a detailed en route airspace module is lacking.[48] The concurrent simulation of various players and aspects in air transport operations, as well as the extensible and modular architecture of the framework, are distinctive advantages of MEANS. Incorporating multiple aspects of the problem inevitably results in growing data requirements such as more specific airline data and schedules, weather data, airport air traffic controller data and capacity statistics, etc. The flexibility offered by a manageable and extensible level of detail in each of its modules allows the user to somewhat circumvent such requirements whenever data is not available. However, the compounding data requirements demands and computational expense inherent in broader or more detailed analyses remain altogether present. Furthermore, within the tradeoff of modeling scope and fidelity MEANS provides limited detail for airport operations simulation where aircraft taxiing movements, surface traffic interaction with departure queues, physical gate usage, runway crossings, and other critical airfield surface details are notably lacking.

The Detailed Policy Assessment Tool (DPAT) is a fast-time parallel discrete-event simulation capability developed at MITRE's Center for Advanced Aviation System Development (CAASD)[3] to model operations in the NAS and produce delay estimates. DPAT has been used in the past to emulate the effect of increased airport and airspace sector capacity on system-wide delay, and to assess broad airspace and airport capacity needs relative to future traffic growth projections. DPAT models the airspace system as a network of finite capacity resources such as airports, airspace fixes, or entire airspace sectors, such that each aircraft flows through a given path in this network and is processed through a series of queues as

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[3]The Center for Advanced Aviation System Development (CAASD) is one of the four federally funded research and development centers hosted by the MITRE Corporation

it competes for services for which there is a waiting time. Accordingly, delay is quantified by means of these queuing waiting times as well as user-defined delay distributions for non-queuing events such as those associated with airline schedule decisions. Despite its broad scope, which includes terminal area and enroute operation phases, DPAT offers very fast simulation times thanks to *Georgia Tech Time Warp*, the parallel discreet event simulation engine at its core.[299, 300] Unlike LMI Network Model (LMINET), DPAT's simulation speed enables a departure from the analytical solution of the queuing problem in order to generate congestion and delay estimates. Its simple web-based user interface results in great ease of use and hence requires less training relative to other tools. Additionally DPAT is particularly flexible in its construct, allowing for the user to model a wide variety of locations and airspace designs.[48] However, a detailed airport model within DPAT is notably lacking, but expected as part of the tradeoff between modeling breadth and depth. As a result DPAT does not explicitly model gate assignment/usage or aircraft movements on the airfield, but rather produces taxi time estimates for arrivals and departures based on user-defined distributions. Furthermore, DPAT does not explicitly simulate individual runways but rather treats an airport's total capacity through a single departure queue and a single arrival queue. In turn, arrival-departure rates are not collectively prescribed by the set of individual airport operations, but rather by user-provided arrival-departure rate Pareto frontiers.[299, 300] Data requirements for DPAT such as the aforementioned arrival-departure rates have been recognized to be a significant disadvantage, and collectively prohibitive in many cases, particularly since much of this data can only be generated through other modeling tools.[48]

The LMI Network Model (LMINET) is a large scale queuing network model of the NAS developed for NASA by the Logistics Management Institute (LMI). It models flights between airports by linking them through sequences of TRACON sectors and Air-Route Traffic Control Center (ARTCC) (i.e. en route) sectors, all of which are represented as queuing models. The airport set in LMINET includes the top 64 busiest of the continental U.S. accounting for approximately 85% of domestic commercial enplanements and 80% of carrier operations. The specific sequence of sectors/queues for each flight is determined by

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the user, thus offering the flexibility to emulate and explore a variety of NAS operating and routing schemes, but also requiring the acquisition of trajectory data from sources such as Enhanced Traffic Management System (ETMS). Operations through the queuing network are dictated by a schedule of departures from the different airports and by a schedule of flight arrivals from outside the network, which also implies availability of scheduling data from sources such as the Official Airline Guide (OAG). Each airport in LMINET is modeled as a simple queuing network consisting of an arrival queue, an aircraft reservoir for which a turn-around delay is sampled from a random distribution, an aircraft queue where aircraft from the reservoir are assigned to flights, and a departure runway queue. The service times in these airport queues are probabilistically treated and sampled from a Poisson distribution.[209] Accordingly, arrival-departure service rates are determined by the capacity at each airport and captured as arrival-departure Pareto frontiers for varying meteorological conditions.[74] These arrival-departure rates represent an additional data set that must be acquired and/or updated for each airport of interest. LMINET features a fast simulation time through the solution of the analytical queuing equations while explicitly capturing the network effect of delays throughout the airports and sectors of the NAS.[213] While capturing the stochastic behavior of operations in reduced run times, this approach is unable to track operational performance on a flight by flight basis and resulting in some loss of resolution. Similarly, flight by flight tracking resolution is further lost through in the hourly characterization of demand and weather data.[48] Most importantly, the airport model within LMINET is recognized to have an inferior degree of sophistication and fidelity with respect to event-driven simulation capabilities such as SIMMOD or TAAM for which air traffic and delay statistics are more accurate. In fact, some effort has been dedicated in the past to integrate SIMMOD or TAAM models with LMINET, not only to provide high fidelity airport operations modeling, but also to provide more accurate demand levels to each of the airports as the network effect of system-wide operations is captured within LMINET.[213]

The Reorganized ATC Mathematical Simulator (RAMS) is a gate-to-gate airport and airspace simulator developed by ISA Software and used by civil aviation authorities such as

the FAA and Eurocontrol. It features fully integrated airside and groundside components, providing a very complete suite of analytical capabilities including capacity, safety, and delay assessments of airport surface and airspace sectors, as well as design/re-design tools with which to emulate a wealth of solutions and improvements. RAMS also features a full graphical user interface that leverages on the power of visualization to greatly facilitate the generation and edition of models as well as the interpretation of results, for instance via the animation of simulated operations. By incorporating numerous other modeling features into the visual environment RAMS is less demanding for model setup, data development, and software support. Though commercial license costs are significant, the academic licenses are available albeit with limited technical support.[270]

5.3.3 Terminal Area Environmental Impact

A number of aviation environmental impact tools have been developed and used in the past to quantify the emission of different species and the noise exposure resulting from aircraft operation activity. A comprehensive suite of state of the art tools are integrated in the Aviation Environmental Design Tool (AEDT), developed by the FAA "*to assess the interdependencies between aviation-related noise and emissions effects, and to provide comprehensive impact and cost and benefit analyses of aviation environmental policy options.*[259][4] More specifically, the AEDT integrates four existing and widely used FAA tools as follows: the Emissions and Dispersion Modeling System (EDMS) to model local emissions [87, 66], the Integrated Noise Model (INM) to model local noise exposure [7], the System for assessing Aviation's Global Emissions (SAGE) to model global emissions [203], and the Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA) to model global noise [117].

To provide an adequate level of integration between these modeling tools and the necessary data constructs, the AEDT is developed in Microsoft Visual Studio primarily due to considerations for scalability, flexibility, and processing efficiency. The AEDT also makes use of a relational database management system to store, access, and manipulate the wealth

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[4]The AEDT was under development at the time that the research for this thesis was conducted, but had undergone ample testing and evaluation of modeling capabilities to be considered for the use.

of data pertinent to inputs, outputs, and intermediate calculations of its M&S components. The airports database contains airport specific data such as runways, geographic location, and local historical weather conditions. The fleet database contains details of the worldwide fleet in terms of airframe and engine definitions, as well as corresponding performance, noise, and emissions parameters. The movements database stores all the flight operations for which environmental impact will be calculated, and includes pertinent information such as origin-destination definitions and trajectories. The results inventory database stores all the emissions and noise estimates generated by appropriate AEDT modules for the prescribed set of operations. The FAA noise and emissions modeling tools are contained in the Noise Module and the Emission Module of AEDT respectively. There are multiple other modules in AEDT, including the Aircraft Performance Module, responsible for processing ancillary data needed in the generation of noise and emissions inventories. Based on the data provided and the settings specified in a configuration file, internal logic within the AEDT determines the appropriate modules and environmental modeling tools that need to be executed. It is worth noting that the AEDT is a stand-alone tool, but that it is meant to be interface with other tools concurrently being developed by the FAA. The Environmental Design Tool (EDS), for instance, is a tool that will provide performance, noise, emissions, and economic characterizations for future aircraft concepts under a variety of technology scenarios. Similarly, the AEDT will interface with the Aviation environmental Portfolio Management Tool (APMT) which will provide valuation assessments of environmental impact and of corresponding levels of mitigation.[136, 137, 259] Although individual modeling components of AEDT are data compatible with a number of airport and NAS modeling tools, the version of the AEDT available at the time this research was completed only had provisions for simulation output from SIMMOD and ACES.[181]

Given that SAGE and MAGENTA are used for global emissions and noise respectively, and are not invoked by the AEDT in the generation of terminal area environmental estimates, they are not discussed any further. However, INM and EDMS are relevant to terminal area calculations and thus are briefly discussed next.

The main capability of the INM is the evaluation of aircraft noise impact in the vicinity

of airports. Currently, it is common practice to utilize the INM for FAR Part 150 noise compatibility airport planning and for FAA Order 1050 environmental assessments and environmental impact statements. The aforementioned environmental studies are normally conducted to assess existing noise impacts, or to assess noise impacts resulting from the implementation of operational changes such new traffic levels and fleet mix, new runways, and new operational procedures. The modeling approach of the INM is primarily based on the noise estimation algorithm prescribed by the Society of Automotive Engineers (SAE) Aerospace Information Report (AIR) 1845 standard.[7] This algorithm details all the calculations necessary for to produce Sound Exposure Level (SEL) for any point on the ground, as well as cumulative noise exposure in terms of Day-Night average sound Level (DNL). Although a description of this algorithm is beyond the scope of this thesis, it suffices to recognize that it uses Noise-Power-Distance (NPD) data for prescribed mode of operation, thrust setting, atmospheric attenuation, acoustic directionality, and other relevant parameters.[269]

The EDMS features an emissions processor that uses a combination CAEP models to calculate and aircraft emissions inventories for a variety of pollutants including carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM). A dispersion module can be optionally used to estimate the atmospheric dispersion of said pollutants based on mixing altitude definitions and atmospheric data. The general approach for calculating emissions inventories uses 'time in mode', which refers to the amount of time an aircraft spends in different segments of landing-takeoff cycle. There are six distinct phases in the cycle: approach, taxi in, gate, taxi out, takeoff and climb out. The time in mode can be calculated from ICAO standard values, or through the Aircraft Performance Module. Calculation via the performance module is more accurate as it incorporates the effect of factors such as aircraft weight, approach angle, elevation, and weather. EDMS modules for emissions calculation and aircraft performance are common with those in AEDT. Each mode prescribes an engine power setting, which in turn determines the the fuel flow. The latter is combined with time in mode to estimate total fuel burn for that phase of the flight. The quantity of each emission species varies with

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fuel flow and power setting, which can be combined with time in mode to calculate total amounts for each species. The relationship between fuel flow and emissions is captured by means of a multiplier referred to as an Emission Index (EI). The fuel flow values and emissions indices for each mode vary between engine types. These values can be found in the ICAO Aircraft Engine Emissions Databank [175], a publicly available database that documents the aforementioned information for a wealth of engine models based on certification data.[87, 66]

5.3.4 Selection of M&S Tools

The AEDT was chosen as for environmental impact modeling based on the adequate capabilities that it provides for the characterization of airport environmental performance, on the wide level of acceptance throughout the community that its constituent FAA models have, and on its immediate availability.

In turn, aircraft operations models for the characterization of airport operational performance were comparatively assessed according to the following criteria:

1. Availability

2. Data compatibility with AEDT

3. Previous use and widespread adoption

4. Modeling flexibility to capture terminal area solution effects

5. Computational resource demand

6. Scope and resolution

The result of this comparative assessment is summarized in Table 11. As can be observed, the availability of each tool was assessed first to provide an initial categorization of tools that were readily available, and those tools that would not be obtainable within a practical time frame and effort. Alternatives that were available to the public 'in principle' but for which a timely acquisition process was not available were also discarded. Given that AEDT is identified as the environmental M&S tool of choice, the second assessment

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involved the compatibility of operational M&S data with AEDT input data requirements. From this assessment, MEANS was discarded as an alternative, leaving only SIMMOD and ACES. The remainder of evaluations for these two alternatives were conducted to realize a final selection. In this regard, the two tools have been widely used in previous efforts. The ability to model a variety of terminal area solutions in SIMMOD was found to adequate, particularly because of its high resolution in the definition of the terminal area architecture and its internal logic. This higher resolution also provides the capability of modeling aircraft movements throughout the airport surface in detail. In contrast, ACES features a lower level of resolution in the definition and simulation of terminal areas, which is appropriate for NAS-wide assessments but may be questionable for dedicated airport-specific studies. The extent to which vectored arrival trajectories and airport surface movements can be modeled in detail in ACES is certainly less than that for SIMMOD. Thus the ability to adequately model the effects of terminal area solutions in ACES is adequate, but lower in resolution when compared to SIMMOD, and thus should be considered with some reservation. The computational resource demand for these two alternatives were assessed from personal observations by users of both modeling tools, and included the simulation run time for a representative case as well as the amount of computer memory required to store all necessary data. Whereas, SIMMOD was recognized to have particularly short simulation times even for very large and complex airport models, ACES has been shown to have considerable run time. However, it is important to note that a full-scale ACES model may involve hundreds of airports and tens of thousands of flights tracked through origin and destination airports as well as through enroute airspace. Due to scalability of model run time, it is expected that an ACES model considering a single airport will feature a run time that is orders of magnitude lower. In this sense, ACES was determined to have adequate computational resource requirements, but with some reservations. Based on the collective of these observations and assessments, SIMMOD was selected as the M&S tool of choice for terminal area operations. Additionally, *Visual SIMMOD* was selected as the visual and database environment with which SIMMOD files will be generated, given that it uses the publicly available and free of cost version of SIMMOD maintained by the FAA.

Table 11: Comparative Assessment of Airport and NAS M&S Tools

	Availability	AEDT data compatibility	Previous use / widespread adoption	Modeling of terminal area solutions	Computational resource demand	Scope and resolution
ACM	✘					
SIMMOD	✔	✔	✔	👍	👍	👍
TAAM	✘					
ACES	✔	✔	✔	✋	✋	?
MEANS	✔	✘				
DPAT	✘					
LMINET	✘					
RAMS	✘					

Legend:	Yes	No		Adequate	Adequate with reservations	Questionable
	✔	✘		👍	✋	?

5.4 Integration and implementation of the M&S Environment

5.4.1 Components of the M&S Environment and General Information Flow

There are three main components for the M&S environment used in this research. The first component pertains to the generation and manipulation of a schedule of operations representative of current levels of aviation activity as well as notional representative operations. This schedule identifies the time of day at which each arrival and departure takes place, the aircraft model used, the airline that operates that flight for the determination of accessibility to gates and terminals, basic flight plan information identifying the arrival or departure route utilized, and the runway used for that aircraft.

The second component pertains to the movement of aircraft on the airfield surface and through the terminal airspace, which is captured by a model of ATL in SIMMOD and uses the schedule of operations as an input. The third and last component pertains to the calculation of fuel burn, emissions, and noise with AEDT, which uses the simulation output of SIMMOD as an input.

5.4.2 Demand and Operations Schedule Component

For the first component, the approach general approach adopted for the creation of new schedules of operations follows previous work and common practices on futuristic flight demand generation, where growth factor multipliers are applied uniformly on on all operations counts, or separately for prescribed groups groups of operations such as international and domestic. The number of additional flights is generated by replicating flights in a baseline schedule, representative of operational activity levels under current/reference conditions. Replicated flights in the new schedule are adjusted for departure/arrival time based on observed time windows for flights connecting distinct origin-destination pairs. This approach may be used to model notional increases or decreases in operational activity within the near future where the fleet mix remains unchanged. Conversely, adjustments to the aircraft fleet can be implemented to account for retirement of aircraft, introduction of current aircraft models assumed to be remain in production, and new aircraft models.[160]

The underlying algorithm to generate additional flights requires that a multiplier be provided for the entire set of flights, or for a given group of flights. Based on the number of operations in the baseline schedule, a corresponding number of new flights is determined as follows:

$$F = RoundUp(F_0 \times \gamma) \tag{2}$$

$$F' = F - F_0 \tag{3}$$

where F_0 is the number of flights, total or pertaining to a given group of flights, in the *baseline* schedule, γ is the operations count multiplier, F is the *new total* number of flights, the *RoundUp* function represents a rounding to the nearest highest integer to guarantee an integer number of new flights that is greater than the baseline number of flights by at least 1, and F' is the number of additional flights that are incorporated into the baseline schedule which is therefore equal to or greater than 1.

The additional flights are generated by replicating existing ones in the baseline schedule. The selection of flights to be replicated is performed through a stochastic process, performed separately for departures and arrivals to guarantee proportional growth of the two types of

operations. First, all baseline departure/arrival flights are indexed $1 \leq i \leq F_0$. For each of the F' additional flights that must be generated a randomly selected index is chosen, assuming an equal probability of selection for all flights in F_0. Thus, the selected index i_k for each of the $1 \leq k \leq F'$ new flights is determined by an integer value sampled from a *discrete uniform distribution* with limits 1 and F_0

$$i_k = Round(x) \tag{4}$$

$$x \sim U_{Discrete}(1, F_0) \tag{5}$$

The selection process is conducted for departures and arrivals separately to ensure that there is an equal proportion of new departures F'_D with respect to the number of departures in the baseline $F_{0,D}$, and new arrivals F'_A with respect to the number of arrivals in the baseline $F_{0,A}$. In using a *discrete uniform distribution* to sample flight indices, origin-destination flights that are most common in the baseline schedule have a greater chance of being replicated, which captures trends observed in industry where flights between high demand origin-destination routes such as Atlanta - Washington D.C. are more likely to grow in number than flights for routes with lower demand such as Atlanta - Gainsville, FL.

To ensure that the stochasticity of the process does not result in an unrealistic clustering of flights for a given time period, time adjustments are conducted to the schedule once all replicated flights have been determined. There are numerous approaches that can be implemented. The most basic one distributes all flights for an origin-destination pair j evenly within a certain time window in which flights for that origin-destination pair are known to occur, which is a good approximation of observed airline scheduling trends.[160] For high demand origin-destination pairs for which the distance is not particularly large there will generally a large number of flights spread throughout a large time window. For example, flights between Atlanta and Washington D.C. occur regularly throughout the day starting as early as 7 a.m. and ending as late as 11 p.m. On other hand, there will be fewer flights between more distant origin-destination pairs for which the effect of time difference in scheduling preferences will result in more specific time periods in which flights occur.

Thus, time adjustments in the new schedule first require that the limits of the time

window $[T_{0,j}, T_{Final,j}]$ of origin-destination pair j be determined from the baseline schedule. The lower limit $T_{0,j}$ is readily identified by the earliest flight for origin-destination pair j, and upper limit $T_{Final,j}$ is defined accordingly by the latest flight. Next, the new total number of flights for that route F_j are evenly distributed within the aforementioned time window such that the first flight occurs at $T_{0,j}$, the last flight occurs at $T_{Final,j}$, and all $(F_j - 2)$ flights in between are separated by a constant schedule time interval T^* defined by

$$T^* = \frac{T_{Final,j} - T_{0,j}}{F_j} \tag{6}$$

Thus the schedule times for all flights for origin-destination pair are assigned times

$$T_{0,j}, T_{0,j} + (n \times T^*), T_{Final,j}; 1 \leq n \leq (F_j - 2) \tag{7}$$

Special considerations are made for origin-destination pairs for which there is only one flight in the baseline schedule. This is often the case with international flights. In this instance an approximate time window is created by defining a time range based on the observed time of arrival/departure for that flight. Special considerations are also made for flights taking place before 6 a.m. which usually correspond to freight operations, and are treated separately from the rest of the flights.

A graphical depiction of this algorithm is illustrated in Figure 11.

To select an appropriate baseline schedule, an actual schedule of operations for ATL, publicly available online, was acquired. This schedule identifies scheduled time of arrival/departure for each flight, airline and flight number identification, and aircraft model.[4] The extent to which this schedule is representative of current operational activity was assessed.

For the purpose of airport capacity benchmarking and planning it is standard practice to use sufficiently large schedules representative of critical/limit operational conditions beyond which an airport will operate rarely. There are numerous standard forms to characterize this type of schedules, such as the ICAO *typical peak hour*, which is the the 30th (or 40th) busiest hour of the year, also referred to as *SBR*. In the U.S., it is FAA standard practice to use of the *design day*, which is the the average day of the busiest month of the year, or

Figure 11: Schedule Generation Algorithm
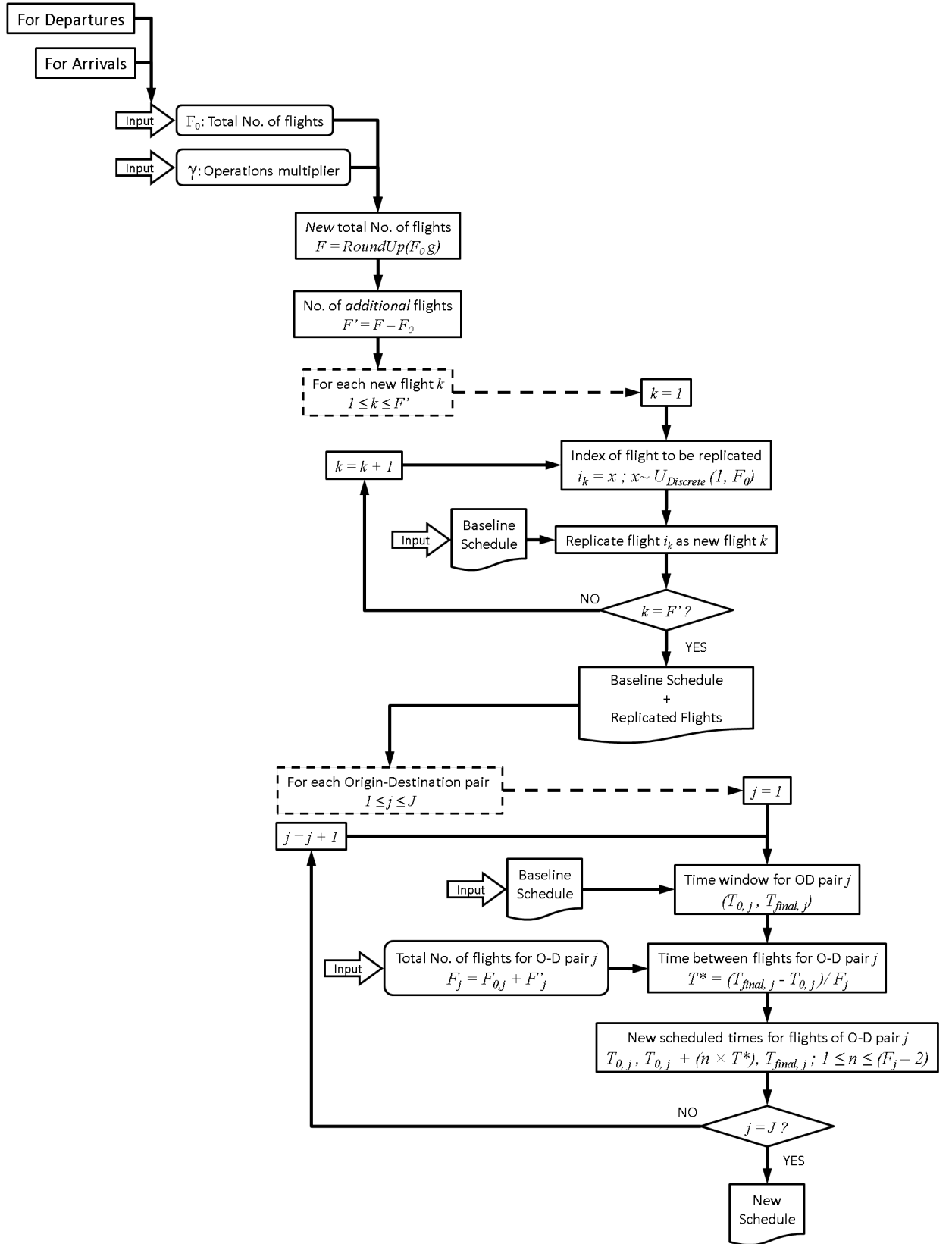
alternatively, the *design hour*, which is the peak hour of the design day.([70] p. 210, [41] p. 174, [200] p. 251) The design day is a statistical construct that does not correspond to an actual day of operation, but rather is a representative statistic of the volume of operations handed on a per-hour basis for an entire day. To generate a design day profile, the busiest month of a calendar year is first identified in terms of the number of operations. Next, the average number of operations is calculated for each hour period throughout the day. The resulting mapping of hour and average number of operations for the busiest month of the year is the design day profile. [272] Other forms of representative limit operational conditions include the Typical Peak Hour Passengers (TPHP).([22] pp. 31-35)

A design day profile was generated using 2008 FAA Enhanced Traffic Management System Counts (ETMSC) data for ATL [85], and then used as a reference to which the actual schedule of operations acquired was compared in terms of total number of operations, time-of-day and duration of arrival and departure peaks, and number of operations of these peaks. The design day profile for arrivals and departures is plotted against the hourly distribution of the schedule of operations acquired, as shown in Figure 12 and Figure 13 . As can be observed, the distribution of the schedule closely matches the design day profile for arrivals and departures. Table 12 summarizes values for design day hourly average, schedule operations count, and relative difference between the two. The difference in total number of arrivals and departures is within 4%, and the average relative discrepancy for the 7 a.m. to 10 p.m. period, accounting for the bulk of operations, is -1.74% and 3.19% for departures and arrivals respectively. Base on this comparison, the schedule of operations was deemed to be representative of current levels of operational activity and was thus used as the reference baseline schedule.

Once the selection of the baseline schedule was finalized, additional flight information required by SIMMOD was acquired and used to further define the schedule. In particular, SIMMOD requires that each flight be assigned a route, which in turn prescribes the use of a given runway. The assignment of routes and runways is based primarily on the arrival/departure heading of each flight, which in turn depends on origin/destination geographic location relative to ATL. The ATL terminal airspace features sixteen departure

Figure 12: Design Day Profile and Schedule Time of Day Arrivals Count
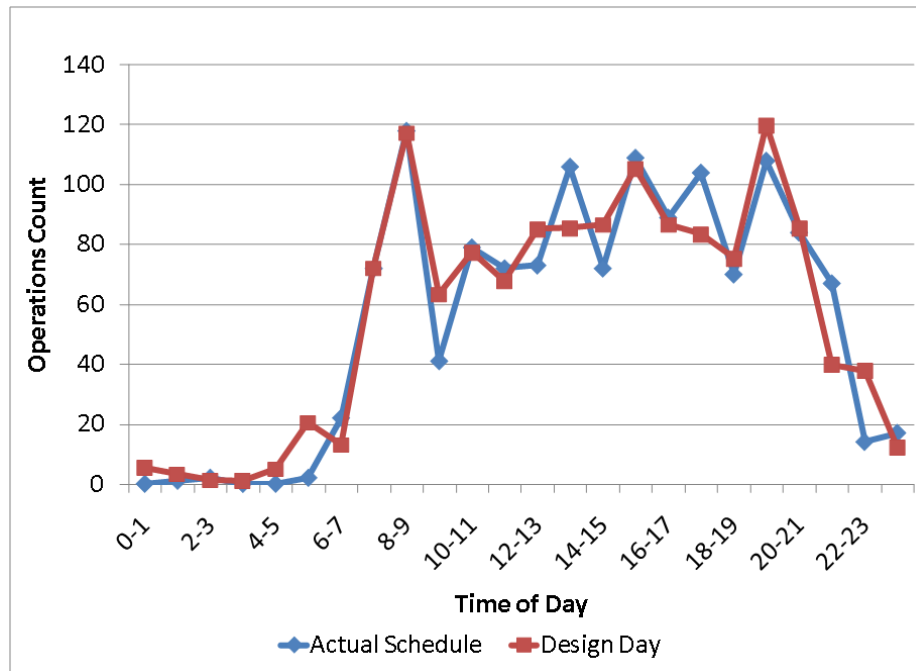
Figure 13: Design Day Profile and Schedule Time of Day Departures Count
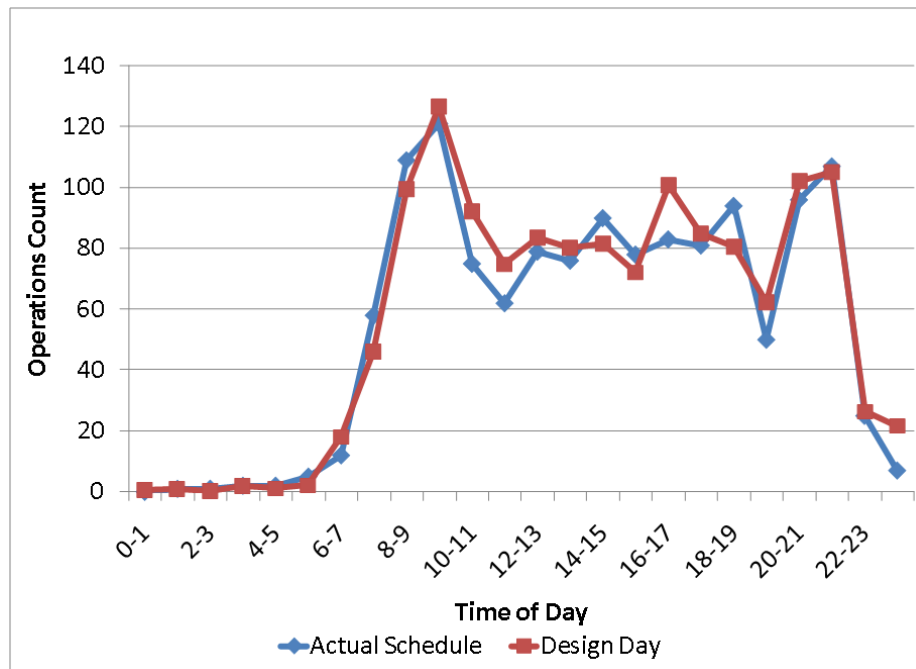
Table 12: Data for Design Day Profile and Schedule Time of Day Operations Count

Hour Period	Departures Design Day Average	Departures Operations Count	Departures Relative Difference	Arrivals Design Day Average	Arrivals Operations Count	Arrivals Relative Difference
0 - 1	0.742	0	-100.00%	5.419	0	-100.00%
1 - 2	1.097	1	-8.82%	3.226	1	-69.00%
2 - 3	0.323	1	210.00%	1.194	2	67.57%
3 - 4	2.032	2	-1.59%	1.000	0	-100.00%
4 - 5	1.194	2	67.57%	4.903	0	-100.00%
5 - 6	2.226	5	124.64%	20.419	2	-90.21%
6 - 7	18.129	12	-33.81%	13.000	22	69.23%
7 - 8	46.032	58	26.00%	72.065	72	-0.09%
8 - 9	99.516	109	9.53%	117.226	118	0.66%
9 - 10	126.677	121	-4.48%	63.290	41	-35.22%
10 - 11	92.097	75	-18.56%	77.355	79	2.13%
11 - 12	74.806	62	-17.12%	67.806	72	6.18%
12 - 13	83.452	79	-5.33%	85.065	73	-14.18%
13 - 14	80.290	76	-5.34%	85.387	106	24.14%
14 - 15	81.452	90	10.50%	86.516	72	-16.78%
15 - 16	72.161	78	8.09%	105.290	109	3.52%
16 - 17	100.774	83	-17.64%	86.484	89	2.91%
17 - 18	84.935	81	-4.63%	83.419	104	24.67%
18 - 19	80.516	94	16.75%	75.226	70	-6.95%
19 - 20	62.323	50	-19.77%	119.806	108	-9.85%
20 - 21	102.000	96	-5.88%	85.452	84	-1.70%
21 - 22	105.161	107	1.75%	39.774	67	68.45%
22 - 23	26.419	25	-5.37%	37.774	14	-62.94%
23 - 24	21.71	7	-67.76%	12.13	17	40.16%
Total	1366.06	1314	-3.81%	1349.29	1322	-2.02%

fixes, four for each north, south, east, and west departure heading. Considerations for aircraft separation and divergence of departure traffic flows dictate that northbound and westbound departures use runway 26R, and that southbound and eastbound departures use runway 27L, as shown in Figure 14 for a west-flow double departure configuration. The same considerations apply for a triple departure configuration that uses runway 28, as depicted in Figure 15.[186]

Flight plans corresponding to departures to each unique destination in the baseline schedule were acquired from a publicly available online source.[3] This information was used to determine the most commonly used departure fix, and hence the corresponding Standard Instrument Departure (SID) procedure, for each unique destination in the baseline schedule. Northbound operations counts per departure fix were used to determine the most common fix, which was hence carried as the only northbound departure procedure to facilitate the

Figure 14: ATL Runway-SID Mapping for West-flow Double Departures
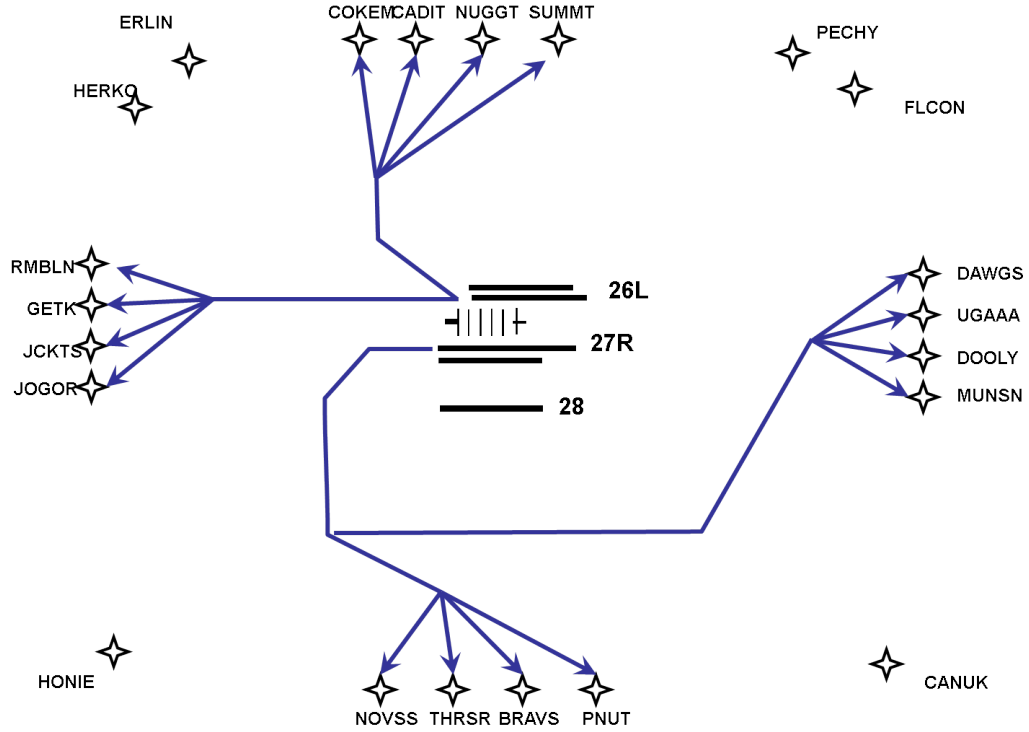
simplification of schedule data and of the SIMMOD model. The same process was repeated for westbound, southbound, and eastbound departures, choosing the most frequently used departure procedure for each departure heading. In this way, the destination airport for each departure in the baseline schedule was mapped to a departure procedure and to a departure runway.

There are also four corner arrival headings for the ATL terminal airspace, namely north-east, north-west, south-east, and south-west. Due to higher traffic volumes, there are two Standard Terminal Arrival Route (STAR) procedures for each north-east and north-west arrival corner, one for primary use and another for offloading. There is only one STAR procedure for each south-east and south-west arrival corner. Due to traffic flow considerations it is standard ATC practice to use the secondary north-east STAR only during west-flow configuration, and to use the secondary north-west STAR only during east-floc configuration. As will be discussed later, secondary STAR procedures were not include in the SIMMOD model for ATL. Assignment of arrival runways is dependent on primarily

Figure 15: ATL Runway-SID Mapping for West-flow Triple Departures
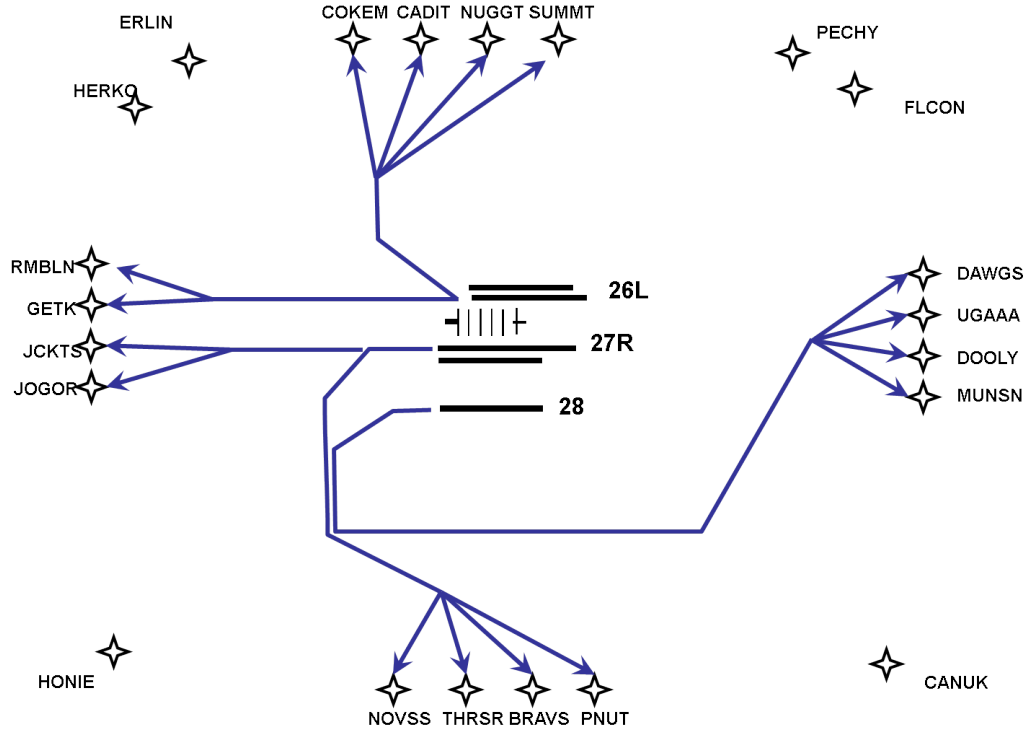
on the STAR being used by a flight to avoid traffic flow and aircraft separation. Traffic from the north-west is generally assigned to runway 26R, traffic from the north-east is generally assigned to runway 27L, and traffic from the two south corners is generally assigned to runway 28. However, air traffic controllers will deviate from this general guideline if demand for runway usage or visibility considerations demand it.[186] This assignment is notionally depicted in Figure 16 for triple arrivals in west-flow configuration, and in in Figure 17 for double arrivals in west-flow configuration.

Flight plans corresponding to arrivals from each unique origin airport in the baseline schedule were acquired from a publicly available online source.[3] In this way, the origin airport for each arrival in the baseline schedule was mapped to an arrival procedure and to an arrival runway.

An important consideration in the assignment of departure procedures and runways is the use of the triple departure configuration in ATL. Runway 10/28 enables the operation of triple independent arrivals, which is the configuration in which the airport is operated for

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Figure 16: ATL Runway-STAR Mapping for West-flow Triple Arrivals
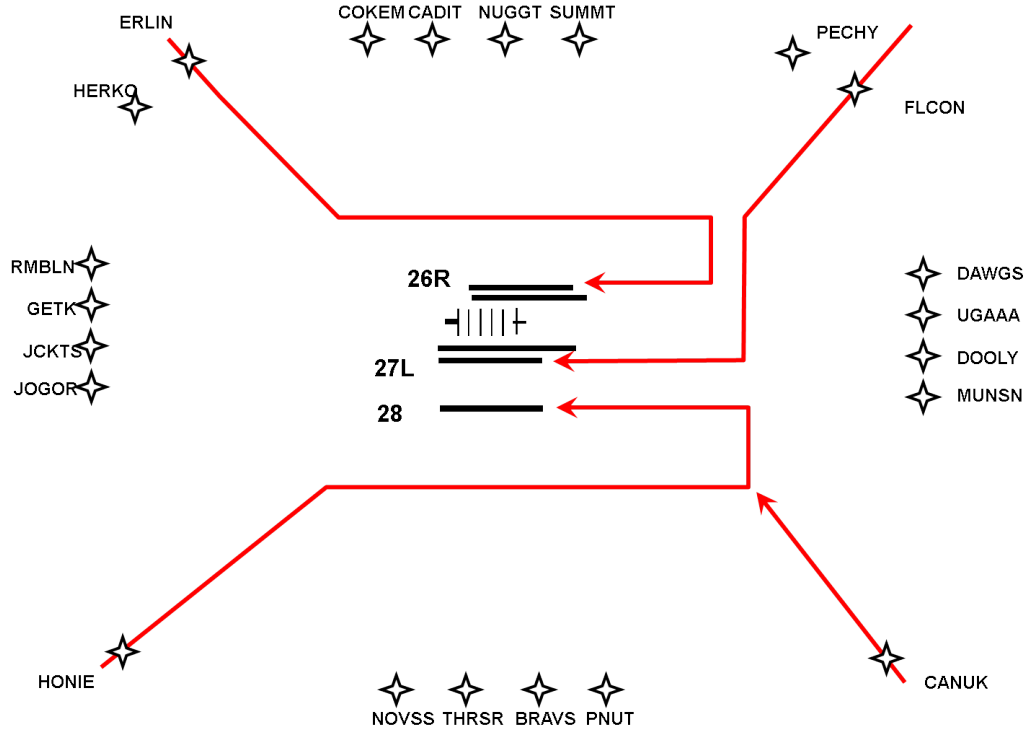
the vast majority of the time. However, significant congestion can be experienced during peak departure-push periods. Given that ATL is a major transfer hub, departure peaks are often observed during low arrival periods, and vice versa. This characteristic allows air traffic controllers to designate runway 10/28 as a departure runway during the most problematic departure peaks, and as an arrival runway the rest of the time. The use of triple departure operations depends on the departure peaking characteristics of a given day, but in general are used only two or three times for periods not extending more than one hour. Examination of the departure schedule profile in Figure 13 reveals the two major departure push peaks in the periods between 8 a.m. and 10 a.m., and 8 p.m. to 10 p.m. After iterations with ATL ATC specialists, and accounting for total taxi-out times, triple departure operations were specified for flights scheduled to depart between 8:45 a.m. and 9:45 a.m., and between 8:45 p.m. and 9:45 p.m. [186]

The implementation of this information into the baseline schedule realizes a fully defined operations schedule that can be passed to SIMMOD. The application of growth factor

Figure 17: ATL Runway-STAR Mapping for West-flow Double Arrivals
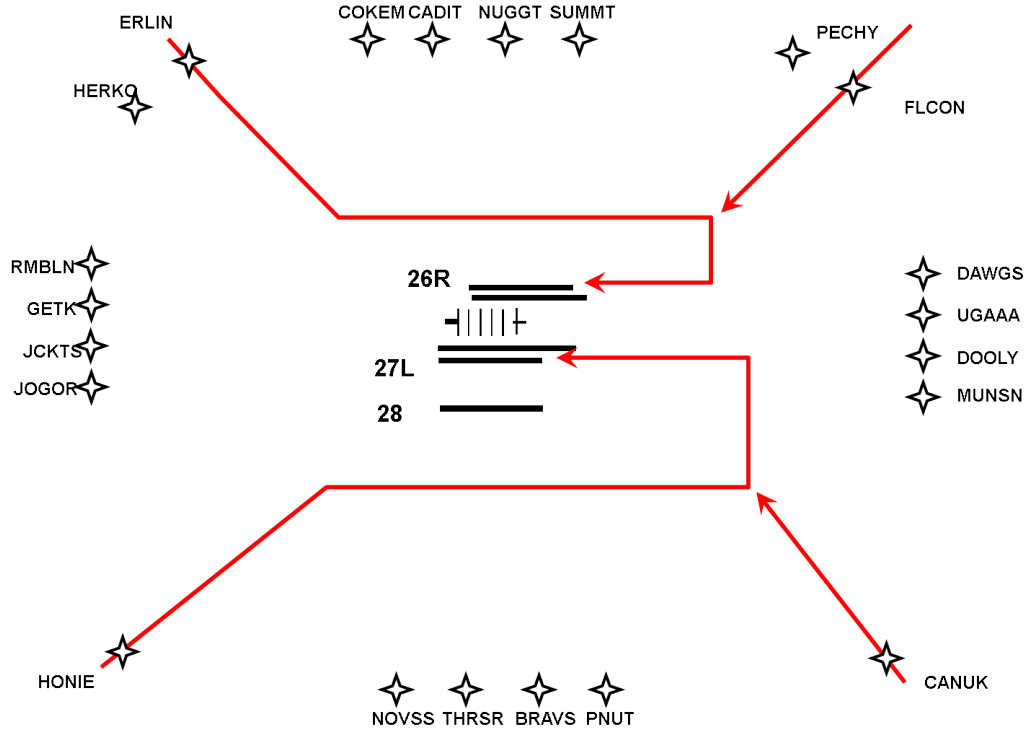
multipliers to generate notional schedules for current and future conditions was implemented through adequate Microsoft®Visual Basic routines that were executed within the Microsoft®Excel environment in which the schedule table was stored and manipulated.

5.4.3 Terminal Area Operations Component - ATL Model in SIMMOD

When completed, a full schedule of operations is passed as an input to the second component of the environment for which the FAA Airport and Airspace Simulation Model (SIMMOD) was chosen. This simulation engine requires a variety of input data that must be specified in a series of text files that follow a specific data formatting and syntax scheme. Table 13 summarizes the list of input files, which are indexed with odd numbers, as well as the primary and most commonly used output files, indexed with even numbers, and identifies the data contents provided in each of them. The selection and use of *Visual SIMMOD* facilitates the generation and management of data records comprising the SIMMOD model, generates the necessary input files automatically, and executes the SIMMOD simulation

engine accordingly.

Table 13: Selected SIMMOD Input and Output Files

File Name	Data Contents
Rundata	Date, Iterations, Seeds
SIMU 01	Aircraft Definitions
SIMU 03	AIRSPACE - Aircraft airspace groups, airspace nodes and links, procedures, airports, routes.
SIMU 07	AIRFIELD - Nodes, links, runways, taxi paths for departure queues, airfield access to different aircraft types, airlines, gates, departure queues, takeoff landing and intrail distributions, concourses.
SIMU 09	Input events − traces, arrivals, and departures
SIMU 02	Echo input data, Warnings and Errors
SIMU 04	Trace messages, error messages
SIMU 10	Ground, air and overall delay and travel times, departure queue times, runway crossings
SIMU 14	Statistics for each flight
SIMU 26	All simulation movements , events, and delays

The SIMMOD model for ATL was constructed using a variety of publicly available sources such as airport charts and arrival/departure procedure charts, as well as subject matter expert input from ATL tower controllers and ATC support specialists.

A diagram of ATL is shown in Figure 18. ATL has a total of five parallel runways aligned in the east-west direction. The terminal and all concourses are located in the middle region of the airport. Runways 8L/26R and 8R/27L are located north of the terminal, runways 9L/27R and 9R/27L are located south of the terminal, and runway 10/28 is located south of runway 10R/27L. The airport operates in one of two primary configurations, east-flow where takeoffs and landings take place towards the east, and west-flow where takeoffs and landings take place towards the west. Based on the frequency of usage of these two configurations reported in the Airport Capacity Benchmark Reports, a west-flow configuration was chosen.[102, 111] Thus, all discussions and descriptions that will follow will refer to the runways based on westerly direction.

Airport charts, diagrams, and satellite imagery publicly available online were used to determine the the links and nodes defining the network of airport taxiways, runways, surface areas, and gates. Airfield traffic flows for west-flow operations were elicited from ATL ATC specialists [186]. The arrangement of concourse gates was determined from concourse diagrams published by the Department of Aviation (DoA) of the city of Atlanta, which is

Figure 18: Airport Diagram of ATL
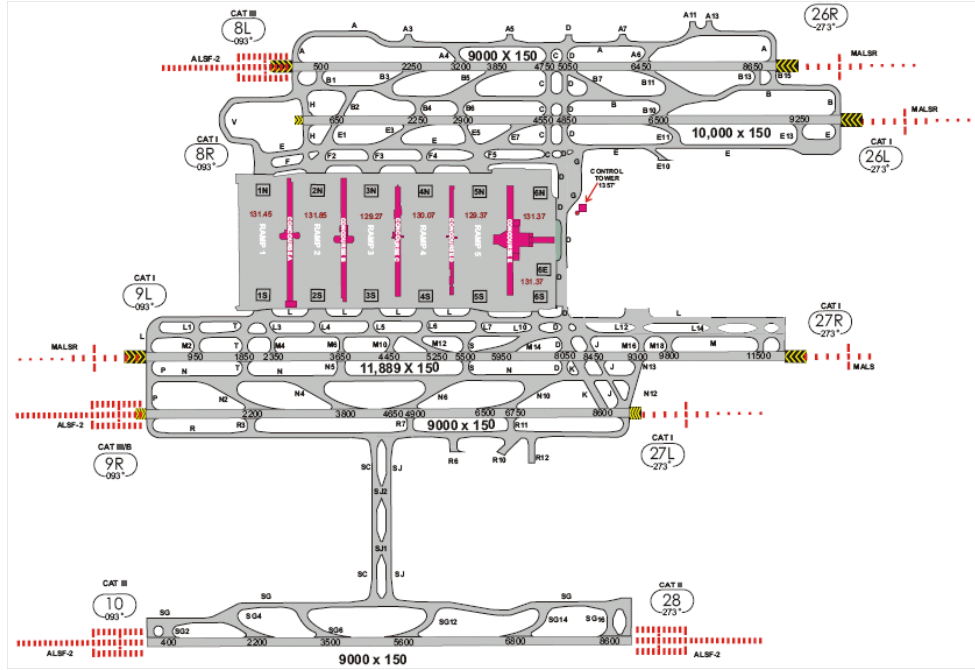
in charge of operating the airport. (See for instance the directory for *Concourse A* in [46].)
The assignment of airlines to individual gates was based on the *Competition Plan* for ATL
but required some modifications to effectively utilize all gates included in the SIMMOD
model.[5][277, 278]

The runway and route assignments for west-flow operations discussed in the previous
section identifies the set of airspace procedures that need be included in the SIMMOD
model. These include STAR procedures for arrivals, SID procedures for departures, and
Instrument Approach Procedures (IAPs) for final approach and landing. The list of pre-
scribed procedures is shown in Table 14. Each procedure is contains a variety of information
that is documented in procedure charts, or 'plates', such as the one shown in Figure 19 for
the *FLCON* arrival. All published procedure charts are publicly available. Because the

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[5]The *Competition Plan* "summarizes the Airports efforts and plans to assure access to all carriers and to
improve air carrier competition at the Airport."[277] As required by the *Wendell H. Ford Aviation Invest-
ment and Reform Act for the 21st Century (AIR21)* airports requesting federal grants or seeking to impose
Passenger Facility Charges must submit a Competition Plan.

procedures chosen are defined for RNAV, which uses and GPS technology, the exact latitude and longitude geographical location of each of them is readily defined. Coordinates for all waypoints are also publicly available online, and were retrieved for the necessary procedures.[1] Altitude information is specified for all waypoints in an IAP. Altitude maxima and/or minima are provided for some points in a STAR procedure whenever a specific altitude is not explicitly stated. usually key metering waypoints and waypoints leading to the transition into final approach have specified altitudes. SID procedures do not provide altitude information because departure profiles depend on aircraft performance. The AEDT uses the Aircraft Performance Module and standard departure profiles stored in the Aircraft database to determine altitudes for departure operations, and thus it is not necessary to provide it to AEDT. However, SIMMOD model definition still requires that altitude information be provided for all airspace nodes, even if it will have no bearing on the aircraft performance within AEDT. Departure profiles were queried for all aircraft models in the baseline schedule, and used to create a single representative profile to be used in SIMMOD. This composite profile was generated as weighted average based on departure frequencies for each aircraft model. All the aforementioned definitions of procedures and waypoints were implemented in the SIMMOD model.

Table 14: Selected Procedures for ATL in West-flow Operations

Departure			Arrival		Instrument Approach
Runway	SID	Heading	STAR	Corner	IAP
26L	SUMMT	North	FLCON	North-East	RWY 26R RNAV
26L	RMBLN	West	ERLIN	North-West	RWY 27L RNAV
27R	RMBLN	West	CANUK	South-East	RWY 28 RNAV
27R	BRAVS	South	HONIE	South-West	
27R	DAWGS	East			
28	DAWGS	East			

The definition of waypoint coordinates and altitude, as well as the arrangement of waypoints into terminal area procedures, allows for the visualization of basic trajectories in a Geographic Information System (GIS) applications such as Google ^{TM}Earth. A view of Google ^{TM}Earth visualization of the selected STAR and SID procedures is shown in Figure

Figure 19: Chart for FLCON Arrival (RNAV) into ATL
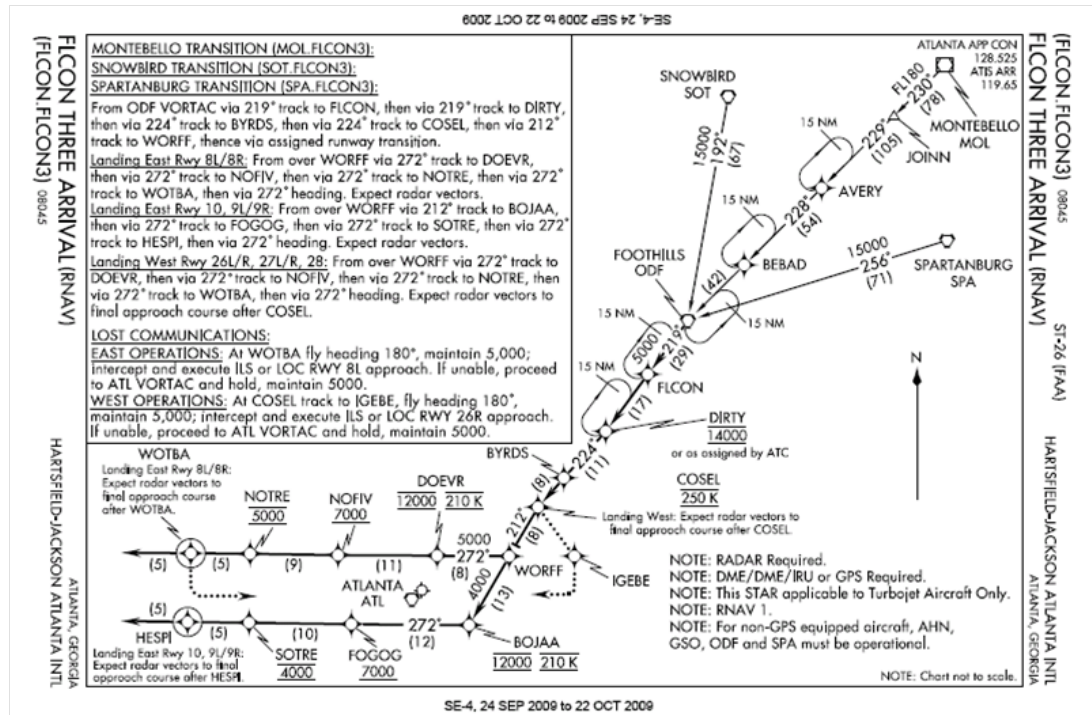
20. Similarly, a visualization of selected IAP's is shown in Figure 21

The SIMMOD model also incorporates aircraft separation minima corresponding to IMC, commensurate with ATC instructed separation for arrivals and departures during instrument conditions. This separation of aircraft follows the radar and wake turbulence separation considerations described in Section A.3 of Appendix A, and is summarized in Table 25. IMC conditions for aircraft separation are chosen because they represent critical/limit operational conditions relevant to the characterization of capacity and operational performance in this research.

Arrival and departure procedures implemented in the model follow rules and guidelines presented in FAA Order JO 7110.65S Air Traffic Control for radar controlled airspace [125] and discussed in Section A.3.3 of Appendix A. Separation for consecutive departures on the same runway, for departure designated runways 26L, 27R, and 28 if using triple departure configuration, is set to two minutes for *Small* and *Large* class aircraft following *Heavy* class aircraft and Boeing 757. As noted in Section A.3.3, for all aircraft following immediately

Figure 20: Google ^{TM}Earth Visualization of STAR and SID Procedures
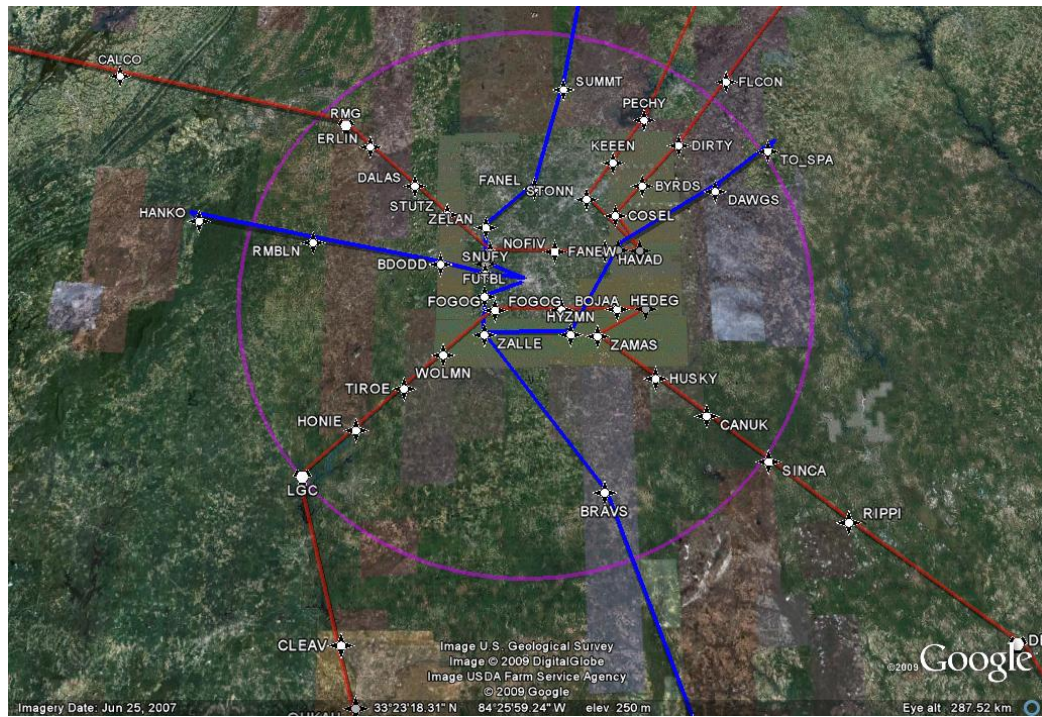
Figure 21: Google ^{TM}Earth Visualization of IAP's

after a *Small* or *Large* class aircraft, separation for consecutive departures is driven by radar considerations only and is therefore limited to 3 miles once airborne, which must be established via adequate visual landmarks or radar equipment. However for Category III Same Runway Separation (SRS) aircraft, which refer to all aircraft that are *not* under 12,500 lbs and do *not* have single or twin propeller driven engines, rules dictate that a preceding departure need only be airborne and more than 6,000 feet down range. It is common practice to assume a 60 second interval as a *conservative* estimate for the 3 mile separation for departures following a *Large* or *Small* class aircraft. However, it is known that SRS rules and considerations for aircraft climb-out speed can effectively result in a separation interval shorter than 60 seconds.

Similarly, the 60 second - 3 mile separation is augmented, due to wake turbulence considerations, to 90 seconds for *Heavy* class aircraft or Boeing 757 following a *Heavy* class aircraft or Boeing 757. Consequently, it is common practice to assume a 2 minute interval for *Large* or *Small* class aircraft departures following a *Heavy* class aircraft or Boeing 757, a 90 second interval for *Heavy* class aircraft or Boeing 757 following a *Heavy* class aircraft or Boeing 757, and a 60 second interval for all other consecutive departures (see for example Ref. [69] and [26]).

Since designated departure runways are more than 2,500 feet apart from each other , simultaneous departures can be conducted and no time or distance separation is required for departures from different runways. Similarly, simultaneous independent arrivals in can be conducted in designated arrival runways 26R, 27L, and 28 by virtue of their separation. Thus no dependent time or distance separations between the three arrival tracks are required. Takeoffs and landings taking place in runways 26L and 26R respectively are dependent due to close proximity. The separation rule for these operations is commonly referred to as "*2 miles increasing to 3*" as noted in Section A.3.3, which means that a departing aircraft can be cleared for takeoff with an arriving aircraft up to 2 miles from the arrival runway threshold, as long as the distance between both aircraft grows to 3 miles within one minute of the takeoff. ([125] §5.8.4) The same rule is applicable for takeoffs and landings on runways 27R and 27L respectively. All the aforementioned considerations were revised and refined

based on ATC expert input.[186]

The *SIMU26* simulation history output file, produced with every execution of the SIM-MOD simulation engine, is the primary output of the model. The file requires a moderate amount of data formatting before it can be imported into the AEDT Operations database for processing. This formatting functionality was implemented in Microsoft Visual Basic, leveraging on the advantage of manipulating the comma-delimited *SIMU26* in Microsoft Excel.

5.4.4 Environmental Impact Component

Once SIMMOD output data is imported into the AEDT Operations database, AEDT is ready for execution. All other information necessary for the generation of emissions and noise outputs is already contained in the other AEDT databases. The configuration file utilized specifies that AEDT must only evaluate arrival and departure operations, but no enroute segments. The file also specifies the use of latitude-longitude geographic data pertinent to the SIMMOD airspace nodes for the definition of ground tracks in AEDT operation evaluations.

However, there are two important modeling limitations in the version of AEDT that was made available for the development of this research. First, the environmental impact of aircraft movements on the airport surface is not modeled. Thus, the details corresponding to airfield operations included in the *SIMU26* file cannot be directly used in AEDT. In fact, preliminary test runs revealed that the provision of operation segments pertaining to aircraft movements on the airport surface results in incorrect estimates of environmental performance metrics. Upon inspection and communication with AEDT developers it was determined that the version of AEDT in question only models the takeoff ground roll and airborne movements for departures, as well as landing movements and the landing roll for arrivals. Moreover, takeoff and landing roll segments are modeled automatically by AEDT based on the runway assignment declaration of each flight and the information contained in its Airport database, and thus the provision of takeoff and landing movements data from the *SIMU26* file is redundant.

This limitation was addressed in two ways. First, the routine used for manipulation and formatting of the *SIMU26* file was modified so that all SIMMOD simulation events corresponding to ground movements are removed prior to import into the Operations database. In this way, the SIMMOD event data that is used as an input to the AEDT is devoid of all ground movement events that may cause modeling or runtime errors. Second, the routine was further augmented by incorporating an algorithm that uses the the simulation events removed from the *SIMU26* file to calculate the total time that each flight spends conducting ground movements. The ground movement time for each flight is combined with appropriate fuel flow and emissions indices from the ICAO Aircraft Engine Emissions Databank [175] to implement a *time in mode* estimation of ground fuel burn and emissions. Consistent with known operating practices, the algorithm assumes that engines are off during boarding and disembarking, as well as during waiting periods at the gate for departures. However, all other waiting times taking place on the ground, such as arriving aircraft waiting for a gate to become available or departure queue waiting times, are included.

The selection of appropriate fuel flow values and emissions indices is based on the the mode of operation and on the engine model. In accordance with the power settings known to be used in all ground movements, other than takeoff and landing segments which are already modeled in the AEDT, fuel flow and emissions indices were selected for *idle* mode. The schedule of operations generated in the first modeling component and used as an input in SIMMOD identifies the aircraft model operated in each flight. In turn, the corresponding engine model is determined by querying relational tables in the AEDT Fleet database that map aircraft airframes to engines models. Thus, the appropriate fuel flow and emissions indices can be selected for each flight, and used to implement the calculations involved in the basic *time in mode* formulation. This modeling approach is consistent with he one implemented in EDMS, as described in Section 5.3.3, and effectively addresses this limitation in AEDT modeling by providing fuel burn and emissions inventories for all ground movements.

The second modeling limitation observed for the AEDT version in question is that path vectoring/stretching, as implemented in SIMMOD, is not captured unless each specific

vector-stretched path is explicitly detailed as an input into AEDT. In other words, SIMMOD output data will implicitly account for any path vectoring that was implemented during the simulation, and will be manifested by flight times between nodes that are longer than what would be required to traverse a straight path connecting these nodes. As mentioned earlier, this simulation technique effectively emulates ATC vectoring functions that are used in real operations to separate and sequence aircraft in the transition to final approach during highly congested periods. However, in the AEDT, unless path vectoring is explicitly considered and contained in the flight trajectories provided as an input, velocity and time data will be in conflict with distance data in said trajectories records.

Flight trajectories explicitly describing path-vectoring can be provided to the AEDT to solve this shortcoming. Such trajectories are obained primarily from *RADAR track* data, which is retrieved and synthesized from multiple radar sources, but which is for the most part *not* publicly available. Beyond being unavailable to the public, RADAR track data does not offer the flexibility that modeling environments provide to vary parameters and assess the resulting impact at multiple levels. Similarly, because it pertains to actual operations under real operating conditions, its applicability is limited said conditions and is not readily extensible to notional/future operating conditions. In this sense, RADAR track data is an ideal source for current performance assessments, granted the data corresponds to a sufficiently representative day, but is not immediately applicable to assessments under notional/future conditions, which are of key interest in strategic airport planning.

For the preferred alternative of modeling capabilities such as SIMMOD over RADAR track data, path vectoring is accounted for, but trajectories provided by SIMMOD output to the AEDT are expressed solely through the
textitnominal nodes explicitly created in the model and used to create the airspace flow structure. In other words, SIMMOD output trajectories do not explicitly incorporate the exact vectored path that is calculated for each arrival flight when the ATC path-vectoring function is simulated. In this thesis, waypoints pertaining to in STAR procedures are used to define said *nominal* airspace nodes in SIMMOD, and experienced ATC specialists were queried to define path vectoring areas and flow patterns for the transition between STAR

procedures and final approach in the SIMMOD model.

As a result, SIMMOD event data passed on to the AEDT reflects the effect of path vectoring in terms of speed values and simulation times at which different aircraft reached specific waypoints. But since it does not explicitly provide trajectories describing strethced/vectored paths, this data is only manifested in AEDT as an inconsistency between speed, distance, and time values, given that AEDT assumes straight (non-stretched / non-vectored) paths between two waypoints. When executed, the AETD Aircraft Performance Module overrides this data conflict and models aircraft flight assuming only straight paths between nodes. This has very important implications on the calculation of emissions and noise. As was discussed in Chapter 2, the interdependencies between operational and environmental performance is realized in part because near system capacity limits operational inefficiencies such as necessary holding times or elongated (vectored) paths emerge, resulting in longer waiting times and distances that cause higher fuel burn, emissions, and noise. From a modeling perspective, longer times in mode result from these operational inefficiencies, which lead to more fuel burn and more emissions. This concept is notionally illustrated in Figure 22 for the south arrivals to ATL using runway 28. The nominal paths are those defined by the links and nodes in the SIMMOD model which follow the geographical arrangement provided, in this example, by the *HONIE* and *CANUK* STAR procedures. Thus, the nominal paths those that aircraft closely follows by aircraft if sufficient airspace link and node capacity is available. An artificial vectored path is automatically generated by SIMMOD for each aircraft based on the amount of path 'stretching' necessary to accommodate all aircraft traversing links for which vectoring is allowed to occur.

It is paramount to recognize that this condition does not occur when trajectory data provided to the AEDT explicitly charecteizes path vectoring, as would be the case of radar track data. For the instance when trajectory data is provided by SIMMOD, as is the case in this research effort, a solution to the calculation of airborne fuel burn and emissions for vectored segments was implemented by explicitly adding series of new (additional) flight segments between the initial and final nodes for which path stretching had been implemented in SIMMOD. The additional flight segments are defined such that they de-conflict distance,

Figure 22: Flight Path Vectoring in SIMMOD
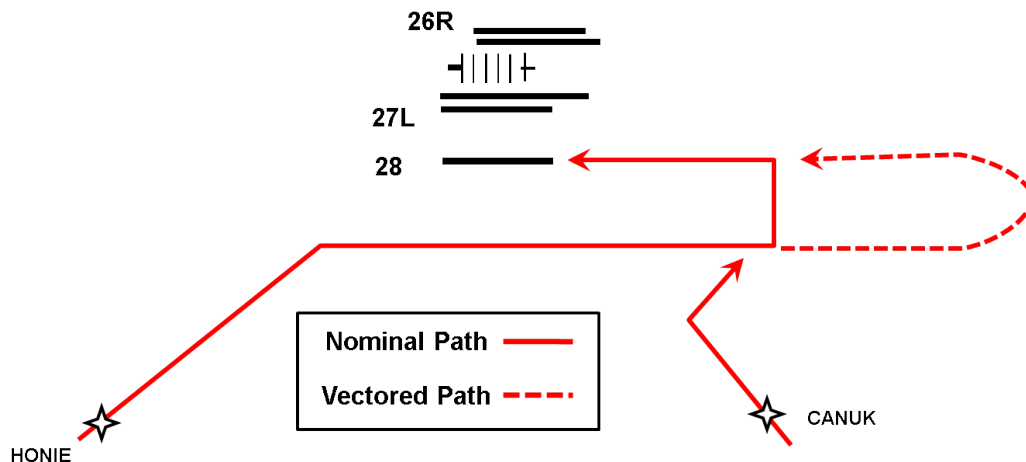
time, and velocity information, and they do not violate internal constraints of the Aircraft Performance Module. It is important to note that the additional paths explicitly defined to realize this data harmonization do not match or correspond to vectored paths that would be expected in reality. Rather, they are a modeling construct that is permissible only because fuel burn and emissions calculations are driven exclusively by time in mode, and not by the geographic representation of trajectories. Thus, this approach effectively captures the effect that vectored paths have on time in mode, which in turn yields fuel burn and emissions calculations correspond to these longer and less efficient flight segments.

On the other hand, noise calculations are directly dependent on the adequate definition of airborne trajectories so that accurate and realistic noise contours can be produced. Since airborne trajectories with vectored flight segments provided by SIMMOD cannot be adequately handled by the AEDT, noise results produced thereof will not be accurate nor representative of realistic operations.

The generation of noise results regardless of this critical limitation could potentially be admissible, if only to illustrate contours in areas of the terminal airspace where vectoring is not implemented. However, noise calculations are very computationally intensive and impose considerable requirements on data storage space availability. With this in mind, it is difficult to justify the generation of noise results, particularly for a plethora of simulation

runs, knowing a-priori that they would have been seriously compromised by the AEDT modeling limitation in question.

Consequently, the decision is made *not* to include noise results in the assessment of environmental performance until this gap in the M&S capabilities of the AEDT are properly addressed. Moreover, the the methodology proposed in this thesis for terminal area performance characterization is still valid and fully applicable to noise calculations. Although the examination of sensitivities of noise metrics, and its tradeoffs with operational and other environmental metrics, would be of great value, the demonstration of the proposed approach is not compromised by the exclusion of noise results. Rather, the demonstration of the method will serve to lay the foundation of future implementations that include noise results, granted that the corresponding modeling limitations are properly addressed.

5.4.5 M&S Environment Layout and Data Flow

The three aforementioned components are integrated into a M&S environment that reflects the general flow of information introduced in Section 5.4.1. The architecture and flow of this environment is visually depicted in Figure 23. The M&S environment is composed of the three primary components discussed in this section, namely the generation of notional and representative schedules, the modeling and simulation of airport operations, and the modeling of aircraft operations environmental impact. The diagram illustrates how these components are executed serially, with the data flow progressing from left to right in order as the output of one component is passed as the input of the next. The core M&S capabilities comprise an *Analysis* layer. Given the critical importance of data and information in the procurement of adequate models and required data constructs, an *Information* layer of the environment is recognized and shown to feed into key analytical components. Similarly, the synthesis and analysis of results and the transparent communication of insight are facilitated by adequate visualization mechanisms that are explicitly recognized in a *Visualization* layer.

The baseline schedule is documented in Microsoft®Excel, where each row corresponds to a distinct flight and columns provide specific parameters pertinent to each flight. Said parameters are the *Flight ID* which is used to track flight numbers and airline codes, the

Figure 23: Modeling & Simulation Environment
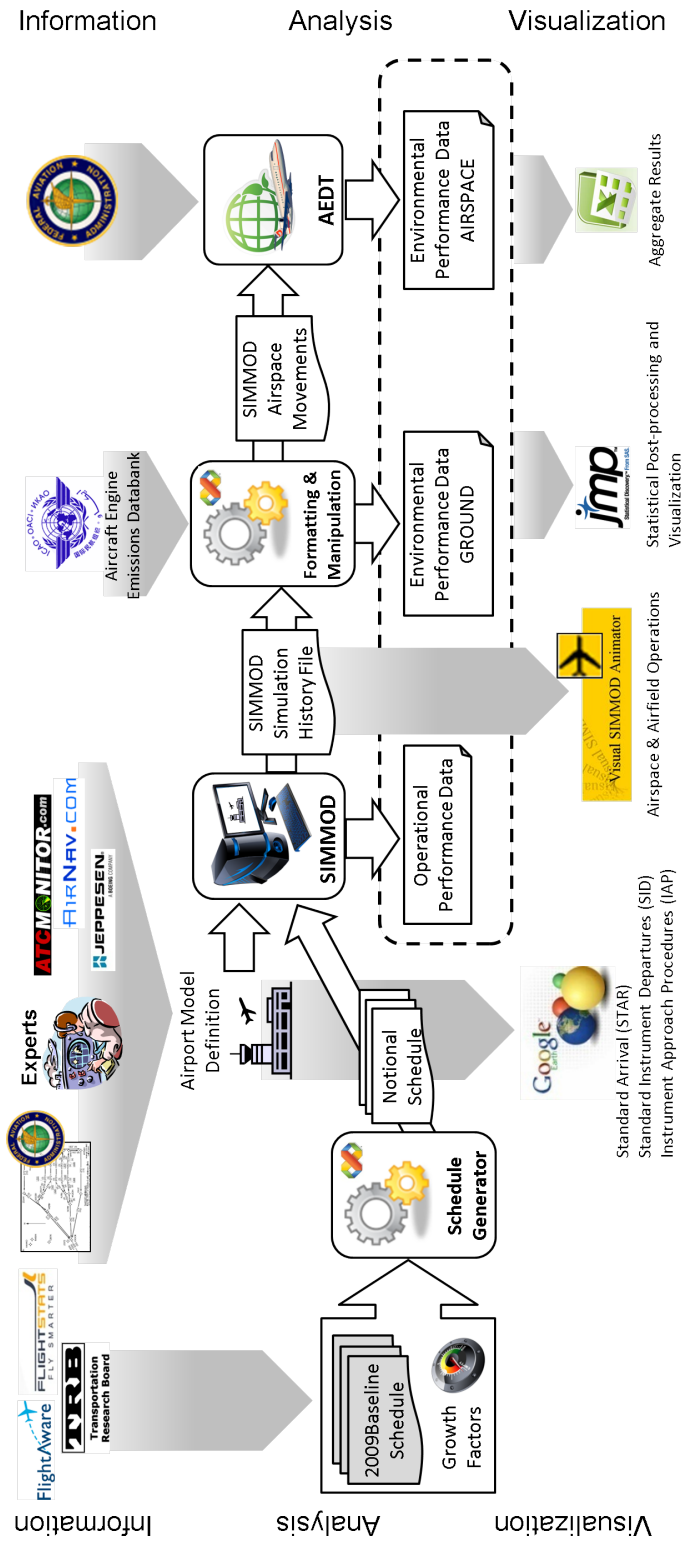
Event Time which identifies the simulation time at which the flight is injected into the simulation, a *Departure-Arrival Flag* identifying the type of operation, *Airline ID* mapping the flight to an airline defined in the SIMMOD model, the *Flight Number*, the *Aircraft ID* specifying the aircraft model conducting the operation, the *Route ID* mapping the flight to one of the airspace arrival/departure routes specified in the SIMMOD model, the *Origin Airport ID* and *Destination Airport ID*, and *Event ID* used in SIMMOD to allow certain flights to be turned ON or OFF by the user. Other data may be optionally defined in the schedule. For instance, gates or entire concourses may be assigned for each individual flight. Since gate definitions provided within the SIMMOD model already specify the airlines and aircraft models that can use each gate, no gates are defined so that SIMMOD stochastically selects among permissible gates for each flight. However for international flights *Concourse E* is specified, given that this is the designated concourse for international flights. The schedules for departures and arrivals are instantiated in separate spreadsheets for ease in the manipulation of data by the schedule generator.

The algorithm for the generation of notional schedules described in Section is implemented as Microsoft ®Visual Basic routine that is applied directly on the departure and arrival schedule spreadsheets separately, generating two new spreadsheets corresponding to the new arrival and departure schedules that follow the aforemention tabular structure. In doing so, said tables can be directly copied into the Visual SIMMOD database, and thus are explicitly incorporated into the SIMMOD model. For the execution of the schedule generation algorithm, ancillary tables were generated in the spreadsheet file and linked to the baseline schedule tables. These ancillary tables determine data necessary in the schedule generation algorithm, namely, unique origin-destination pairs and time windows for origin-destination pairs

As mentioned before, all data sets and records pertaining to the SIMMOD model are defined and documented within the Visual SIMMOD environment through the appropriate visual interfaces, windows, and applications. Visual SIMMOD stores this data in its internal relational database and uses it accordingly to generate the necessary SIMMOD input flat files prior to invoking the SIMMOD simulation engine executable. Standard SIMMOD

output flat files are generated if the simulation run is successfully completed.

STAR, SID, and IAP procedure data used to define the airspace structure in the SIM-MOD model can also used to generate a Keyhole Markup Language *KML* file that defines placemarks and polygons to represent waypoints and trajectories in Google ^{TM}Earth, as illustrated in Figure 20 and Figure 21. The KML is a file format based on the Extensible Markup Language (XML) that uses a tag-based structure with nested elements and attributes. KML files are used to display geographic data in GIS browsers and visual applications such as Google Earth, *NASA WorldWind*, and *ESRI ArcGIS Explorer*[144]. There is no unique way to construct such a file, and it does not need to result directly from SIM-MOD output. In this thesis, all procedures were first organized in a spreadsheet identifying relevant waypoints and necessary associated geographic data, namely latitude, longitude, and altitude. This data was used to construct both the SIMMOD model in the Visual SIMMOD environment, as well as the KML file for visualization in Google ^{TM}Earth.

The SIMMOD output flat files can be queried to extract values of operational metrics and relevant statistics, or to generate this information directly from the simulation event history file *SIMU26*. This constitutes the operational performance data. The *SIMU26* file is directly invoked by the Visual SIMMOD Animator application where the movement of aircraft and all simulation events are visually represented.

The manipulation of SIMMOD simulation data is conducted through a Microsoft ®Visual Basic routine which imports the *SIMU26* flat file as a delimited text structure into a Microsoft®Excel spreadsheet. The Visual Basic routine separates airfield and airspace movements, creating a table of all flights and associated ground movement times, and a separate table of airborne movements appropriately formatted for import into the AEDT. Importing of airspace movements is realized through a *Movements Pre-processor* for which the origin table file and the destination AEDT database are specified. This preprocessor is provided by the AEDT development team for SIMMOD and ACES data import into the Microsoft ®SQL Express database containing AEDT supporting data, movements data, and used to store all AEDT results. The pre-processor is comprised of a *Python* script that can be invoked from the operating system command prompt, and is supported by

executable files.

When movements are imported into the SQL Express relational database for AEDT, three tables are created in the *MOVEMENTS_SIMMOD* database: 1) a *FLIGHT* table which contains information such as aircraft model, origin, destination, and airline; 2) a *FLIGHT_TRAJECTORY* table describing the flight trajectory and ground track for each flight; and 3) a *OD_PAIR* table containing all the unique origin-destination pairs in schedule of operations. As part of the data import routine, airframe and engine models are determined for each flight based on the aircraft model code provided and on airline-specific aircraft data from the *FLEET* database. A simple query is made whereby the *FLIGHT* table containing the aircraft model for each flight is mapped to the *EQUIPMENT* table in the *FLEET* database to determine the number of engines of the aircraft used for each flight, and the idle fuel flow and emissions indices for the corresponding engine model. The fuel flow and emissions indices stored in the AEDT correspond to the ICAO Aircraft Engine Emissions Databank [175]

The result for this query is a table that can be directly copied into the Microsoft®Excel spreadsheet containing the ground movement time for each flight produced by the Visual Basic routine. With the ground operations total time, the idle fuel flow, the idle emissions indices, and the number of engines for each individual flight, ground fuel burn and emissions are readily calculated on a per-flight basis by implementing the time-in-mode calculation for fuel and emissions consistent with the approach of the EDMS in the AEDT.

Next, with the movements data already located in its database, the AEDT is executed to calculate performance, fuel burn, and emissions, using the provided flight trajectories as ground tracks, following the performance characteristics of each aircraft modeled in the Aircraft Performance Module, and limited only to the terminal are of ATL for movements under 10,000 feet Above Ground Level (AGL). AEDT results are stored in the *EVENTRESULTS* database and queried accordingly to extract total fuel burn, and total emissions quantities for each flight, providing sufficient resolution and allowing for subsequent aggregation such as all departures, all arrivals, all operations, etc.

The collection of operational performance data queried from SIMMOD output files,

ground environmental peformance data produced by the Visual Basic routine, and airborne environmental data produced by the AEDT and stored in its relational database, can be synthesized and imported into specific applications for data analysis and post processing. For this thesis preliminary data analysis and visualization was conducted in Microsoft ®Excel, whereas the bulk of statistical analysis, visualization, and implementation into interactive visual schemes was conducted in the statistical discovery software *JMP*®[262].

CHAPTER VI

CHARACTERIZATION OF OPERATIONAL-ENVIRONMENTAL PERFORMANCE

6.1 Introduction

This chapter presents the implementation of the proposed approach for the characterization of operational-environmental performance of the ATL terminal area under reference conditions. This characterization corresponds to *Step 2* of the strategic airport planning process illustrated in Figure 9. A discussion of the results is provided with regards to the explicit quantification of tradeoffs between operational and environmental metrics, sensitivities of metrics to different factors, and the interactions among endogenous and/or exogenous factors. Hypotheses relevant to these three types of relationships are formulated in the context of the sample problem. In turn, these hypotheses are tested with appropriate experiments whose results reveal whether hypotheses should be accepted or rejected.

The implementation and demonstration of the proposed methodology to the sample problem addresses the thesis objective *Thesis Objective 2* defined in Chapter 3:

- *Thesis Objective 2:*To quantitatively characterize the operational-environmental performance of terminal areas by investigating the interactions between exogenous and/or exogenous factors, the sensitivity operational and environmental performance metrics to different factors, and the tradeoffs and correlations between operational and/or environmental metrics.

Additionally, the implementation and demonstration of the proposed methodology to the sample problem and the test of relevant hypotheses serve to support *Methodological Hypothesis 1*, formulated in Chapter 4:

- *Methodological Hypothesis 1:* A quantitative characterization of interactions, sensitivities, and tradeoffs for airport operational-environmental performance metrics with

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respect to *endogenous and exogenous factors* is realized through regression analysis, statistical testing techniques, and interactive visualization of RSE's.

6.2 Preliminary Assessment - Tradeoffs and Sensitivities

The first approach taken to explore and characterize airport performance in its reference state focuses on variations on demand as the primary exogenous factor, the basic tradeoffs that can be readily observed between operational and environmental metrics, and the sensitivity of these metrics to changes in the number of operations under referencee conditions. This assessment is implemented by uniformly varying the number of operations with the reference fleet mix unchanged. Each variation was implemented by applying an operations count factor γ_i to the total number of operations as was described in Section 5.4.5. This assessment captures demand variations under reference conditions, which could be interpreted as the near to mid term, because no changes in the fleet mix are considered, and not terminal area solutions are evaluated or assumed.

In the generation of this data it was noted that taxiway congestion was a major driver to overall performance, and that moderate increases in traffic volumes led to airport surface gridlock conditions that cause the SIMMOD simulation to fail. Upon inspection it was determined that departure peaks were saturating the taxiways which in turn affected gate access of arriving traffic. In an attempt to emulate more realistic operational logic commensurate with common practices in airport ground traffic control, and primarily based on subject matter expert recommendations, a *gate-hold program* was implemented in the ATL model. This controlled pushback program delays the release of departing flights from the gate based based on predetermined departure queue size thresholds, and coordinates the ordered release of aircraft into the taxiway system using a virtual gate-hold queue that facilitates the management of ground traffic volumes.

The gate-hold control mechanism was originally investigated in previous work by Pujet, Delcairey, and Feron, who articulate the motivation for this approach by noting that Direct Operating Cost (DOC), comprised primarily of fuel, crew, and maintenance components, is greater for runway queueing times than for gate holding times. More specifically, whereas

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a minute of gate delay has been associated with DOC values of \$2.5, \$4.5, and \$6 for *Small*,*Large*, and *Heavy* class aircraft, DOC values for a minute of departure queue delay are estimated at \$13, \$25, and \$54 respectively. Thus, a scheme that transforms runway queuing time to gate delay can potentially represent savings ranging between \$10.5 and \$48 per minute of delay. This work also notes that aircraft ground operations account for approximately 45% of pollutants emitted on the airport surface, with another 45% pertaining to landside access vehicles and the remaining 10% pertaining to Auxiliary Power Units (APUs) and Ground Support Equipment (GSE). Thus, the incentive to reduce emissions from aircraft ground operations may be realized by such a gate hold scheme. Finally, the work in question recognizes that air traffic controllers are not likely to accept new procedures whenever they involve major changes in the airport control system, unless there is ample evidence of operational benefits that do not compromise safety and do not represent increased workload. Hence there is a natural appeal in simple control schemes such as gate holding which realize benefits by supporting decisions in ATC the work process. [251]

Although a comprehensive evaluation of the gate-holding scheme would require considerations pertaining to interactions with pre-existing control tower functions and established procedures, Pujet, Delcairey and Feron suggest that conservative modeling and evaluation of gate-holding is realizable by assuming and implementing a *gate queue* control downstream of control tower functions such that control tower actions remain unchanged and unaffected. The gate-holding scheme proposed is based on the observation that runway throughput experiences marginal increases whenever the number of aircraft on the departure queue N is larger than a saturation departure queue value N_{Sat}, or in other words, when the runway is at maximum capacity and there is more demand for departure runway usage than what can be actually serviced by the runway on a time unit basis. Naturally, if N is allowed to reach values close to or greater than N_{Sat}, more aircraft will occupy taxiways and enter the departure queue, without any corresponding increases in throughput. Thus, a gate-hold scheme would control the departure gate release of aircraft based on some threshold or critical value value N_C. Pujet, Delcairey and Feron note that for $N_C < N_{Sat}$ the control scheme replaced departure runway queue time with gate delay time which is lest

costly and results in less environmental impact because "*mostly because the aircraft engines are not running while the aircraft is at the gate.*"[251] However, two primary undesirable effects are expected to result from the implementation of a gate-hold strategy. The first is a reduction in the number of available gates for arrivals, where the number of available gates diminishes with lower values of N_C for which more departure aircraft would be held at the gate, potentially requiring adjustments in the airline's gate allocation and management practices. The second pertains to the impact that departure gate delay would have on the on-time push-back statistics reported by airlines, and the resiliency that could be expected by airlines in accepting any ground control measure that could inflate the perceived gate delay figures.[251]

In their published work Pujet, Delcairey and Feron demonstrate the implementation and quantitative evaluation of a feedback gate holding scheme and a predictor-based gate holding scheme, using a departure queuing model calibrated for Boston-Logan International Airport (BOS) based on Airline Service Quality Performance (ASQP) data. The results confirm that runway capacity increases marginally as N approaches N_{Sat}, and that N_C less than N_{Sat} reduces runway throughput whereas N_C greater than N_{Sat} replaces departure queue delay with less costly and less environmentally noxious gate delay that does not affect runway throughput.[251]

The gate-hold scheme has been incorporated in other research efforts such as the development of the *Departure Planner*, an automation aid implemented at the core of decision-aid systems enabling air traffic controllers to improve airport departure operations performance by optimizing resources and runway time allocation, among other ATC functions, for major airports experiencing congestion. The gate-hold scheme is implemented within the *Tactical Planner* of this system, which "*has approximately a 15-30 minute time horizon, performs tactical planning of runway operations under a specific runway configuration and exercises appropriate control to implement the generated plans.*"[19] The gate-hold plans are executed collectively by the *Virtual Queue Manager*, the *Gate Manager*, and the *Taxiway Entry Manager*. The use of virtual queues enable the formulation and use of notional waiting queues for departing aircraft, and consist of a physical component that captures aircraft occupying

certain areas of the airport surface, whereas the a virtual component is an extension of the physical counterpart that captures the sequencing and waiting of aircraft scheduled to occupy an area of the airport surface but not physically present at the takeoff queue at that time.[19]

Other noteworthy research efforts relevant to gate-hold control schemes include those of Balakrishnan and Chandran who explicitly addressed the *Constrained Position Shifting* problem where runway throughput is maximized by minimizing the departure time of the last flight given a set of n schedule-ordered departures, considerations for precedence and departure separation margins, and k allowable position shifts in the departure queue.[26] In a similar fashion, Simaiakis and Balakrishnan, show results consistent with the work by Pujet, Delcairey and Feron, where "*the number of departing aircraft on the ground [are used] as an indicator of the loading of the departure runway,*"[267] illustrating how N_C can be used to define a threshold beyond which runway throughput emerges as the primary capacity constraint and how gate-holding caps ground traffic density thus reducing taxi-out time and departure aircraft ground fuel burn and emissions.[267] Balakrishnan and Jung explicitly quantified the impact of the gate-holding control scheme on departure operations for current and projected demand levels at Dallas - Fort Worth International Airport (DFW) for 2007 demand levels and projected demand levels. Results of this work show that gate-holding procures enable a management mechanism of ground traffic density for ramps, taxiways, and departure queue, enabling up to 18% reduction in taxi-out time for current and future demand levels, as well as decreasing runway crossing queue average waiting times.[27]

The gate-hold control scheme was implemented in the SIMMOD model for ATL as follows. The *SIMU07* file defines all airfield nodes, links, and elements such as gates, runways, and departure queues. Within the *SIMU07* the *GATES* record defines gates by identifying the node associated with each gate, the airfield links blocked whenever the gate is in use, and assigning gate properties such as airlines allowed to use that gate, aircraft size classes not allowed to use the gate, and associated distributions for boarding and disembarkment times defined for aircraft size classes. Similarly, the *DEPARTQ* record of the *SIMU07* file defines departure queues by identifying the airfield nodes where departure

queues begin, associating departure queues with specific runways, and defining multiple features such as allowable queue sizes, time thresholds, and routes associated with with each departure queue. The *GteHold* variable in the *GATES* record is a flag that activates gate-holding for each individual gate if assigned a value of "1", and does not model gate-holding if assigned a value of "0". If *GteHold* is set to "1" for a given gate, aircraft at that gate will hold at the gate if the number of aircraft at the departure queue assigned for the flight currently occupying the gate, plus the number of aircraft en route to the assigned departure queue, equals or exceeds the value of *Maxnoq*. The *Maxnoq* variable is optionally specified for each departure queue in the *DEPARTQ* record, and refers to the departure queue size threshold value beyond which gate holding is effected, although it may also be used if staging/holding areas other than gates are specified in the model.[23] Thus, *Maxnoq* is the SIMMOD instantiation of the critical value N_C defined by Pujet, Delcairey and Feron. Consequently, the gate-holding scheme was implemented by setting *GteHold* to "1" for all gates defined in the *GATES* record, and by specifying desired values for *Maxnoq* for each departure runway in the *DEPARTQ* record. The values for *Maxnoq* were chosen based on ATC and subject matter expert advise, and set to 30 for runways 26L and 27R, and to 25 for runway 28 whenever the triple departure configuration was used.[186]

The reduction in gate availability associated with gate-holding noted by Pujet, Delcairey and Feron is expected to have a notable detrimental impact on gate delay for arrivals. Recognizing this side effect, and in an attempt to mitigate this negative impact, arrival aircraft were allowed to utilize alternate gates other than the one originally specified by the simulation engine for that flight. This logic is instantiated through the *AltGteFlag* variable for each gate in the *GATES* record, so that if set to "*YES*" aircraft scheduled to use a gate that is currently unavailable may seek alternative gates. The gate reassignment logic takes into consideration other gate definition constraints such as allowable airlines and allowable aircraft size classes specified for each gate. [23]

With the gate-hold logic in place, the baseline schedule of operations was grown in 5% increments until 25%, beyond which unrealistic delay figures were observed. This range was chosen to more broadly explore the effect of growing operations count and more readily

identify performance relationships of interest, but it is recognized that a 25% increase in operations count is not realistic for a near or mid term growth projection.

Varying levels of change were observed for arrival and departure gate-hold delay as well as for arrival airborne delay. In contrast, taxi-in/out times, departure queue times, and airborne departure delays featured negligible variability. Taxiing times remained relatively unchanged because the implementation of the gate-hold program effectively caps the ground traffic density that is observed. Thus, for a constant ground traffic density, aggregate and average values of total taxiing time and taxiing delay are unaffected. Departure queue times depend only the allowable size of the queue and on the rate at which departures are processed. Since neither of these factors was changed in this preliminary study average departure queue time for each runway remained constant. Finally, given the divergent airborne departure traffic flows in the ATL airspace, described in the previous chapter, departing aircraft observe no impedances once each of them become airborne because separation assurances are effected at the runway departure queue. Thus, for this sample problem and for those with comparable departure traffic flows, departure traffic congestion/delay is observed on the runway departure queue and not on the airspace. In contrast, arrival traffic congestion occurs primarily in the airspace and results in airborne holding or elongated vectored trajectories.

A comparative assessment of delay and fuel burn figures captures basic operational-environmental performance tradeoffs with respect to operations count variability for ATL in its reference state, and reveals the inherent sensitivity of each metric. As shown in Figure 24, average gate-hold delay for departures increases by a factor of 55, from 90 seconds to over 1 hr and 20 min, suggesting that the implementation of the gate-hold program and its departure queue size threshold comprise a critical operational factor that warrants further investigation. Accordingly, arrival gate wait times follow a similar trend.

As mentioned in the previous chapter, gate waiting times for departures were assumed to occur with engines off, whereas gate wait periods for arrivals were modeled with engines on idle mode. Thus, departure ground fuel burn is insensitive to the sharp increase in gate hold delays, and as can be expected, experiences a relative increase that closely follows that

Figure 24: Gate-hold Delay vs. Operations Count Percent Increase
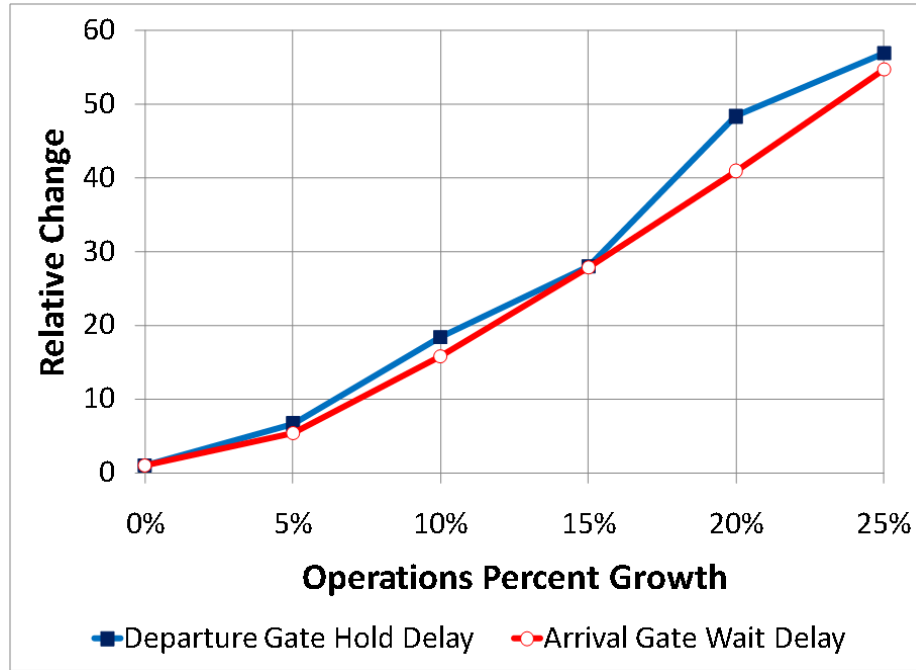
for operations growth, reaching approximately 25%. On the other hand, ground fuel burn for arrivals is directly affected by gate waiting times, and thus is highly sensitive to changes in this delay metric. Compared to the moderate 25% increase in departure ground fuel burn, arrival ground fuel burn is observed to increase by a factor of 13, as shown in Figure 25.

Given that departure operations do not experience airborne delay, the increase in airborne departure fuel burn closely follows the corresponding increase in the number of operations, as can be expected. The increase in airborne departure fuel burn is illustrated in 26. In contrast, airborne arrival delay was observed to grow by 90% for the the 25% increase in operations counts, which resulted in an increase of arrival airborne fuel burn reaching 47%, as shown in Figure 26. Inspection of SIMMOD results for arrival total airborne time and airborne delay reveal that, although the increase in delay was significant and almost doubled the value for the baseline schedule, airborne delay times only account for up to 10% of total airborne travel time. Thus for arrival airborne fuel burn, the effect of increasing the number of operations is augmented by the effect of growing airborne delay, which has

Figure 25: Ground Fuel Burn vs. Operations Count Percent Increase
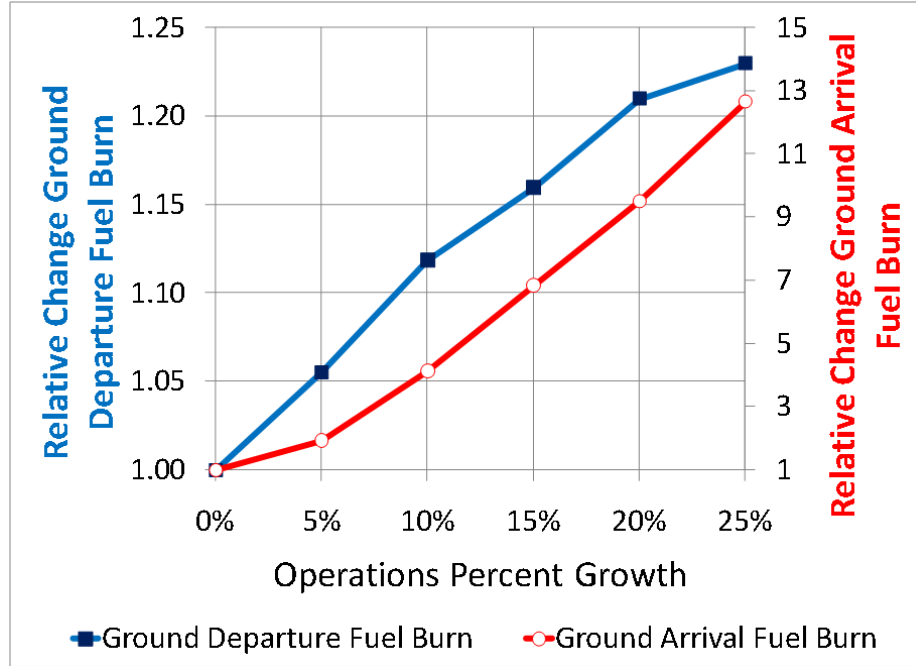
a direct impact on time in mode calculations within the AEDT. the resulting performance assessment quantitatively characterizes how fuel burn grows non-linearly with increases in the number of operations and how environmental impact is exacerbated by operational inefficiencies.

6.3 Endogenous-Exogenous Factor Interactions - Departure Queue Threshold and Number of Operations

The implementation of the gate-hold program was observed to have a major impact on airport performance, suggesting that that airport performance will be affected by changes in the departure queue size threshold used to manage departure gate holding. The departure queue size threshold, referred to as the *queue size* for brevity from here on, is an endogenous parameter because it is controllable by the operators of the system and defines its internal configuration. Consequently, this endogenous parameter was incorporated in a second study to assess its relative importance and level of interaction with operations count variations, which capture exogenous factors, across operational and environmental metrics. Based on ATC specialist recommendations and on preliminary test simulation runs, departure queue

Figure 26: Airborne Delay and Fuel Burn vs. Operations Count Percent Increase
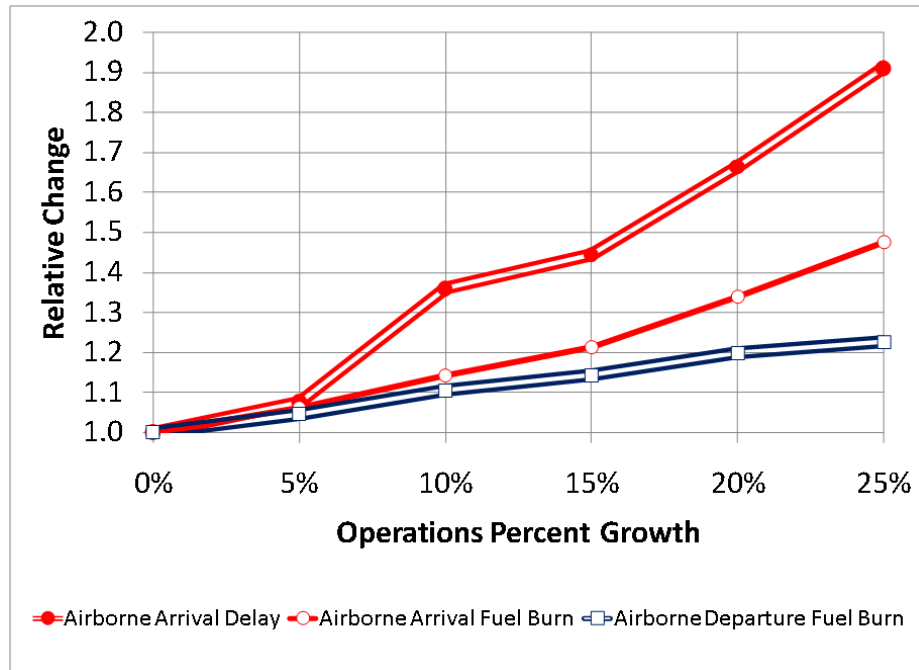
size was varied from 15 to 30 aircraft in increments of 5 for all departure runways, and mixed with the 5% increment variations in operations count within a full factorial DoE, selected based on the acceptable number of simulation runs required.

As can be expected, variations in queue size have an impact on ground traffic operations, and will have minimal or no impact on airborne movements. Accordingly, results show negligible impact on airborne delay, and airborne fuel burn and emissions, for arrivals and departures. Although implementing a gate-hold program limits ground traffic density, and in turn reduces taxi-in and taxi-out delay, variations in queue size for the gate-hold program do not have an impact on ground traffic density and taxi delay times. Rather, the latter are driven by the rate at which aircraft take off, which determines the rate at which aircraft progress through the departure queue and consequently the rate at which aircraft are released from the gate. Changes in aircraft departure rates can be implemented, for instance, by reducing the separation minima for consecutive takeoffs, or for total airport departure rates by utilizing an additional runway. Accordingly, results show that taxi-in/out times remain unchanged.

Figure 27: Gate Hold for Varying Operations Count and Departure Queue Size
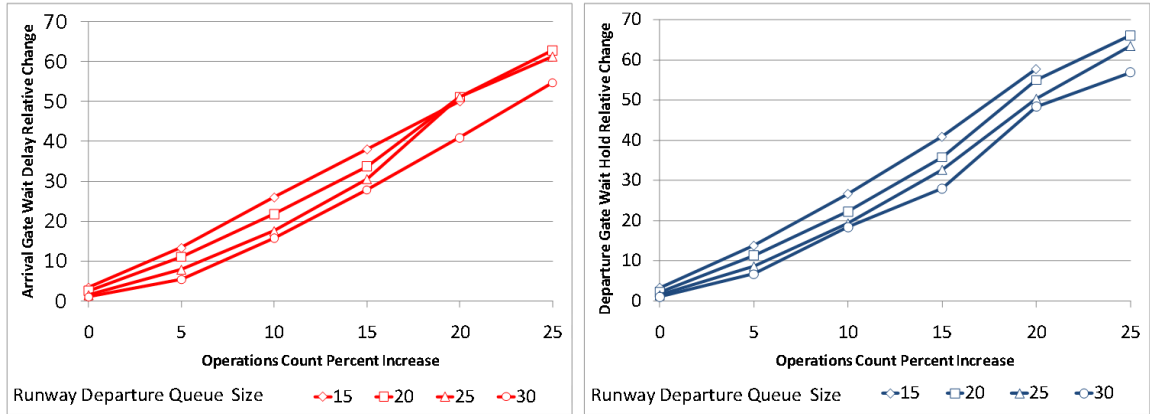
However, for a fixed departure rate, increasing the queue size results in an increase of departure queue waiting time. Thus, changes in queue size have an impact on how long departing aircraft will hold at the gate vis-a-vis how long they will wait in the departure queue. This in turn has an effect on gate availability and thus results in a secondary impact on the gate wait times for arrivals. As was shown in Figure 24, changes in the number of operations also has a major impact on gate delay results, and hence it is expected that both queue size and number of operations will have an impact on gate delay. Results for gate delay, shown in Figure 27, confirm that greater gate hold times for arrivals and departures result from smaller queue size and greater traffic volumes. These results also confirm that the relative increases in gate delay for arrivals and departures are very similar, and that this relative change is considerable reaching in both cases a factor of 60.

Of particular interest is the characterization of ground fuel burn and emissions tradeoffs for arrivals and departures, illustrated in Figure 28 for all data points generated for this particular study. Given that gate wait times for arrivals are modeled with engines on idle, fuel burn trends closely follow sharp increases in wait time, which in turn are driven primarily by growth and to a lesser extent by queue size. However, gate hold times for departures were modeled with engines off. Thus, departure ground fuel burn is primarily driven by the impact that queue size has on departure queue waiting times, and is insensitive

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Figure 28: Ground Fuel Burn for Varying Operations Count and Departure Queue Size
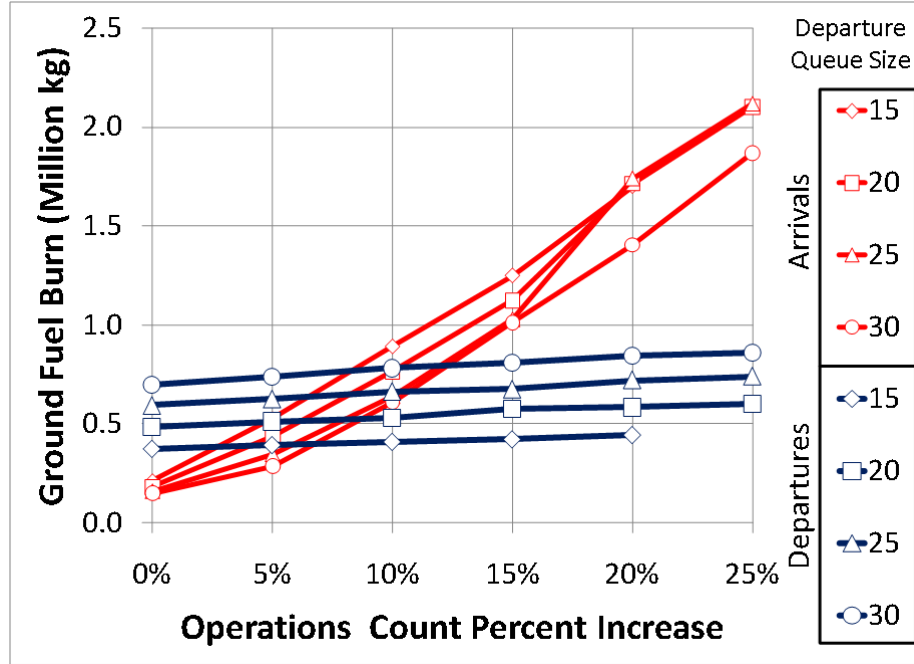
to the the sharp increases observed for gate hold time due to changes in operations count and departure queue size.

Given that emissions inventories for ground operations are obtained directly from fuel burn quantities, and that all fuel burn and emissions calculations for ground operations assume an idle engine power setting, all the trends and inherent systemic behavior observed for fuel burn are directly translated into those for emissions species by virtue of the emissions index scaling factors. Thus, an assessment of fuel burn and emissions is redundant for the purpose of studying the environmental impact resulting from ground operations. Attentions is therefore given to fuel burn with the understanding that all insight attained through this particular investigation is directly applicable to emissions.

The visualization of data points in Figure 28 and Figure 27 enable qualitative assessments of the impact that number of operations and departure queue have on the gate delay and ground fuel burn metrics. However, a quantitative and explicit characterization of their effects is not directly provided by these data points alone, even if said data points are quantitative in nature. It can be observed that that arrival gate wait, departure gate hold, and

arrival ground fuel burn, are primarily driven by number of operations and to a lesser extent by queue size. However, a quantitative measure of how much more significant are the effects of number of operations relative to those of queue size cannot be directly deduced from the data points alone or even from the visualization of said data points. Likewise, the existence and significance of an interaction between the two factors is not readily discernible.

In a similar fashion it is noted that departure ground fuel burn is insensitive to the increases in gate hold delay, and thus is only affected by increases in the number of operations due to traffic flow phenomena other than the increase in gate hold delay. Although M&S results suggest that number of operations does not have a major impact on departure ground fuel burn, there is no direct quantification of the multiple effects of number of operations, however small they may be. In contrast, queue size appears to have a greater impact on this metric, but the quantification of its multiple effects is also not directly discernible. Lastly, the existence and significance of an interaction between queue size and number of operations can only be speculated upon by observation of the data in the results, absent a quantitative assessment.

To procure this quantitative assessment of factor effects, a second order regression model (RSE) was generated for each gate delay and ground fuel burn metric, which are handled as *response variables*. The regression was conducted with respect to number of operations and queue size, which were handled as the *regression variables*. The resulting models define estimates for the coefficients associated with main effects ($\hat{\beta}_i$), interaction effects ($\hat{\beta}_{i,j}$), and quadratic effects ($\hat{\beta}_{i,i}$). The magnitude of each regression coefficient provides a measure of magnitude of their associated factor effect, but does not provide an indication of the inherent error associated with the estimate.

To account for the magnitude of factor effects relative to the inherent error in the regression model coefficients, a coefficient estimates *t-test* was conducted to quantify the the statistical significance of regression for all factor effects. As described in Section D.6 of Appendix D, the t-statistic generated for each factor effect is the ratio of the coefficient estimate $\hat{\beta}$ to the standard error of that estimate, and a p-value for the t-test is calculated from each t-statistic. p-values lower than 0.01 are indicative of statistical significance of

regression, whereas values between 0.01 and 0.1 indicate marginal statistical significance.

Inspection of regression coefficient estimates and corresponding t-test p-values can thus be used to confirm or rectify qualitative assessments and to formulate them quantitatively, as well as to quantitatively characterize factor effects that are indiscernible in qualitative observations of the M&S data. Based on the qualitative observations and assessments discussed above, the following hypotheses are formulated for arrival gate wait, arrival ground fuel burn, and departure gate hold:

- *Hypothesis 1.1* - Number of operations is a statistically significant factor.

- *Hypothesis 1.2* - Departure queue size is less statistically significant than number of operations.

- *Hypothesis 1.3* - The interaction between departure queue size and number of operations is a statistically significant factor effect.

Similarly, the following hypotheses are formulated for departure ground fuel burn:

- *Hypothesis 2.1* - Departure queue size is a statistically significant factor for departure ground fuel burn.

- *Hypothesis 2.2* - Number of operations is less statistically significant for departure ground fuel burn than departure queue size.

- *Hypothesis 2.3* - The interaction between departure queue size and number of operations is a statistically significant factor effect for departure ground fuel burn.

Note that hypotheses 1.3 and 2.3 refer to the statistical significance of the interaction between queue size and number of operations, and that based on the qualitative observations presented thus far there is no direct indication whether this interaction is in fact statistically significant or not. In this sense, these hypotheses are formulated as testable contingent statements regarding *unknown* systemic behavior in airport performance.

On the other hand, all other hypotheses refer to *qualitative* assessments about the significance of factors, based on the results shown in 28 and Figure 27, that must be *quantified*.

Hypotheses 1.1 and 2.1 refer to the statistical significance of the factor that has been qualitatively observed to be dominant, whereas hypotheses 1.2 and 2.2 refer to lower statistical significance of the the other factor. In this sense, these hypotheses are formulated as testable contingent statements regarding systemic behavior in airport performance that is *partially known.*

The p-values are used to test the aforementioned hypotheses as follows:

- *Hypothesis 1.1* is accepted if, for the regression model in question, the p-value for any of the factor effects of number of operations is lower than 0.01, and rejected otherwise.

- *Hypothesis 1.2* is accepted if, for the regression model in question, the p-values for factor effects of number of operations are lower than the p-values for factor effects of queue size, and rejected otherwise.

- *Hypothesis 1.3* is accepted if, for the regression model in question, the p-value for the interaction effect between number of operations and queue size is lower than 0.01, and rejected otherwise

Similarly,

- *Hypothesis 2.1* is accepted if, for the departure ground fuel burn regression model, the p-value for any of the factor effects of queue size is lower than 0.01, and rejected otherwise.

- *Hypothesis 2.2* is accepted if, for the departure ground fuel burn regression model, the p-values for factor effects of queue size are lower than the p-values for factor effects of number of operations, and rejected otherwise.

- *Hypothesis 2.3* is accepted if, for the departure ground fuel burn regression model, the p-value for the interaction effect between number of operations and queue size is lower than 0.01, and rejected otherwise

Table 15 summarizes p-values for the t-tests conducted, where p-values lower than 0.01 indicative of statistical regression significance are highlighted in green, and p-values between

0.01 and 0.10 indicative of marginal statistical regression significance are highlighted in yellow. Table 16 summarizes the coefficient estimates resulting from the regression models generated. To facilitate comparison of this data with data presented in Table 15, the same table structure is use, and the color highlights of factor effects is replicated.

Table 15: p-Values for Coefficient Estimates t-Test - Gate Hold Delay and Ground Fuel Burn

	Effects	Arrival Gate Wait	Arrival Ground Fuel Burn	Departure Gate Hold	Departure Ground Fuel Burn
Main	Operations	<.0001	<.0001	<.0001	0.0962
	Queue Size	0.7134	0.9052	0.2917	<.0001
Interaction	Operations * Queue Size	0.0569	0.0968	0.0035	<.0001
Quadratic	Operations * Operations	<.0001	<.0001	<.0001	0.0347
	Queue Size * Queue Size	0.4355	0.65	0.4375	0.0326

Table 16: Regression Coefficient Estimates - Gate Hold Delay and Ground Fuel Burn

	Effects	Arrival Gate Wait	Arrival Ground Fuel Burn	Departure Gate Hold	Departure Ground Fuel Burn
Main	Operations	178.53	56,006.30	215.12	1,531.50
	Queue Size	25.96	3,191.80	-71.85	27,736.64
Interaction	Operations * Queue Size	-1.81	-592.58	-2.85	218.96
Quadratic	Operations * Operations	3.25	1,424.77	3.11	-52.69
	Queue Size * Queue Size	-1.23	-270.03	1.16	-129.54

Results shown in Table 15 show that operations count is a significant factor for arrival gate delay, where main effects and quadratic effects are statistically significant. Given the modeling assumption for idle engines during arrival gate waiting periods, arrival ground fuel burn is significantly affected by the associated gate delay time and, as expected, factor effects pertinent to number of operations are also statistically significant regression factors. Since the p-values for the main and quadratic effects of number of operations are lower than 0.01, *Hypothesis 1.1* is accepted for arrival gate delay and for arrival ground fuel burn.

Results for arrival metrics also reveal that the p-values for number of operations effects are larger than those for queue size, and in fact indicate that queue size main and quadratic effects are *not* statistically significant. This indicates that the effects of number of operations on these two metrics are more significant than those of queue size. Thus, *Hypothesis 1.2* is

accepted for arrival gate delay and for arrival ground fuel burn.

On the other hand, the p-values for the interaction effect between queue size and the number of operations is greater than the threshold value of 0.01, both for arrival gate delay and arrival ground fuel burn. This result is indicative that this effect is not statistically significant for the aforementioned metrics, and hence, *Hypothesis 1.3* is rejected. However, the p-values for the interaction effect are in the range between 0.01 and 0.10, suggesting *marginal* statistical significance of regression. In other words, the interaction effect can be said to exist for arrival gate delay and arrival ground fuel burn, but its has a marginal impact on the variability of these response variables that can not be completely distinguished from the variability associated with error. Moreover, a comparison of the p-values for the interaction effect reveals that that this interaction is more significant for delay than for the ground fuel burn. With this insight in mind, *Hypothesis 1.3* can be revised to say that the interaction effect is *marginally significant* for the two arrival metrics in question.

For departure gate hold, results in Table 15 indicate that number of operations is a significant factor given that p-values for its main, interaction, and quadratic effects are indicative of statistical significance. This result confirms the close similarity in behavior between arrival gate wait and departure gate hold, expected by virtue of the logical modeling relationship between them, and qualitatively assessed from the data shown in Figure 27. Thus, *Hypothesis 1.1* is accepted for departure gate hold. Since p-values for queue size effects do not suggest statistical significance, *Hypothesis 1.2* is logically accepted for this metric. Finally, the interaction effect is found to be statistically significant by virtue of its p-value, and thus confirms *Hypothesis 1.3* for departure gate hold.

In contrast, departure ground fuel burn behavior is noted to be explained primarily by queue size. The p-values for queue size main effect and interaction effect are lower than 0.01 and indicate statistical significance. In addition, the p-value for the quadratic effect is found to be on the lower end of the range for marginal significance. Thus, *Hypothesis 2.1* is accepted. A comparison of p-values for queue size and number of operations effects shows that, overall, the p-values for queue size factors are smaller. This observation indicates that queue size is a more significant factor than number of operations for departure ground fuel

burn, such that *Hypothesis 2.2* is accepted. Lastly, the p-value for the interaction effect indicates statistical significance, and in fact is the most significant factor along with the main effect of queue size. Thus, *Hypothesis 2.3* is accepted.

Beyond providing evidence for accepting or rejecting the aforementioned hypotheses, the results shown in Table 15 provide detailed, quantitative assessments that explicitly characterize how queue size and number of operations collectively impart a number of effects on ground fuel burn and gate delay performance, some of which are found to be of statistical regression significance.

The quantitative characterization of sensitivities and complex interrelationships through this analysis can be further enhanced with adequate interactive visualization schemes that provide additional insight, and are instrumental in communicating this insight with clarity and transparency. One of these visualization schemes is the dynamic interactions profiler, illustrated in Figure 29(A) and (B) respectively for departure and arrival ground fuel burn. This profiler depicts response trends and graphically reveals sensitivities and interactions through differences in extreme-value profile curves, as well as tradeoffs between metrics. In each plot, the top right quadrant shows ground fuel burn as a function of departure queue size (abscissa), and plots curves corresponding to the two extreme values of percent operations count increase, namely 0% and 25%. Conversely, the bottom left quadrant shows ground fuel burn as a function of percent increase in number of operations (abscissa), and plots curves corresponding to the two extreme values of departure queue size, namely 15 and 30.

In each of these plots, larger differences between extreme value profile curves and more pronounced curves are indicative of larger effects by factors. For departure ground fuel burn, the greater effect of queue size is revealed by the large difference between profile curves corresponding to minimum and maximum queue size values, and by the small slope in profile curves with respect to number of operations, shown in the lower left quadrant. In contrast, the same curves for arrivals are close together indicating a small impact by queue size, but feature a large positive slope on those curves caused by the more significant effect of number of operations. These same relationships are visualized from a different perspective

Figure 29: Interactions Profiler for Departure Ground Fuel Burn and Gate Delay

(A)   (B)
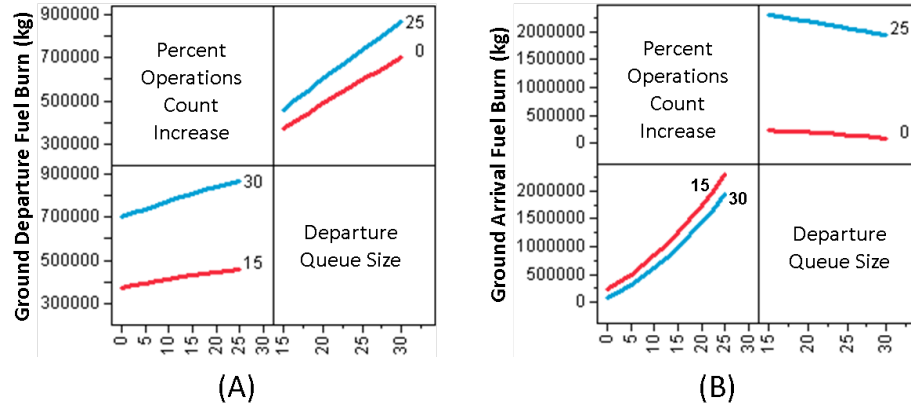
with the profile curves with respect to queue size, shown in the upper right quadrant. For departures, closely separated curves with greater slopes indicate a predominant effect of queue size over number of operations, whereas for arrivals the large separation between curves with small slope values indicate the predominant effect of number of operations over queue size.

These profiler plots also visualize interaction effects, which are manifested by differences in the slope, or curvature, of extreme value profile curves within the same plot. As noted before, the t-test results shown in Table 15 suggest that the interaction effect is statistically significant for departure ground fuel burn, and only marginally significant for arrival ground fuel burn. However, the difference in slope for the profile curves are only slightly noticeable. This suggests that although the interaction effect is statistically significant for departure ground fuel burn, the value of the corresponding regression coefficient is not particularly large.

The regression model can also be used to plot metrics as constraints with prescribed threshold values, revealing feasible and unfeasible regions in the operational-environmental space. Figure 30 shows a contour plot where notional constraints for gate delay and ground fuel burn have been implemented, revealing feasible combinations of the queue size and relative operations count increase for the constraint values chosen. Moreover, if these visualization mechanisms are implemented dynamically with available software, rather than

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Figure 30: Constraint Plots for Departure Ground Fuel Burn and Gate Delay
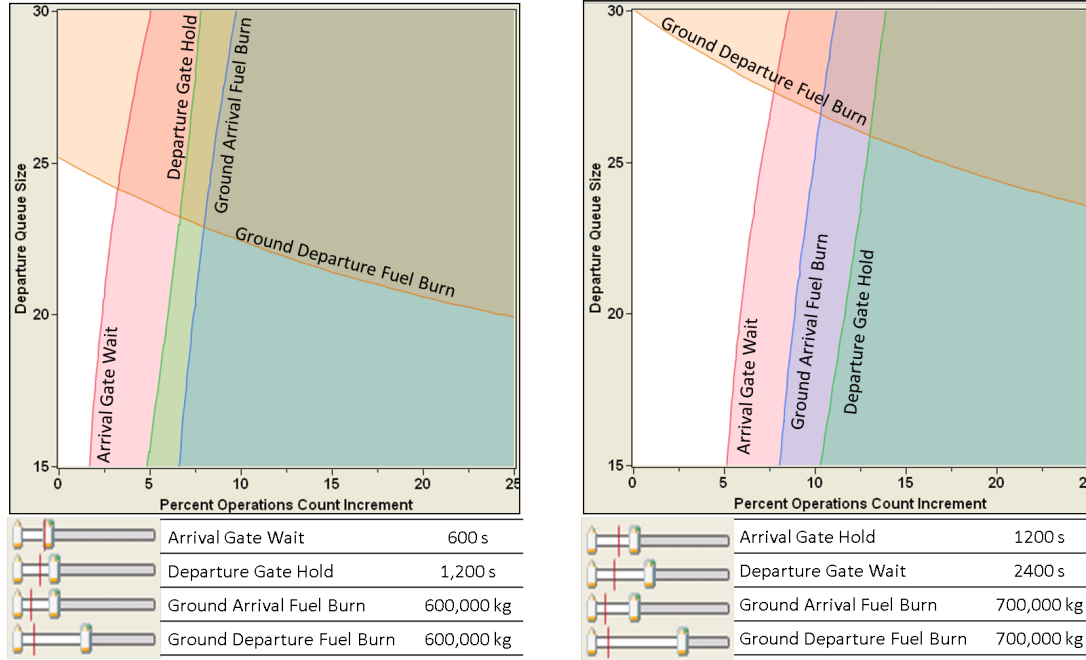
statically, varying constraint values lends itself as a useful way of assessing the sensitivity of metrics to certain parameters. Figure 30(A) and (B) graphically illustrate the impact of relaxing operational and environmental constraints, thus opening the feasible operational space to more increases in operations counts as well as greater departure queue sizes. This visualization scheme also offers a sensitivity assessment for the constraint values in question. For instance the constraint value for arrival and departure gate delay is doubled, and although in absolute terms the relaxation of the arrival gate wait is greater than that for departures, the constraint plot easily reveals that the change in the constraint is notably smaller, indicating a more moderate sensitivity. Similarly, an equal absolute value relaxation of ground fuel burn for arrivals and departures results in a greater constraint relaxation for departures than for arrivals.

Another valuable visualization mechanism for this type of sensitivity analyses is the prediction profiler which also leverages on the fully defined regressed model to graphically represent trends, and for which sensitivity markers can be generated based on the closed-form analytical solution for the local gradient of the response. Figure 31 illustrates how

Figure 31: Sensitivity Profiler for Departure Ground Fuel Burn and Gate Delay
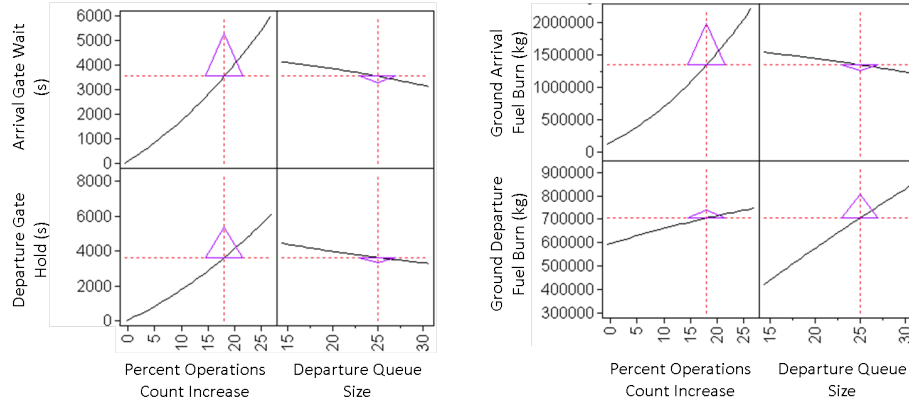
the sensitivity of gate hold and ground fuel burn to operations count and queue size can be compared explicitly side by side, leveraging insight and transparency in the characterization of complex relationships and tradeoffs between these parameters. Note for instance the close similarities in trends patterns and sensitivity for arrival gate wait and fuel burn, explained by the gate hold strategy and the modeling of arrival flights with idle engines during gate wait periods. A strong positive sensitivity is readily observed for percent operations count increase, whereas a moderate negative sensitivity occurs for departure queue size. However, the engine-off modeling assumption for departures gate holds result in vastly differing trends and sensitivities among gate hold and ground fuel burn, evident in Figure 31. Whereas departure queue size has a small negative impact on gate hold time, it also features a strong positive effect on departure fuel burn. Similarly, the strong positive sensitivity to operations count for gate hold is considerably more moderate for departure fuel burn.

6.4 Exogenous Factor Characterization - Regional Classification of Operations

The realization that operations growth is such a significant parameter driving most metrics motivates the execution of a third and final explorative analysis on airport performance characterization under reference conditions. Recognizing that the previous assessments described changes in the number of operations by *uniformly* applying notional growth factors, this study explores whether *non-uniform* variations in the number of operations can be

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used to characterize airport performance. This consideration requires that a classification scheme for operations be conceived so that growth factors can be applied individually to each class of operations.

It is well known that fleet mix, time-of-day distribution, and spatial allocation of operations across airspace and airport surface, are key aspects of demand affecting operational and environmental performance. However, there is a significant challenge with classifying operations according to these characteristics. The number of operations groups implied by all these three characteristics is very large. The number of operation groups necessary to capture fleet mix is the same as the number of unique aircraft models because the performance characteristics of each of them affecting environmental impact and terminal area operations are sufficiently distinct. To adequately capture time-of-day, the number of groups needed is equal to the number of time bins used to describe the time-of-day distribution. To capture airspace allocation of operations, the number of operation groups needed is equal to the number of distinct arrival and departure routes. Finally, airport surface characteristics requires a number of operation groups equal to the number of distinct ground routes of interest. For M aircraft models, N time bins, O airspace routes, and P airport surface routes, the total number of operation groups Γ required is given by:

$$\Gamma = M \times N \times O \times P$$

Such a large number of operation groups makes any performance characterization approach prohibitive.

As an alternative, an origin/destination regional classification scheme that can capture these fleet mix, time-of-day, and route allocation characteristics, is proposed. This regional classification is based on the idea that flights to and from certain regions share inherent trends in fleet mix usage, time-of-day occurrence, and airway/runway assignments. The definition of such a regional classification scheme was explored by mapping flights in the baseline schedule to FAA. Some of These regions were then combined based on geographic adjacency to reduce the number of operation groups, and to minimize operations count disparities among regions that could bias results in the regression analysis. The final regional

Figure 32: Proposed Regional Classification of Operations
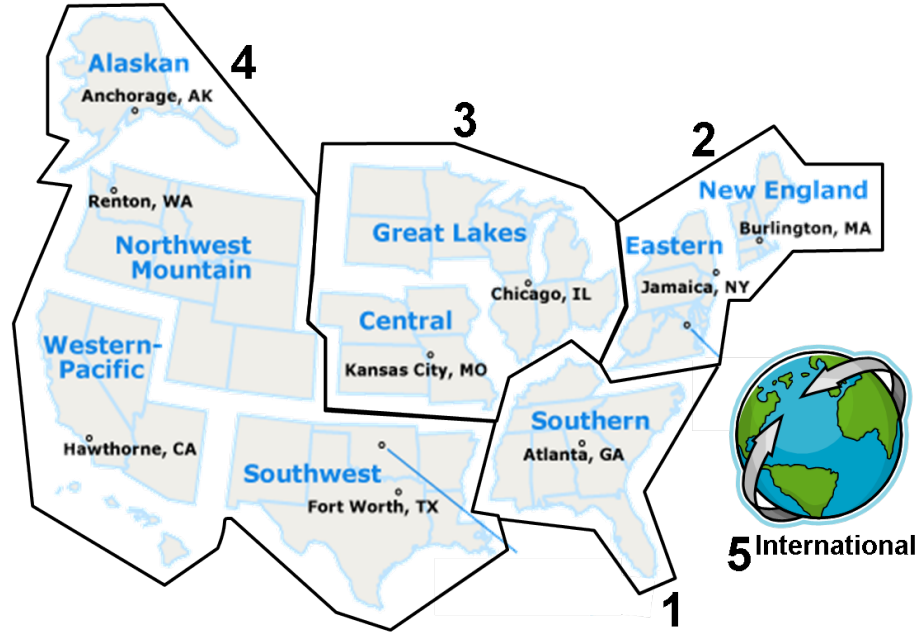
classification is graphically illustrated in Figure 32.

With a total of five operation groups, the task of examining performance characterization through variations in the number of operations for these groups is deemed manageable. Next, however, it is necessary to determine whether this classification scheme is appropriate for airport performance characterization. To do so, the proposed approach described in Chapter 4 and demonstrated in the previous section must be implemented. First, the characterization of airport performance with multiple operations groups requires that a design of experiments be created, specifying the settings for the different growth factors corresponding to the five operations groups. The corresponding experiments must then be conducted as M&S runs to create airport performance data for these cases. Regression analysis must follow accordingly to create regression models that relate airport performance metrics to changes in the number of operations for each group. Finally, ANOVA and a t-test need to be conducted to determine the statistical significance of regression for the operation groups in question. The results of the t-test would indicate whether the individual effects of the five factors, representing the five operations group, are statistically significant for a

given airport performance metric. The results of ANOVA would indicate whether all the factor effects collectively explain the behavior of a given airport performance metric.

Denoting the regional classification scheme proposed with the symbol Ω, its adequacy for the characterization of a given metric of interest can be assessed by testing the following hypothesis for each metric:

- *Hypothesis 3* - The regional classification scheme of operations Ω comprises a set of factor effects for which at least one is statistically significant.

In turn, the regional classification scheme of operations Ω can be considered an adequate form of operations segmentation if *Hypothhesis 3* is accepted for a majority of representative operational and environmental metrics of interest.

To test this hypothesis, the proposed approach was implemented as described above. A D-optimal DoE, which minimizes the covariance of parameter estimates for the specified model, was generated to explore main effects, interaction effects, and quadratic effects, for the five factors. Each of the five factors had three settings representing percent increase in number of operations for the corresponding regional category of operations. The settings varied from no change to a 25% increase using the factor values [1, 1.125, 1.25]. The DoE was also constructed based on considerations for the number of runs, which totalled 33 experiments after augmenting the original DoE with a center point to further reduce parameter estimates covariance. Accordingly, a schedule of operations was generated for each experiment in the DoE by applying the corresponding factor to each group of operations. This was practically implemented with the schedule manipulation routine described in Section 5.4.5, applied to each group of flights individually. Each schedule was then passed on to SIMMOD for operational performance evaluation, and its output passed to the AEDT for environmental impact evaluation. Results for all experiments in the DoE were processed to regress models for selected operational and environmental metrics. These metrics were selected as being the most relevant and representative ones, as well as those having the most variability that could be captured by the regression model: arrival gate wait, departure gate hold, taxi out delay, taxi in delay, arrival airborne delay, departure airborne fuel

burn, arrival airborne fuel burn, ground departure fuel burn, and ground arrival fuel burn. Regression results were then used to conduct statistical tests accordingly. For this assessment, a critical value of 0.05 was chosen for the ANOVA F-statistic p-value and for the t-statistic p-value.

The results produced are used to test *Hypothesis 3* for each metric analyzed as follows:

- *Hypothesis 3* is accepted if, for the regression model in question, the ANOVA F-statistic p-value is less than 0.05 *AND* if the t-statistic p-value of at least one factor effect is less than 0.05.

ANOVA results for selected operational and environmental metrics are summarized in Table 17. Metrics for which the p-value was greater than 0.05 are highlighted in red. The t-test p-values for all factor effects in the regression models of the metrics in question are summarized in Table 18. The factor effects are denoted as G_i to refer to the five groups, numbered as shown in Figure 32. Additionally, p-values in this table are highlighted in green if they are lower than 0.5, and in yellow if they are greater than 0.5 and lower than 0.10 to denote marginal values.

Table 17: ANOVA Results - Regional Grouping

	Arrival Gate Wait	Departure Gate Hold	Taxi Out Delay	Taxi In Delay	Arrival Airborne Delay	Departure Airborne Fuel Burn	Arrival Airborne Fuel Burn	Ground Departure FuelBurn	Ground Arrival Fuel Burn
RSquare	0.9679	0.9766	0.9265	0.5577	0.9937	0.6601	0.9706	0.9967	0.9839
RSquare Adj	0.9144	0.9375	0.8040	-0.1795	0.9833	0.0937	0.9216	0.9912	0.9572
F Ratio	18.0849	25.0043	7.5637	0.7565	94.9562	1.1654	19.8150	181.1076	36.7504
Prob > F	<.0001	<.0001	0.0004	0.7193	<.0001	0.4027	<.0001	<.0001	<.0001

With the exception of taxi-in delay and departure airborne fuel burn, ANOVA results for all other metrics considered featured p-values under the critical value, suggesting for each of them that at least one of the coefficient estimates is non-zero. For taxi-in delay and departure airborne fuel burn these results indicate that *Hypothesis 3* is rejected.

For the remaining metrics, values for the coefficient of determination R^2 and the adjusted coefficient of determination R^2_{Adj}, are observed to be acceptably high, except taxi-out delay. These coefficients provide a measure of the variability of the data explained by the regression

Table 18: Coefficients Estimates t-Statistic p-Values - Regional Grouping

Term	Arrival Gate Wait	Departure Gate Hold	Taxi Out Delay	Taxi In Delay	Arrival Airborne Delay	Departure Airborne Fuel Burn	Arrival Airborne Fuel Burn	Ground Departure FuelBurn	Ground Arrival Fuel Burn
G1	0.2903	0.0111	0.5952	0.8699	0.0072	0.8114	0.7212	0.9031	0.4025
G2	0.2005	0.2725	0.6504	0.3513	0.0013	0.7144	0.9097	0.8838	0.8418
G3	0.0934	0.1359	0.7204	0.1963	0.0026	0.8391	0.7394	0.197	0.4193
G4	0.2665	0.6472	0.0224	0.5512	0.0005	0.8059	0.6719	0.4995	0.982
G5	0.8537	0.9319	0.341	0.4073	0.1726	0.5619	0.2234	0.577	0.6583
G1*G1	0.5291	0.0457	0.6403	0.6375	0.0083	0.7902	0.5672	0.265	0.655
G1*G2	0.1177	0.0719	0.821	0.3311	0.7418	0.9739	0.7799	0.1734	0.917
G2*G2	0.2806	0.6938	0.6757	0.2859	0.0005	0.7978	0.7723	0.5129	0.9745
G1*G3	0.4199	0.0357	0.2094	0.78	0.9505	0.4753	0.7627	0.5593	0.9842
G2*G3	0.8851	0.3235	0.5425	0.527	0.8972	0.9054	0.7216	0.8387	0.812
G3*G3	0.2523	0.8607	0.4543	0.1102	0.0011	0.5089	0.6024	0.1768	0.3455
G1*G4	0.2328	0.0382	0.0766	0.8615	0.0001	0.4845	0.2519	0.4915	0.5061
G2*G4	0.9806	0.3643	0.0092	0.6512	0.4949	0.3789	0.5241	0.8331	0.4505
G3*G4	0.0791	0.0744	0.4359	0.8336	0.7433	0.4088	0.5134	0.1621	0.356
G4*G4	0.5905	0.5985	0.3165	0.7369	0.0015	0.8784	0.6141	0.9101	0.7791
G1*G5	0.9783	0.6282	0.1283	0.8646	0.8968	0.2036	0.2131	0.2237	0.475
G2*G5	0.6884	0.6017	0.6076	0.4369	0.1521	0.8013	0.9548	0.2065	0.8384
G3*G5	0.479	0.1755	0.1873	0.7709	0.3987	0.7295	0.9288	0.6585	0.6127
G4*G5	0.5128	0.7794	0.3609	0.243	0.2581	0.9613	0.9045	0.2422	0.3307
G5*G5	0.5959	0.8376	0.9544	0.1583	0.4155	0.6517	0.3475	0.4271	0.9491

model relative to the error. Thus, taxi-out delay F-statistic p-value is under the critical value, but its model representation accuracy is questionable. The highest values for the F-statistic and corresponding low p-values are observed for arrival airborne delay, ground departure fuel burn, and ground arrival fuel burn.

Results for the t-test indicate that for some regression models none of the factor effects are found to be statistically significant. For these metrics, highlighted in red in 18, *Hypothesis 3* is rejected. It is worth noting that arrival airborne delay, ground departure fuel burn, and ground arrival fuel burn, were a identified with the highest F-statistic values, but they feature no statistically significant factor effects.

Consequently, only four of the nine metrics tested feature p-values for the F-statistc lower thatn 0.05, and at least one factor effect with t-statistic p-value lower than 0.05. These metrics are arrival gate wait, departure gate hold, taxi out delay, and arrival airborne delay. For these metrics *Hypothesis 3* is accepted.

In conclusion, the use of the regional classification scheme denoted by Ω to characterize airport operational-environmental performance is questionable because *Hypothesis 3* is *not* accepted for a majority of the representative operational and environmental metrics chosen for this study. In fact, said hypothesis was clearly rejected for five out of the nine metrics under consideration. Moreover, results from the ANOVA and the t-test feature noteworthy inconsistencies across metrics for which *Hypothesis 3* was accepted, raising suspicion about the ability to properly characterize these different metrics with the same regional grouping of operations.

However, these results do not reject the use of regional classification as a general approach altogether, but rather are specifically concerned with the formulation proposed and denoted by Ω. Considering that *Hypothesis 3* was accepted for about half of the metrics used for this study, there is promise in this general approach for the differentiation and characterization of operational demand as a viable mechanism to fleet mix, time-of-day, and route allocation characteristics. Furthermore, it is conceivable that alternative formulations of regional classification will yield favorable ANOVA and t-test results more consistently and across a larger number of metrics, and thus represent an adequate scheme for operations segmentation for the purpose of characterizing terminal area performance.

CHAPTER VII

ASSESSMENT OF SOLUTIONS IMPACT ON AIRPORT PERFORMANCE

7.1 Introduction

This chapter presents the implementation of the proposed approach for the evaluation of terminal area solutions and the characterization of their impact in terms of interactions among terminal area solutions, sensitivity of operational and environmental metrics of interest to terminal area solutions, and tradeoffs between metrics with respect to the effect of specific terminal area solutions. This performance characterization corresponds to *Step 6* of the airport strategic planning process illustrated in Figure 9. In accordance with this process, the definition of future contextual conditions is realized by generating an appropriate operations schedule that incorporates anticipated changes in the fleet mix. Next, terminal area solutions that had been identified in Chapter 3 are further described as applied to ATL in the sample problem. The proposed methodology for performance characterization is then implemented accordingly, and used to generate statistical analysis results that test corresponding hypotheses. Finally, visualization of results are presented and discussed to illustrate how interactions, sensitivities, and tradeoffs are visually analyzed.

The implementation and demonstration of the proposed methodology to the sample problem addresses the thesis objective *Thesis Objective 3* defined in Chapter 3:

Thesis Objective 3: To quantitatively characterize the effect that different solutions, and combinations thereof, have on the operational-environmental behavior of terminal areas, both in terms of solution main effect and their mutual interactions.

Additionally, the implementation and demonstration of the proposed methodology to the sample problem and the test of relevant hypotheses serve to support *Methodological Hypothesis 2*, formulated in Chapter 4:

- *Methodological Hypothesis 2:* A quantitative characterization of interactions, sensitivities, and tradeoffs for airport operational-environmental performance metrics with respect to *terminal area solutions* is realized through regression analysis, statistical testing techniques, and interactive visualization of categorical RSE's.

7.2 Definition of Future Conditions

The assessment of terminal area solutions requires the generation of a notional future state. For this study a notional scenario for a 25 year horizon was selected based anticipated dates at which Atlanta airport will reach capacity limits based on its current configuration, as well as current plans and implementation time lines for various terminal area solutions.[112, 119] Consistent with available scenarios and forecasts, a 25% uniform increase in domestic operations was assumed for the year 2035, as well as a 30% increase in international flights.[191, 194, 52] The development of scenarios and the generation of corresponding schedules of operations is discussed at length in Chapter 8. However, for the purpose of conducting the assessment in this chapter and illustrating the implementation of the proposed approach on the sample problem, it is sufficient to define directly a representative schedule.

To capture the evolution of the operational fleet mix and its anticipated composition in 2035, the scenario takes into consideration the retirement of aircraft from the reference fleet on an individual aircraft model basis, as well as the introduction of new aircraft models and existing models that are anticipated to be production during the time frame of the scenario. The process for describing the evolution of the fleet mix implemented for this characterization of terminal area performance follows published work on the matter for assessments of future technologies for environmental benefits.[244, 215] The evolution of the fleet mix is comprised of three fundamental components. The first one is the fraction, or total number, of aircraft retired between a reference year and a future year. The definition of aircraft retirements logically yields the fraction of surviving aircraft. The second component is the replacement of retired aircraft by existing or new aircraft models on a future year. The last one is the the the introduction of new aircraft that increase the total size of the

Figure 33: Fleet Replacement Approach for Future Operations Growth
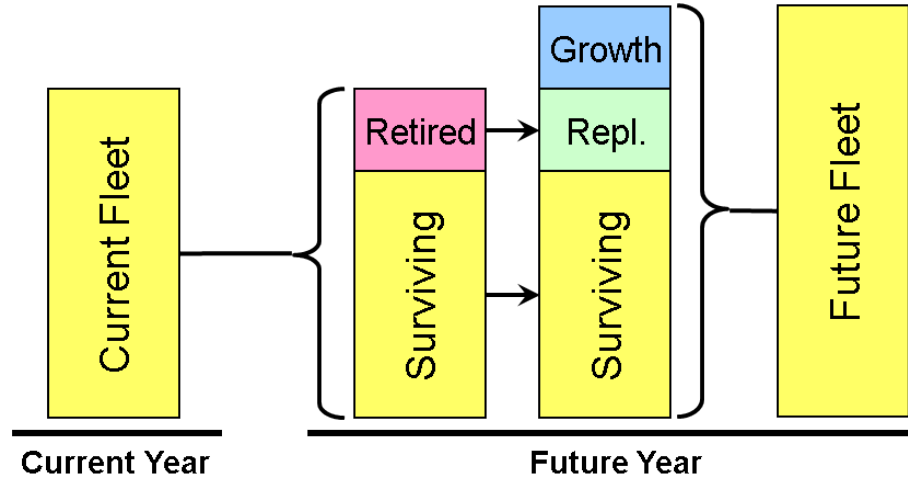
fleet. The relationship between these three components is illustrated in Figure 33.

A constant load factor and utilization can be assumed so that fraction/percentage estimates of *fleet* survival, replacement, and additions can be directly applied for *operations* performed by each aircraft model. Thus, parts of the fleet evolution process are hereby described in terms of aircraft fleet evolution but but are implemented at the operations level. The first step is to specify the survival and retirement percentages on a yearly basis of each aircraft model in the baseline schedule. This information is procured from known aircraft inventories and aircraft survival curves. This assessment utilized CAEP 8 survival curves for narrow-body and wide-body aircraft, CAEP 8 data on yearly production rates for all aircraft models up to the year 2006, and where appropriate, estimated number of surviving units of the 2006 fleet.

Next, the growth factor defined by the scenario in question is used to determine the number of additional operations for a future year. Thus, the number/fraction of retired operations and additional operations for a given aircraft model need to be assigned a new aircraft. The assignment of aircraft is conducted on a seat-class basis, whereby all aircraft models are assigned to a seat class, and operations requiring the assignment of an aircraft model are given the 'best-in-class' aircraft. For some seat-classes new models are introduced in future years, and compete for fleet assignment with an existing aircraft model still in

production and designated as the best-in-class. In this instance fleet assignments included both the best-in-class and the new model, which were distributed proportionately based on the relative number of operating aircraft for these models for the future year under consideration. The reference condition for the future scenario assumes the introduction of aircraft known or anticipated to enter the fleet. These anticipated models are: Boeing 787-8, Boeing 787-9, Boeing 747-8, Airbus 350, and Airbus 380.

7.3   Terminal Area Solutions

The three different types of terminal area solutions identified in Section 3.3.2 study, namely new airport infrastructure, technology-enabled operational improvements, and advanced aircraft concepts beyond the anticipated industry response, have very distinct impacts on terminal area performance and affect operational and environmental metrics in different ways. Thus, it is paramount to conduct comparative assessments for all three types of terminal area solutions and assess the characterization of performance behavior due to their implementation.

It is important to recognize that within each terminal area solutio family there is a plethora of possibilities, and thus it is not practical to conduct assessments for all these alternatives. Thus, the selection of *representative* solutions for each family of solutions is crucial, and should be driven by their applicability, realistic implementation, and relevance for the sample problem. For instance, there is a myriad of possible configurations for new runways and taxiways at ATL, but there are only a handful that are being actively and seriously pursued by the DoA based on their feasibility, relevance to operating conditions at ATL, and on preliminary studies that have been conducted. Similarly, there is a vast amount of operational improvements and supporting technologies that could be conceivably implemented at this airport. However, based on the unique operational characteristics at this facility, and the capacity needs that can be expected by the FAA, only a handful of distinct operational improvements have been identified by the FAA and the JPDO based on their relevance and applicability. Finally, any number of advanced aircraft could be conceivably introduced into the fleet, but NASA's spiral approach focusing on the most

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relevant seat classes and aggressive environmental targets has led to the convergence of a small number of subsonic advanced aircraft concepts for different time frames.

New airport infrastructure solutions considered include a new runway project currently under study by the Atlanta DoA, which would be located parallel to the five existing runways, about 1,300 feet north of runway 10/28 and 2,750 feet south of runway 9R/27L. The new runway is designated for departures to support independent triple departures, which compliment the current infrastructure allowing for triple independent arrivals. With this configuration the need for triple departure operations during departure push peaks, as was discussed in Section 5.4.5, is eliminated. Due to budgetary and space availability constraints this new runway would only span 8,000 feet, prohibiting departure of heavy class aircraft. Following the runway designation scheme observed in ATL, the new runway is from here on referred to as runway 10L/28R, or simply 28R if considering west-flow operations for M&S purposes. Current runway 10/28 is thus renamed 10R/28L. The location of runway on 28R is shown in Figure 34, which was generated based on DoA diagrams and information provided for this thesis. Figure 34 also depicts the other infrastructure solutions considered. One of them is the addition of new taxiways, shown in green, to facilitate access to runway 28R beyond that provided by taxiways *SC* and *SJ*. The other one is the construction of the new international terminal, east of Concourse E, which is currently under construction and which will provide 12 gates exclusively for international flights that will make available gates in Concourse E for domestic operations. The construction of the new terminal includes the extension of taxiway *L* to provide access to and from the new terminal, particularly to runway 27R. Based on subject matter expert input, the configuration of the terminal airspace and corresponding runway assignment for west-flow is shown in Figure 35. The original SIMMOD model for ATL was modified accordingly to include the new runway, new terminal gates, and new taxiways, as well as the new departure route for runway 28R.

Operational improvement solutions for this assessment were chosen from the FAA's 2007-2025 national airspace system capacity needs study (*FACT2*)[119], which identify planned and potential improvements for ATL based on the unique capacity needs of this airport and the projected growth in operations. Two key improvements are detailed for ATL in

Figure 34: Airport Infrastructure Solutions for ATL
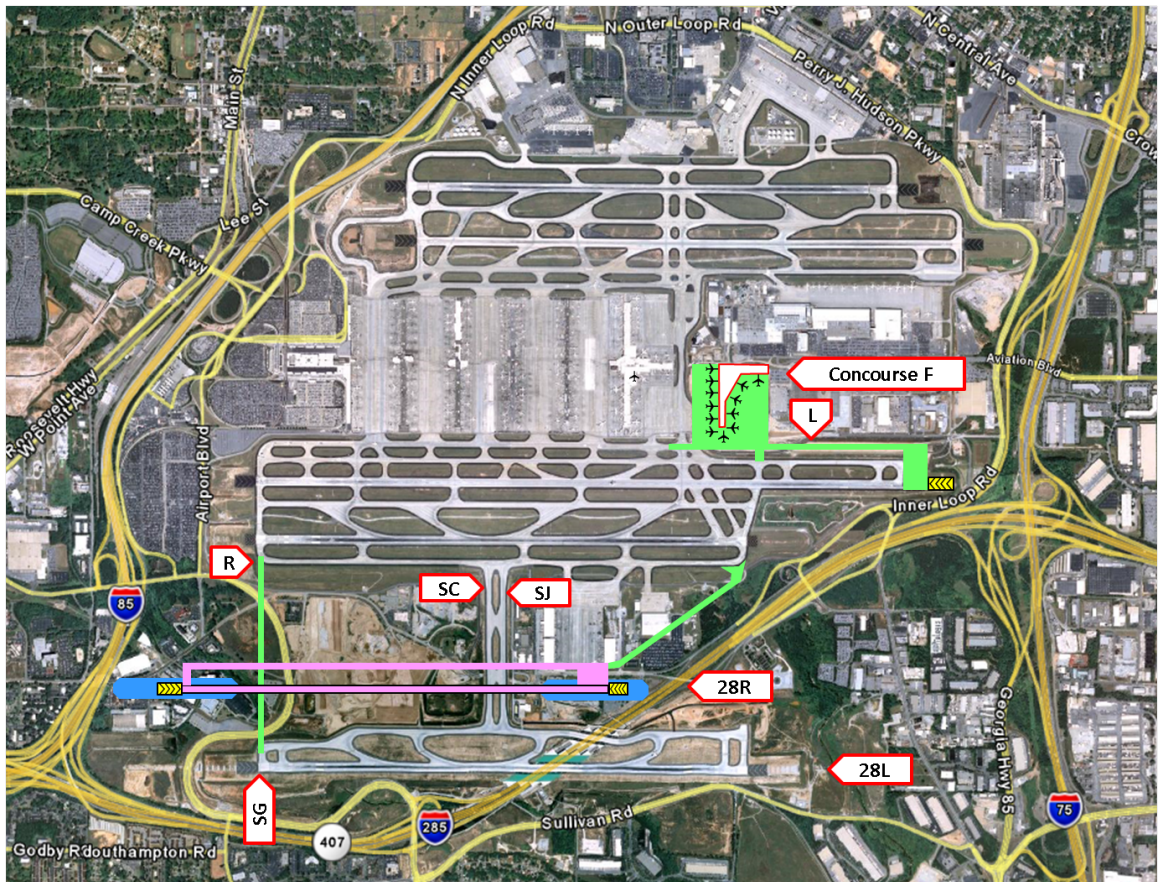
Figure 35: Airspace and Runway Assignment Reconfiguration for ATL
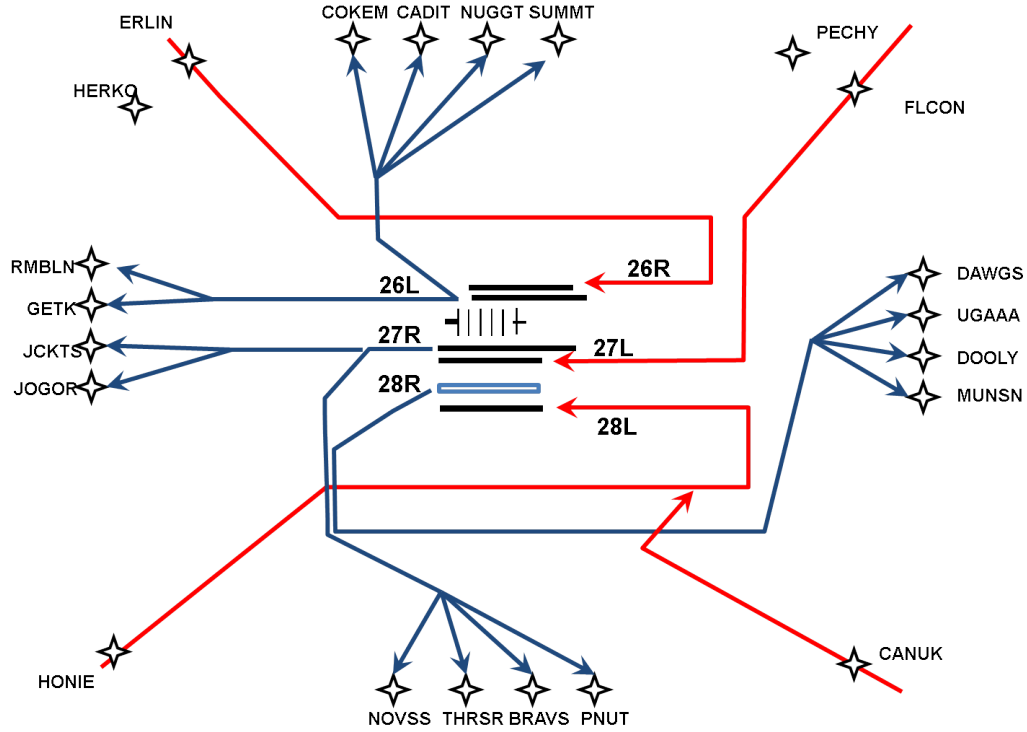
this report. One is a reduction in aircraft longitudinal separation enabled by an appropriate suite of operational technologies within ATC systems and an onboard aircraft. These technologies include ADS-B, LAAS, CDTI, and leverage on the widespread use of Area Navigation (RNAV) navigation systems and corresponding RNAV procedures. The second improvement identified in the *FACT2* study is the reduction of separation for consecutive departures, including reduced departure wake separation reductions, that would allow for Visual Meteorological Conditions (VMC) equivalent separation during IMC. This improvement is also enabled by appropriate operational technologies such as the ones mentioned above, as well as wake detection systems such as NASA's AVOSS

These improvements were captured in the SIMMOD model in two ways. The definition of longitudinal separation rules were modified to reflect VMC-equivalent separation. The values for VMC separation implemented are those shown in Table 26, in Appendix A, which were obtained from published literature.[147] Takeoff procedure definitions were modified to reflect separation of consecutive departures on the same runway commensurate with VMC.

These reduced separation/interval values were procured by ATC specialists.

Finally, advanced aircraft concepts considered were based on NASA's multi-tiered development of next generation commercial airliners whose design responds to stringent performance and environmental goals. These advanced aircraft concepts include an N+1 concept for the 150 passenger class to be introduced in 2018, a tube-and-wing N+2 concept for the 300 passenger class introduced in 2025, and a Blended Wing Body (BWB) N+2 concept for the 300 passenger class also introduced in 2025. Each of these advanced aircraft implement a variety of performance improvements with respect to current best-in-class aircraft.[228, 233] The aforementioned advanced aircraft models were included in the calculations of fleet mix evolution accordingly based on their introduction date. These aircraft were modeled in SIMMOD by instantiating new aircraft models for which the only requirement was the assignment to an aircraft size class for airborne separation, and an aircraft ground size class for procedural logic regarding access to airport areas. Similarly, advanced aircraft concepts were also incorporated within the AEDT by adding the appropriate entries into relational tables of the Aircraft database to account for modeled aircraft performance and to account for environmental performance in flight. Said aircraft performance specifications were provided with the version of the AEDT made available for this thesis' research.

7.4 Characterization of Terminal Area Solutions Impact

The aforementioned terminal area solutions were grouped according to solution types so that the assessment of their impact on terminal area represents a solution 'bundle'. In other words, all infrastructure solutions were handled as a group, as were operational solutions and the different advanced aircraft concepts respectively, resulting in three terminal area solution alternatives.

Contrary to the assessment presented in Chapter 6 which used exogenous and endogenous factors to characterize performance, the present assessment uses each terminal area solution bundle as a performance characterization factor. Solutions can only have two possible discrete settings, namely "Yes" and "No" to indicate whether each solution type is

implemented or not. Although an RSE is mathematically defined only for continuous variables, it is possible none the less to implement regression analysis to quantify factor effects for which t-statistic and corresponding p-values are generated. In this sense, main effects capture the impact of a solution in isolation, whereas interaction effects capture the interdependencies of solutions being implemented in combination. Quadratic and other higher order effects have logical interpretation for discrete factors, and thus are not taken into consideration. Additionally, the data set can also be used in visualization schemes to further examine sensitivities, interactions and tradeoffs.

In accordance with the proposed approach discussed in Chapter 4, and illustrated in Chapter 6 for airport performance characterization under reference conditions, the characterization of airport performance resulting from terminal area solutions requires the selection of a DoE to specify the settings for all relevant factors in each M&S experiment. The three solution alternatives, for which two discreet settings have been defined, were arranged in a 2^3 full factorial DoE, covering all possible combinations of solutions. Resulting M&S data was analyzed and used to generate corresponding coefficient estimates for all factor effects.

Since terminal area solutions are meaningful artifacts of the terminal area system, but are also represented by regression variables, the following notation is used to refer to regression variables:

- The variable $RWY28R$ is the regression variable corresponding to airport infrastructure solutions, which feature runway 28R, the new international terminal, and corresponding taxiways.

- The variable $VMCSep$ is the regression variable corresponding to operational improvement solutions, which feature reduction of departures and in-trail separation to VMC equivalent levels.

- The variable $AdvFleet$ is the regression variable corresponding to the advanced aircraft concepts introduced into the fleet.

Prior to the statistical analysis of M&S results, the magnitude and significance of solution alternatives effects on terminal area performance are completely unknown. It is none

the less possible to speculate on a number of trends based on basic understanding of how terminal area solutions affect airport performance. In turn, qualitative speculations are stated with corresponding hypotheses for testing, and are organized according to metrics groupings.

Advanced Aircraft Concepts

- The addition of advanced aircraft concepts is not expected to have any impact on the operational performance of the airport, but rather will have an impact on fuel burn and emissions for ground and airborne operations given the improvements on aircraft performance targeting reductions in environmental impact.

- $\implies$ *Hypothesis 4.1*: For all operational metrics considered, none of the factor effects of $AdvFleet$ are statistically significant

Departure Ground Operations

- The addition of a designated departure runway and the reduction in consecutive departure separation will effectively increase the departure throughput of the airport, which is expected to reduce taxi out time, departure queue wait, and departure gate hold time. Thus, these two solutions are expected to be significant for the aforementioned metrics. The significance of the interaction between the two solutions is unknown.

- $\implies$ *Hypothesis 4.2*: For taxi out delay, departure queue wait, and departure gate hold time, $RWY28R$ and $VMCSep$ effects are statistically significant

- The reduction in ground movement times for departures will result in corresponding reductions for departure ground fuel burn and emissions. Thus, the additional runway and separation reduction are expected to be significant for departure ground fuel burn and emissions, but the significance of the interaction effect is unknown.

- $\implies$ *Hypothesis 4.3*: For departure ground fuel burn and emissions, $RWY28R$ and $VMCSep$ effects are statistically significant.

- Advanced aircraft concepts will contribute to reductions in ground fuel burn and emissions for departures. However, since these aircraft do not impact departure ground times, the impact of this solution on ground fuel burn and emissions for departures is expected to be smaller than that from the additional runway the reduction of departure separation

- $\Longrightarrow$ *Hypothesis 4.4*: For departure ground fuel burn and emissions, *Adv.Feet* effects are less statistically significant than effects for $RWY28R$ and $VMCSep$

Arrival Ground Operations

- The reduction in departure ground times resulting from the additional runway and the reduction in departure separation is expected to have an effect on ground operations for arrivals, given that departure ground traffic density will be lower and gates used by departing flights will be made available sooner (in the implementation of a gate-hold program). Thus, the additional runway and the reduction in separation are expected to be significant factors for arrival gate wait and taxi-in delay, but the significance of the interaction is unknown.

- $\Longrightarrow$ *Hypothesis 4.5*: For arrival gate wait and taxi-in delay, $RWY28R$ and $VMCSep$ are statistically significant.

- By virtue of the reductions in arrival ground times, ground fuel burn and emissions for arrivals are expected to be reduced with the additional runway and separation reduction.

- $\Longrightarrow$ *Hypothesis 4.6*: For arrival ground fuel burn and emissions, $RWY28R$ and $VMCSep$ are statistically significant.

Airborne Operations

- The reduction in in-trail separation will have a significant impact in the reduction of arrival airborne delay. Similarly, the addition of the designated departure runway

eliminates the need of using runway 28(L) for triple departure operations during departure push peaks, and thus arrivals can use the three runways all the time. This is expected to have a distinguishable effect on arrival airborne delay.

- $\implies$ *Hypothesis 4.7*: For arrival airborne delay, $VMCSep$ and $RWY28R$ effects are statistically significant.

- By virtue of the reductions in arrival airborne delay, it is expected that the additional runway and the reduction in separation will produce a distinguishable effect on airborne fuel burn and emissions for arrivals.

- $\implies$ *Hypothesis 4.8*: For arrival airborne fuel burn and emissions, $VMCSep$ and $RWY28R$ effects are statistically significant

- The advanced aircraft concepts are expected to produce a distinguishable effect on arrival airborne fuel burn and emissions.

- $\implies$ *Hypothesis 4.9*: For arrival airborne fuel burn and emissions, $AdvFleet$ effects are statistically significant

- Given that departure airborne delay was found to be negligible, departure airborne time can be use as a more measurable metric. Since no significant airborne delay is observed for departures, it is expected that the additional runway and reduced separation will not have an effect on departure airborne time.

- $\implies$ *Hypothesis 4.10*: Departure airborne delay will not observe variability - no factor effect is statistically significant.

All of the above hypothesis are formulated to test the veracity of qualitative, preliminary assessments made about the expected effect that different terminal area solutions will have on airport performance. Since each hypothesis is stated in terms of the statistical significance of regression of the effects of a given terminal area solution, all hypotheses can be tested by means of the corresponding t-test p-value. More specifically, each of the hypotheses in question is accepted if the p-value is below the critical value, and rejected

otherwise. Thus, the results of the regression analysis and statistical tests conducted for the M&S runs performed for the present assessment provide the necessary data to test all of the hypotheses.

However, the value of these results extend beyond the immediate need to test the hypotheses in question. The insight that regression and statistical analysis results provide is realized by the explicit and quantitative characterization of sensitivities, interactions, and tradeoffs, which are made more evident through visualization mechanisms.

The results for the regression and statistical tests conducted are presented next. A critical value of 0.5 was used for the t-statistic p-value, and a range of marginal significance was set between 0.05 and 1.10. Table 19 summarizes regression fit and t-test p-values for relevant *operational* metrics. p-values below the critical value are highlighted in green, whereas those within the marginal significance range were highlighted in yellow. In a similar fashion, Table 20 and Table 21 summarize results for *arrival environmental* metrics corresponding to *airborne* and *ground* operations respectively. Table 22 and Table 23 summarize results for *departure environmental* metrics corresponding to *airborne* and *ground* operations respectively.

Table 19: t-Test p-Values - Operational Metrics - Terminal Area Solutions

	Taxi-Out Delay	Taxi-In Delay	Arrival Gate Wait	Departure Gate Hold	Departure Airborne Time	Arrival Airborne Delay	Mean Departure Queue Time 26L	Mean Departure Queue Time 27R
R Square	0.9971	1.0000	0.9989	0.9998	0.9979	0.9999	0.9994	0.9958
R Square Adj	0.9799	0.9999	0.9925	0.9987	0.9854	0.9990	0.9960	0.9705
RWY 28R	0.0871	0.0042	0.0230	0.0105	0.0363	0.0222	0.0267	0.0494
Adv. Fleet	0.5770	0.0335	0.5308	0.2244	0.4762	0.3572	0.1678	0.7098
VMC Sep	0.0379	0.0053	0.0704	0.0217	0.0873	0.0085	0.0221	0.0837
RWY 28R * Adv. Fleet	0.5921	0.0099	0.5380	0.2211	0.2328	0.5138	0.2553	0.7340
RWY 28R * VMC Sep	0.1900	0.0079	0.0707	0.0217	0.0603	0.0349	0.0338	0.1763
Adv. Fleet * VMC Sep	0.4037	0.0114	0.4906	0.5009	0.5072	0.3821	0.9269	0.4630

The p-values of *AdvFleet* effects for all operational metrics in Table 19 are observed to be above the critical value, with the exception of taxi-in delay for which all effects were found to be significant. These results suggest that the effects associated with advanced aircraft concepts are not statistically significant for operational metrics. Thus, *Hypothesis 4.1* is accepted.

Table 20: t-Test p-Values - Arrival Airborne Environmental Metrics - Terminal Area Solutions

	Fuel Burn	CO	CO_2	NO_X	SO_X	HC	PM	VOC
R Square	0.9999	1.0000	0.9999	0.9999	0.9999	1.0000	1.0000	1.0000
R Square Adj	0.9995	1.0000	0.9995	0.9992	0.9995	0.9999	0.9999	0.9999
RWY 28R	0.0162	0.0088	0.0162	0.0197	0.0162	0.0156	0.0140	0.0156
Adv. Fleet	0.0175	0.0017	0.0175	0.0609	0.0175	0.0024	0.0023	0.0024
VMC Sep	0.0062	0.0034	0.0062	0.0076	0.0062	0.0059	0.0054	0.0059
RWY 28R * Adv. Fleet	0.6165	0.1987	0.6165	0.5525	0.6165	0.2572	0.2309	0.2572
RWY 28R * VMC Sep	0.0255	0.0138	0.0255	0.0310	0.0255	0.0241	0.0223	0.0241
Adv. Fleet * VMC Sep	0.6882	0.0586	0.6882	0.4493	0.6882	0.0798	0.0777	0.0798

Table 21: t-Test p-Values - Arrival Ground Environmental Metrics - Terminal Area Solutions

	Fuel Burn	CO	CO_2	NO_X	SO_X	HC	VOC
R Square	0.9991	0.9982	0.9991	0.9988	0.9991	0.9974	0.9974
R Square Adj	0.9934	0.9877	0.9934	0.9916	0.9934	0.9816	0.9816
RWY 28R	0.0210	0.0287	0.0210	0.0237	0.0210	0.0351	0.0351
Adv. Fleet	0.9865	0.5064	0.9865	0.7328	0.9865	0.4135	0.4135
VMC Sep	0.0738	0.1023	0.0738	0.0839	0.0738	0.1285	0.1285
RWY 28R * Adv. Fleet	0.9413	0.5523	0.9413	0.7689	0.9413	0.4769	0.4769
RWY 28R * VMC Sep	0.0744	0.1032	0.0744	0.0845	0.0744	0.1297	0.1297
Adv. Fleet * VMC Sep	0.4837	0.4850	0.4837	0.4845	0.4837	0.4855	0.4855

For departure queue wait for runways 267L and 27R, and departure gate hold time in Table 19, $RWY\,28R$ main effects are statistically significant, and marginally significant for taxi out time. Similarly, all $VMCSep$ main effects these metrics are statistically significant or marginally significant. Although some p-values for the interaction effect are found to be beyond the marginal range, as is the case for taxi-out time and departure queue time for runway 27R, these results collectively provide an obvious indication of the the significance of $RWY\,28R$ and $VMCSep$ effect. In turn, *Hypothesis 4.2* is accepted. The expected effect that reduced ground operation times for departures have on corresponding fuel burn and emissions is confirmed by the p-values for $RWY\,28R$ and $VMCSep$ effects in Table 23. Main effects for the two factors are found to be statistically significant for fuel burn and all emission species, whereas the interaction effect between $RWY\,28R$ and $VMCSep$ is consistently found to be marginally significant. In lieu of these results, *Hypothesis 4.3* is accepted.

Table 22: t-Test p-Values - Departure Airborne Environmental Metrics - Terminal Area Solutions

	Fuel Burn	CO	CO_2	NO_X	SO_X	HC	PM	VOC
R Square	1.0000	1.0000	1.0000	0.9996	1.0000	1.0000	1.0000	1.0000
R Square Adj	1.0000	1.0000	1.0000	0.9975	1.0000	1.0000	1.0000	1.0000
RWY 28R	<.0001	0.0310	<.0001	0.0311	<.0001	<.0001	0.0166	<.0001
Adv. Fleet	<.0001	0.0005	<.0001	0.0130	<.0001	<.0001	0.0002	<.0001
VMC Sep	1.0000	0.7952	1.0000	0.7952	1.0000	1.0000	0.7942	1.0000
RWY 28R * Adv. Fleet	0.0006	0.8686	0.0006	0.7608	0.0005	0.0005	0.5517	0.0002
RWY 28R * VMC Sep	1.0000	0.7952	1.0000	0.7952	1.0000	1.0000	0.7942	1.0000
Adv. Fleet * VMC Sep	1.0000	0.5000	1.0000	0.5000	1.0000	1.0000	0.5000	1.0000

Table 23: t-Test p-Values - Departure Ground Environmental Metrics - Terminal Area Solutions

	Fuel Burn	CO	CO_2	NO_X	SO_X	HC	VOC
R Square	0.9981	0.9984	0.9981	0.9983	0.9981	0.9989	0.9989
R Square Adj	0.9868	0.9891	0.9868	0.9883	0.9868	0.9920	0.9920
RWY 28R	0.0444	0.0424	0.0444	0.0419	0.0444	0.0393	0.0393
Adv. Fleet	0.7491	0.0997	0.7491	0.2015	0.7491	0.0522	0.0522
VMC Sep	0.0388	0.0360	0.0388	0.0367	0.0388	0.0327	0.0327
RWY 28R * Adv. Fleet	0.4500	0.3807	0.4500	0.4615	0.4500	0.3345	0.3345
RWY 28R * VMC Sep	0.0883	0.0787	0.0883	0.0843	0.0883	0.0714	0.0714
Adv. Fleet * VMC Sep	0.5440	0.6440	0.5440	0.6005	0.5440	0.7851	0.7851

The impact of advanced aircraft on ground fuel burn and emissions was anticipated to have some statistical significance, but lower than that for $RWY28R$ and $VMCSep$ effects. Table 23 shows that p-values for $AdvFleet$ effects are not below the critical value, and that only for CO, HC, and VOC they are in the range of marginal significance. Thus, *Hypothesis 4.4* is accepted, but it is worth noting that the significance of $AdvFleet$ effects is lower than anticipated.

Reductions in departure ground operation times were expected to be accompanied by corresponding reductions in arrival ground operations. Thus, the significance of $RWY28R$ and $VMCSep$ effects noted for departure ground operation metrics are also expected for arrival gate wait and taxi-in delay. Table 19 confirms that $RWY28R$ and $VMCSep$ effects for these two metrics are statistically significant, noting that the main effect for $VMCSep$

and the interaction effect are only marginally significant. Thus, *Hypothesis 4.5* is accepted. The anticipated corresponding reductions in arrival ground fuel burn and emissions prescribe that statistically significant $RWY28R$ and $VMCSep$ effects be expected for these metrics. Results in Table 21 indicate statistical significance for the main effect of $RWY28R$ for fuel burn and all emission species. However, $VMCSep$ effects are only marginally significant for fuel burn CO_2, NO_X, and SO_X, and not significant for the other emissions. Thus, *Hypothesis 4.6* is rejected as formulated, noting that it can be revised to account only for the effects of $RWY28R$.

The capacity enhancement resulting from the runway 28R and reduce separation is expected to have a significant effect on airborne delay for arrivals. The p-values for this metric in Table 19 confirm this observation, showing that $RWY28R$ and $VMCSep$ main effects and the interaction effect are statistically significant. *Hypothesis 4.7* is therefore accepted. The corresponding reductions in airborne fuel burn and emissions for arrivals suggest that $RWY28R$ and $VMCSep$ effects should also be statistically. Results in Table 20 confirm that $RWY28R$ and $VMCSep$ main and interaction effects are statistically significant for fuel burn and all emissions species. Furthermore, the $AdvFleet$ main effect is also found to be statistically significant for fuel burn and all emissions, except for NO_X for which it is marginally significant. These results indicate that all three solutions have a major bearing on airborne environmental performance for arrivals, and that noteworthy interactions are in play. Thus, *Hypothesis 4.8* and *Hypothesis 4.9* are accepted. Lastly, the airborne delay and total travel time for departures is not expected to be affected by any of the solutions analyzed. However, results in Table 19 show that contrary to this expectation, runway 28R appears to have an impact on departure travel time, as evidence by the statistical significance of the main $RWY28R$ effect. Consequently, *Hypothesis 4.10* is rejected.

7.5   *Visualization of Terminal Area Solution Effects*

DoE simulation data and regression results indicate that the addition of the new runway increases departure taxi delay by up to 5%, but that reductions of up to 10% can be observed with VMC separation, which is found to be a statistically significant regressor. Due to the

aggregate effect on surface traffic density of these two solutions, similar trends are observed for arrival taxi delay, with more moderate improvements due to VMC separation. The implementation of runway 10L/28R caused the reduction of departure gate delay to negligible levels, and consequently had a major impact on arrival gate delay as gate availability increased. VMC separation for departures also reduced departure queue wait times which reduced departure gate delay by 50% if implemented in isolation. Both of these solutions, and their interaction, are statistically significant for gate delay. However, improvements due to VMC separation become negligible if the new runway is implemented first, whereas improvements due to VMC separation can be further augmented via the new runway.

The interactions profiler for departure gate delay, shown in Figure 36, graphically illustrates the relative magnitude of new runway and reduced departure separation, as well as their mutual interaction, on departure gate delay as an illustrative metric of interest. The strong interaction between the additional runway and separation reduction can be readily identified by the notable difference in slope between trend lines in the top-right and bottom-left quadrants. Conversely, the impact of advanced aircraft concepts is null on this operational metric, which is noted by the overlapping trend lines for the ON and OFF settings. These effects can be visually represented in a similar fashion with the dynamic prediction profiler, shown on Figure 37, where the relative impact of infrastructure and operational solutions on departure gate hold reduction are explicitly characterized.

Reductions in arrival airborne delay were primarily obtained via VMC separation, reaching 75% improvement, making it the most statistically significant regressor. However, the additional runway had an impact on arrival delay given that the original 5 runway configuration makes use of runway 10/28 for arrivals, as well as for departures only during two 1-hour peak periods in the simulation day, causing some delay to arrivals during these periods. Implementing runway 10L/28R leaves 10/28 exclusively for arrivals during the entire simulation day, thus reducing airborne arrival delay and making the interaction between the new runway and VMC separation statistically significant. Finally, the new departure runway and reduced wake separation for departures have a compounding effect on the reduction of departure queue wait times for runways 26L and 27R, for which interaction effects

Figure 36: Interaction Profiler for Departure Gate Delay - Terminal Area Solutions
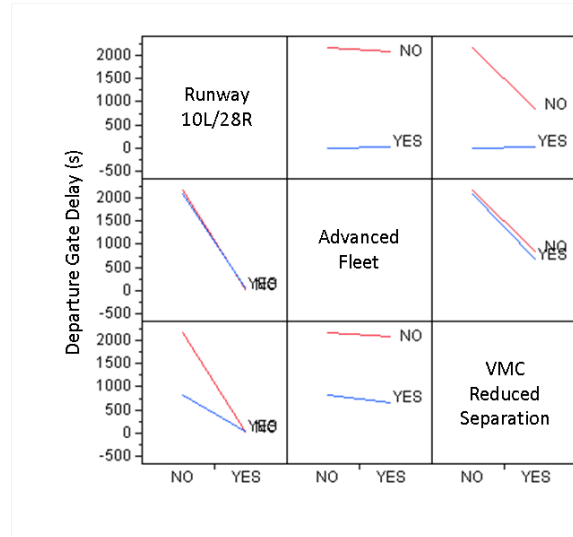
Figure 37: Dynamic Profiler for Departure Gate Delay - Terminal Area Solutions
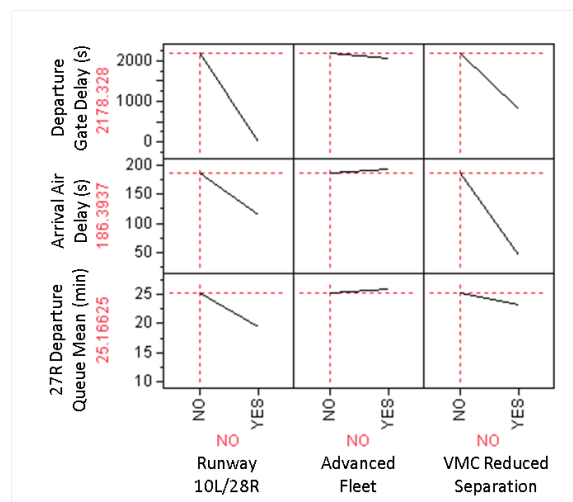
are also found to be statistically significant. Again, the prediction profiler graphically illustrates the relative impact of these solutions to the arrival airborne delay and departure queue wait, and confirms the expected null effect that advanced aircraft concepts have on operational performance.

Environmental impact reduction for airport surface arrival operations was found to be primarily driven by the implementation of the new runway and to a more moderate extent by the reduction in departure wake separation. Compared to these two solution types, the reduction in fuel burn due to the introduction of advanced aircraft concepts was unexpectedly low, but some appreciable improvements were noted on several species such as particulate matter, or unburned hydrocarbons as illustrated by the prediction profiler in Figure 38. In contrast, the relative impact of the new runway was much more moderate for departure surface operations while the relative contribution of advanced aircraft concepts was greater and comparable to departure wake separation reduction for various emissions species, as shown in Figure 38, making all three solutions types statistically significant regressors. This behavior can be explained by the fact that arrival surface fuel burn is driven by the time spent with engines on, which includes gate waiting times as had been previously explained. As was shown, the new runway practically eliminates gate delay and thus its statistical significance is considerable for arrival ground fuel burn and emissions. On the other hand ground departure fuel burn and emissions are not affected by gate delays, and rather improvements provided by the new runway are limited to the inherent additional departure processing capabilities. Though statistical significance was found only for main effects, interactions between the three solution types are still noticeable for departure ground emissions as graphically illustrated by the interactions profiler in Figure 39 for unburned hydrocarbons as an illustrative species.

For arrival airborne fuel burn, reductions were primarily enabled by VMC separation which, as expected, considerably increases arrival throughput and reduces the airborne holding prior to final approach. Though still statistically significant, the smallest relative impact to said fuel burn reductions is enabled by the advanced aircraft concepts. However, for the majority of emissions species these advanced aircraft concepts are the dominant regressor,

Figure 38: Visualization of Interactions, Sensitivities, and Tradeoffs - Terminal Area Solutions
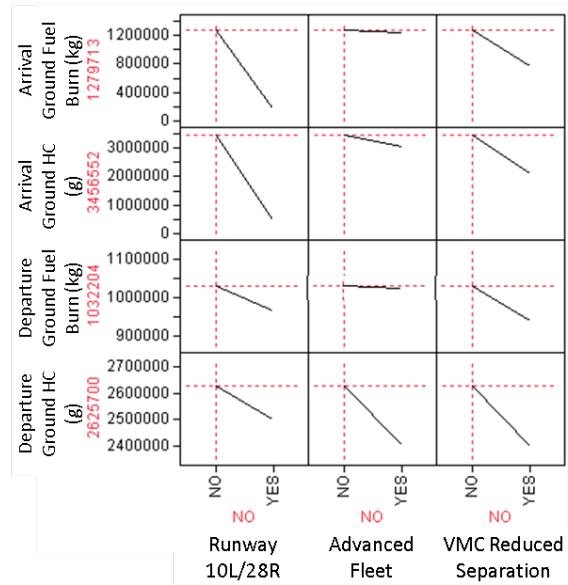
Figure 39: Interaction Profiler for Departure Ground HC - Terminal Area Solutions
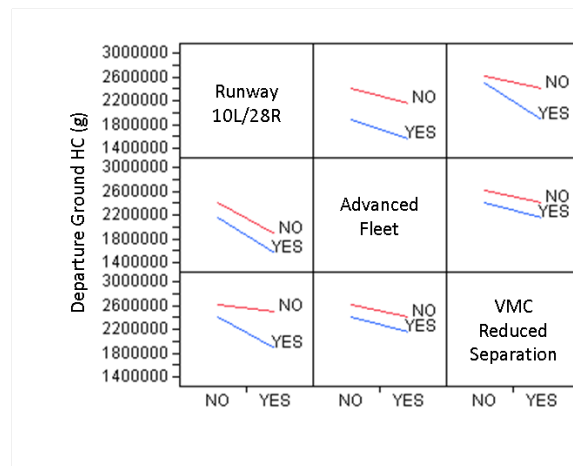
responsible for up to 15% reductions for particulate matter as an illustrative example. Advanced aircraft were also the greatest enabler for departure airborne reductions in fuel burn and emissions, for which the new runway and VMC reductions provided negligible relative impact, and for which no interactions were found to be statistically significant. Collectively, these results support the idea of a balanced approach to terminal area improvements where the sensitivity of various operational and environmental performance metrics to infrastructure, operational, and fleet solution types can be explicitly compared side by side to enable educated tradeoffs. Moreover, characterizing significant interactions leverages transparency and insight in the characterization of terminal area performance, and demonstrates how different combinations of solutions provide greater/lesser aggregate results under various conditions.

7.6   Considerations for Terminal Area Solution Selection

Based on the results for statistical significance shown, and the visualization of tradeoffs and sensitivities for the three solution types on operational and environmental metrics, it is possible to offer some observations and considerations regarding the selection of a strategic solution. First, it is evident that the impact of separation reduction and the added airport infrastructure on operational performance is significant. For ground operations, the additional infrastructure practically eliminates departure gate delay from the average 48 minutes observed with no solutions implemented, as well as the approximately 36 minutes average arrival gate delay. Reductions achievable by means of separation reduction are also significant, but only in the order of 50% of the reductions achieved by the additional infrastructure. If separation reduction is applied first, the additional runway enables the complementary reductions in gate delay. However if the additional infrastructure is implemented first, it is noted that the effect of separation reduction becomes negligible for gate delay metrics. It is also key to point out that additional infrastructure leads to increases in taxi-out and taxi-in delay in the order of 50 seconds, whereas separation reduction leads to taxi-in/taxi-out delay reductions of comparable magnitude. None the less, these variations in taxi delay are negligible compared to the reductions achieved in gate delay.

Because of engine-off assumptions departure gate-holding, the sensitivity of departure ground fuel burn and emissions to additional infrastructure and separation reduction is different from that for arrivals. In the case of departures, it was noted that that there was little sensitivity when both types of solutions were not implemented, and showed only marginal to moderate improvements if implemented one at a time. However, the sensitivities changed dramatically whoever one of the solutions was implemented, indicating very strong interactions between additional infrastructure and separation reduction, featuring considerable reductions in ground fuel burn and emissions when implemented jointly.

On the other hand, arrival ground fuel burn and emissions are considerably sensitive the addition of airport infrastructure and to a more moderate extent to separation reduction. The implementation of additional infrastructure results in a dramatic reduction of arrival fuel burn and emissions, and makes the impact of advance aircraft concepts and separation reduction practically negligible. However, if separation reduction is implemented first, a moderate improvement is observed, as well as potential for further improvements primarily through additional infrastructure. This behavrior is consistent with previous observations regarding the dominance of arrival gate delay in arrival ground operations for delay, fuel burn, and emissions. Thus, the addition of gates and runways is the primary form to reduce operational ground inefficiencies for arrivals which drive ground fuel burn and emissions for arrivals. The impact of separation reduction is moderate and noteworthy but only if additional infrastructure has not been implemented. If it is implemented, separation reduction has negligible impact on arrival ground operations and is therefore diffusible to justify for these metrics.

For airborne operations it had been noted that departure airborne delay was negligible and that departure queue waiting times serves as a more appropriate measure for departure delay. For departure queue waiting times, it was noted that the interaction between additional infrastructure and separation reduction was very significant. More specifically, the improvements that are realizable from the two solutions in combination are considerably greater than those realizable from each solution in isolation. Thus, there is an incentive to implement both solutions jointly.

Arrival airborne delay was shown to be reduced by approximately 76% due to the separation reduction, reducing average delay times from approximately 186 s. to under 45 s. and making the effect of additional infrastructure negligible. If separation reduction is not implemented, the additional infrastructure can realize airborne arrival delay reduction of up to 38%, half of the total reductions achieved by separation reduction. This effect is translated to a strong sensitivity of airborne fuel burn and emissions with respect to separation reduction. However, it is noted that the impact of the advanced aircraft concepts is of comparable magnitude to that of additional infrastructure for fuel burn, CO_2, NO_X, and SO_X. Moreover, for HC, PM and VOC, which are characteristically higher for lower power settings observed during arrivals, reductions resulting from the introduction of advanced aircraft concepts are approximately twice as big as those realizable with additional infrastructure or separation reduction. These findings suggest that operational improvements through separation reduction are crucial in reducing fuel burn and some pollutants, whereas advanced aircraft concepts are necessary to reduce the latter group of emissions beyond reductions realizable through more efficient operations.

It is important to note that the benefits of advanced aircraft concepts assessed in terminal area performance characterizations such as this one are inherently limited to performance within that operational domain. The benefits of such aircraft are none the less realized throughout all phases of flight. Conversely, infrastructure addition and operational improvements in the terminal area may have a compounding effect in the NAS, but for the most part have a direct effect limited to the terminal area. Thus, the environmental benefits that are achievable through the mitigation of operational inefficiencies are readily observable, and while the benefits of advanced aircraft concepts may appear to be smaller, they are in fact significant when considered beyond the scope of the terminal area.

The direct impact that additional infrastructure and separation reduction have on arrival operations, and the very significant interaction that exists between them for departure operations, strongly suggest that these two solutions should be implemented jointly to realize operational and environmental benefits. Based on observations about the relative sensitivity of different metrics of interest to these two solutions, it appears that separation

reduction can more strongly justified if it is implemented *before* the addition of runway 28R, so that a phased approach in the improvement of operational and environmental performance may be realized and culminated with the construction of the sixth runway.

The introduction of advanced aircraft concepts will be vital for the mitigation of some emissions, particularly for airborne arrival operations which are known to have a dramatic impact on local air quality. However, their introduction will likely be more dependent on the overall benefits that are realizable throughout all phases of flight, rather than solely on the improvements hereby characterized for the terminal area.

CHAPTER VIII

SCENARIO-DEVELOPMENT FOR STRATEGIC AIRPORT PLANNING

8.1   Introduction

This chapter presents an extension of the discussion pertaining to the use of a scenario-based approach for the strategic airport planning process, and presents the selection and development of formal methods to construct, evaluate, and select scenarios for this application. This scenario development effort corresponds to *Step 3* of the airport strategic planning process illustrated in Figure 9. First, the argument against the use of scenarios is developed at length and used to introduce the scenario-based approach. Appropriate definitions of scenario and scenario planning are presented, along with a review of the current paradigm in the scenario planning process and noteworthy applications thereof. The scenario development process is then discussed at length illustrating the general approaches that have been proposed as well as notable methodological shortcomings. A morphological approach for scenario probabilization and valuation is then proposed as a traceable and rigorous method for scenario construction, evaluation and selection. The use of probabilization and valuation in this approach is tested against a mathematical definition of parameters appropriate for morphological operations.

Thesis Objective 4: To formulate a traceable, repeatable, and rigorous approach for the definition, generation and down-selection of future scenarios in the context of strategic planning.

8.2   Sources of Risk and Failure Conditions for the Traditional Strategic Planning Paradigm

The traditional strategic planning paradigm is recognized to fail under different conditions, and for a variety of reasons that embody sources of risk for the planning process. In general, the process fails when it is inconsistent with the reality that conforms the context,

or environment[1], within which a given entity or organization exists. One of the causes of this misalignment refers to the challenge of contextual cognition by the organization's leadership; the factors comprising the organization's context may be so numerous, interrelated, and complex, that management fails to understand and characterize its aggregate behavior. In turn, a subjective and fractional interpretation of reality is generated by leaders, passed on through the entire organization, and perpetuated by organizational inertia. In this sense, sources of risk to the planning process can be attributed to contextual features such as the level of competitiveness or the natural dynamism of demand levels, that add difficulty to assessment tasks within planning. The rate of technological change is an archetypal factor of contextual dynamism, particularly when emerging technologies and concepts are developed so fast that planners and decision makers do not have enough time to adequately assess the impact that they have on the business environment, or the impact that they can have when fully implemented in an operational setting. Similarly, regulatory bodies have a strong bearing in the environment where an entity operates, and thus represent another important source of planning risk especially when management fails to fully recognize their importance or changes in the general policies they support.[140]

Uncertainty is another critical source of risk to the planning process. The traditional paradigm dictates the use of forecasts as the primary tool to assess and describe the future. Yet, the inherent uncertainty and assumptions contained in forecasts are not always acknowledged by management or decision-makers, which leads to their misuse and abuse given that they are interpreted as factual predictive constructs rather than abstractions of a future reality.[140] More importantly however, the traditional strategic planning paradigm has been widely recognized to be grossly inadequate whenever uncertainty about the future of the organization's environment is high relative to its management's ability to generate predictions and estimates of the future, or adjust to change. Such a capability gap is often

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[1]In strategic planning the term "*environment*" refers to the collection of factors that are external, or exogenous, to the organization and that comprise a *context* within which the organization exists. This includes, social, economic, and regulatory factors among others. Although the terms *environment* and *context* can be used interchangeably in strategic planning, caution must be taken not to confuse the use of "*environment*" in this thesis, as it may be used for its connotation in strategic planning, or in reference to environmental impact.

reflected by a history of 'costly surprises', a history of instances where the organization was ill prepared to exploit unexpected opportunities, or a lack of consensus about the future and the direction of the organization.[264]

The aforementioned sources of risk to the strategic planning process readily reveal the type of implementations and conditions under which the traditional paradigm fails. These sources of risk must also be recognized as prevalent and defining features of the air transport industry, a sector driven by complex and highly dynamic contextual forces that span economic, social, political, and regulatory considerations among many others, and for which there is considerable uncertainty in future time frames. Thus, it is imperative to adopt an alternative approach to strategic planning for air transportation applications that explicitly incorporates methodological improvements to address shortcomings in contextual cognition and uncertainty management. In recent decades *scenario-based* strategic planning has been proposed and developed as such an alternative paradigm particularly geared towards organizations facing highly uncertain and dynamic contexts, often accompanied by fast-paced technological evolution and potential changes in regulatory bodies.[140]

8.3 The Scenario-Based Strategic Planning Alternative

8.3.1 Definition of Scenarios and Scenario-Based Planning

Scenario-based planning is a structured approach where possible futures are imagined and formulated in terms of an organization's context, or environment, and used to choose strategies based on their robustness, resiliency, and adequacy across these possible futures so that uncertainty and risk are properly managed.

The concept of scenarios and the scenario-based approach were originally developed by Herman Kahn in the early 1960's while conducting work for the department of defense related to possible nuclear war strategies. Much of this work was published in his 1962 book "*Thinking About the Unthinkable*", where he indicated that a nuclear war would yield no clear 'winners', and suggested changes in nuclear policy that were later adopted.[198] The use of scenarios was further developed and refined in in his 1967 book "*The Year 2000*".[199] To better understand the formulation and implementation of scenario-based planning, it is

convenient to begin with a formal definition of *scenario*.

Early in his work, Khan's definition of scenario merely alluded to them as the "*result from an attempt to describe in more or less detail some hypothetical sequence of events*," ([198], p 143) noting that such a description serves as an aid to the imagination of the analyst who tries to assess in a systematic fashion the events resulting from certain decisions of interest.([198], p 143) The focus on decisions an causality inherent in scenarios was stated more explicitly by Kahn later on, when he defined scenarios as "*hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision-points.*"([199] p. 6) Thus, a scenario contains the answers to two fundamental questions for the strategic analyst: 1) How might some hypothetical situation come about? and 2) What choices and alternatives exist for each stakeholder, at any given point in time, for altering that sequence of events in some way?([199] p. 6)

The *hypothetical* nature of scenarios is highlighted in Godet's definition, indicating that "*a scenario is a coherent set of hypotheses issuing from a given original situation to a future situation.*"([142] p 22) In this spirit, a scenario is not to be interpreted as a future reality, but rather as a "*a means to represent a future reality in order to shed light on current action in view of possible and desirable futures.*"([142] p 109)

8.3.2 The Scenario-Based Strategic Planning Process

It is important to recognize that the significance of scenarios, and the methodological benefits they can provide, are realized inasmuch as their generation and implementation occurs within the fundamental strategic planning framework. By themselves, scenarios provide no strategic planning value. A scenario does not provide any indication of the goals of an organization, or about the specific strategies that should be adopted. Similarly, scenarios do not replace (and should never be confused with) strategies, even if some strategies are exclusively linked to a scenario. Scenarios describe an external context, or environment, within which an organization may hypothetically exist. On the other hand, a strategy describes the internal decisions and actions made by an organization so that it can attain prescribed goals and levels of performance as it operates within that context.

Consequently, the generation, evaluation, and selection of scenarios, as well as their implementation for strategy evaluation, do not replace the traditional strategic planning process. Rather, they are incorporated into it, becoming fundamental components that leverage the insight accrued in all other steps and enhance the value of the process as a whole.

As with most other strategic planning approaches, a formalized process for scenario-based planning is not defined with a detailed procedural formulation, but rather in terms of general steps and guidelines. In this way, the process is flexible and easily adaptable to the unique challenges and needs of each implementation, while following the overarching philosophy of the scenario-based paradigm. With this in mind, there is not one 'official', or 'correct', process that can be referred to. Instead there is a a variety of them that have been suggested in published literature where each author has incorporated certain details and refinements. Recognizing these minor differences and variations, is convenient to consider the formulations proposed by certain authors to illustrate the general steps and components of the scenario-based strategic planning process.

The process proposed by Godet [142] is particularly illustrative because it follows closely the fundamental steps in general strategic planning, and dedicates the first steps of the process with additional detail to the generation of scenarios. As shown in Figure 40, the first step is to formulate and analyze the problem, providing a context within which any planning or futures effort must take place. A complete assessment of the organization's competencies is then performed, aided by the identification of key internal and external variables. Competencies and key variables are used to capture and characterize the dynamics of the organization within its environment, which facilitates the generation of scenarios describing the organization's environment and the determination of the range of its strategic options. Strategic options are then evaluated with respect to each other in the context of each scenario chosen, leading to a decision-making task based the hierarchical prioritization for the organization's objectives, and the robustness of strategies across scenarios. Finally, a plan of action that will implement the selected strategy is created, executed, and its progress monitored. In this formulation the core scenario method, namely the process by which

Figure 40: Scenario planning process by Godet (Reproduced from [142], p. 128. ©*Marc Giget and Michel Godet 1990*)
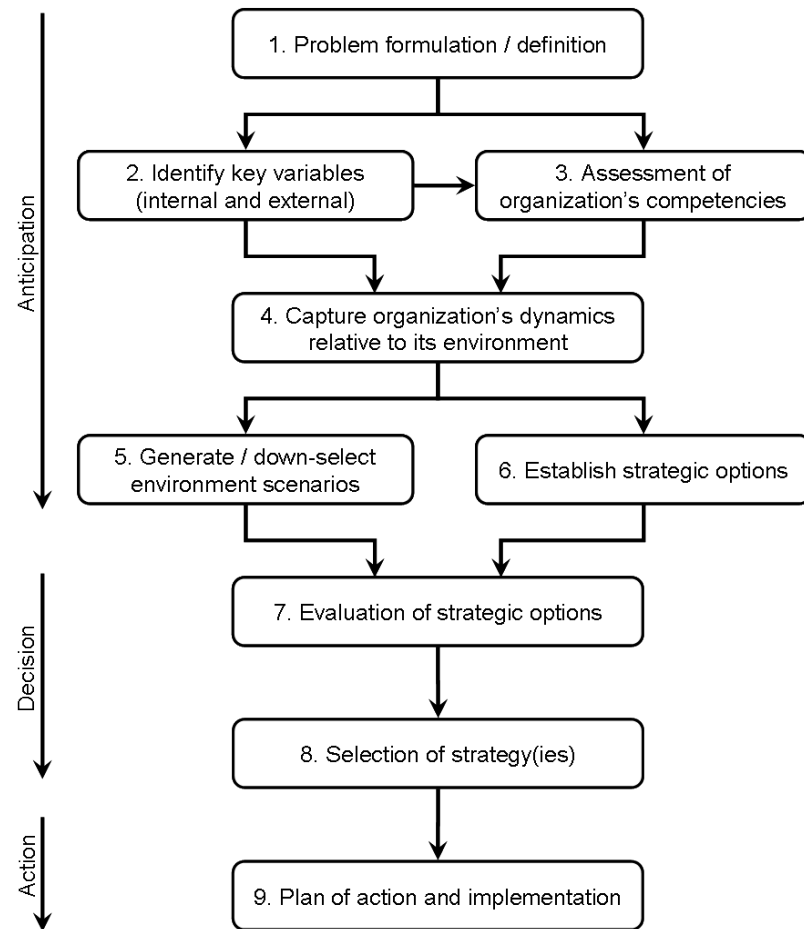
scenarios are created, is composed of steps 1, 2, 4, and 5 as shown in Figure 40. In steps 1, 2, and 4, analysts collect, structure, and synthesize the information that compose the building blocks of scenarios and the internal logical rules that will govern them. Step five is where scenarios are actually built and down-selected.([142] pp. 126-128)

8.3.3 Advantages and Disadvantages of Scenario-Based Planning

There are numerous advantages and benefits associated with the scenario-based approach for strategic planning, particularly with respect to the methodological shortcomings and sources of risk of the traditional forecasting-based planning paradigm. However, while explicitly addressing key gaps, the benefits of incorporating scenarios in strategic planning

prescribe a greater level of difficulty for the task as well as the need for additional resources, thus revealing the fundamental tradeoff between resources required and the degree of insight and understanding that is accrued. The advantages and disadvantages of scenario-based planning must be therefore equally recognized.

One of the most important advantages of using scenarios is that they are instrumental in managing uncertainty and revealing the gamut of possibilities that can, and should, be considered by strategic analysts, forcing them to immerse themselves systematically in an uncertain context that takes into consideration events or outcomes that would otherwise be overlooked.([199] p. 263) In this sense, scenario planning is best implemented and capitalized on by entities whose leadership recognizes that the future can, and most likely will, be sufficiently different from the past. However, the task of planners becomes more difficult as they are required to consider and explicitly incorporate sources of planning risk, particularly in terms of uncertainty over key factors such as demand, as well as disruptive events and phenomena. Similarly, the responsibilities of management and decision makers grow as they are required to consider contexts beyond the immediately predictable future.[140]

Experiments have demonstrated that the use of scenarios broadens confidence ranges on estimates for future events, outcomes, and/or performance, suggesting that overconfidence in estimates is mitigated and uncertainty is more adequately captured with the use of scenarios. Other results have been shown to support the idea that scenarios are useful to decision makers even if they were not directly involved in the generation of those scenarios. However, empirical data has also been used to explore the inadvertent injection of bias into scenarios. For instance, a relevant and known phenomenon is that an analyst tend to be biased towards confirming evidence when developing a given trend, whereas disconfirming evidence is often neglected or discounted.[264]

Since plans based on forecasts emphasize comprehensiveness and rigor in projection drivers, the excessive number of factors and the complexity in their interrelationships often forces planners to downgrade the fidelity of available data, fixing many variable trends into operating assumptions. In consequence, all resulting insight is contingent and conditional, which greatly reduces the value that a forecast may have as decision-making tool. In

contrast, a set of scenarios places emphasis on understanding what it means to live under certain conditions, rather than adopting a predictive perspective that seeks to determine what the 'correct' conditions will be in the future. In fact, some early criticism of the use of scenarios argued that they were so far removed from reality that they were useless for planning purposes and in some instances dangerously misleading. None the less, a scenario is *not* a predictive tool, and therein lies the major difference between scenario-based and forecast-based planning.[37]

Moreover, the formulation and use of scenarios also require that special attention be placed on the interactions among relevant contextual factors and maintained throughout the analysis. Whereas these interactions are eliminated early in a forecast-based planning effort and are notably absent within its final results, scenario-based planning intelligently incorporates these interactions into the process and effectively manages the contextual complexity of the planning effort. In this sense, scenarios are instrumental in illustrating basic principles that may not be readily discernible due to the inherent systemic complexity observed in the real world, or that may be altogether washed out with a forecasting approach.([198] p. 144, [199] p. 263) However, an explicit characterization of these interactions is rarely an easy task, and often necessitates analytical models, relevant data, and/or subject matter experts, all of which translates to a larger resource commitment by the for the planning effort.

Likewise, the formulation and use of scenarios require that analysts explicitly account for the dynamic, and often fast-paced changing nature of events. Planning activities that use forecasts inevitably conceive the future as a well defined future state that sits still while the elements of a plan are implemented and set in motion. A good scenario presents the future dynamically and with the possibility of disruptive elements occurring without much warning.[37] A scenario-planning effort also requires that different potential paths be considered, particularly when focusing on issues such as technological development which require considerations for planning risk associated with high technology change rates.[140] Again, incorporating considerations for dynamism and and multiple evolutionary paths adds value to the planning process and embeds more information in each scenario, but also

increases the complexity of the task and prescribes resources such as adequate dynamic models or subject matter experts.

Other advantages of the scenario-based planning approach are revealed by recognizing that it is not the only alternative to the traditional forecast-based paradigm, and that the use of scenarios offers benefits over other alternative approaches. For instance, *contingency planning* makes use of a reference state and a single alternative outcome to which some level of uncertainty is associated, whereas scenarios embody a whole plethora of alternative outcomes incorporating multiple uncertainties that are systematically explored throughout the development and evaluation of strategies. A *sensitivity analysis* in planning efforts quantifies the change of a given parameter of interest resulting from perturbations on another factor, but does so one factor at a time in the basic and traditional formulation. By definition, scenarios are internally consistent, that is, all the factors that comprise it are in accordance with each other. This required internal agreement among scenario factors adds complexity to the planning task and may prescribe the use of models or experts, but in turn allows planners to vary all factors at the same time and, leveraging on the characterization of interactions among factors, assess the sensitivity of scenario parameters resulting from changes in all factors. It is also worth noting that quantitative models and simulations are a major component in scenario-based planning, but rather than being limited to objective or quantitative relationships, scenarios greatly enriched by the subjective interpretation of decision makers and the experience of experts.[264]

Scenarios must also be recognized as inherently multidisciplinary because they require knowledge about a number of topics, but are particularly demanding in that the interrelationships between all said aspects must be sufficiently understood. Thus, the best scenarios are developed by "*approximating multidisciplinary wholeness*,"[37] prescribing a strong reliance on experts to the point where they may become expert-based artifacts.

The consideration of various scenarios and appropriate courses of action in each one of them involves communication, discussion, and debate, where decision makers are forced to incorporate and process large amounts of information. As such, scenario based planning serves as a learning tool and an enabler of communication. However, key decision-makers

and top management rarely have the time to fully engage in these discussions and conduct scenario-based planning. In turn, this responsibility is often delegated to middle management for which effort and time commitment is still significant. Consequently, the time and resource investment required for a full-scale scenario-based planning effort may be difficult to justify in some instances.[140]

Scenario-based planning also faces challenges in terms of perceptions and expectations about it within an organization. For instance, whenever the bulk of scenario generation efforts are delegated to middle management, it is not uncommon to find at this level the perception that results and recommendations do not fully reach top management, that they are totally or partially discarded due to lack of top-level involvement, or that they will not meet expectations. Moreover, this disconnect between corporate levels may result in instances where top management does not have a clear understanding of the type of results that scenario-based planning can bring and thus may have inaccurate expectations. Some scenarios can be framed at a very high level of abstraction and help define a vision, but can often fail to produce actionable items that many middle and top level managers may expect from this type of exercise.[140] However, this difficulty can be easily averted by adequately selecting and agreeing upon the type of scenarios that are needed and that must be constructed, based on the needs of the organization and the purpose of the planning effort. Important distinctions between vision-driven and decision-driven scenarios are discussed later in this chapter in section 8.4.1.

8.3.4 Applications of Scenario-based Planning

There are innumerable accounts of scenario-based strategic planning in industry applications. One of the earliest, and certainly one of the most successful and widely known cases, is that of the multinational oil company Royal Dutch / Shell. Starting in the early 1970's the company began adopting the use of scenarios for the generation and evaluation of strategic options. This approach allegedly allowed the organization to account for disruptive events in their planning efforts enabling them to better respond to the oil crises of 1972, 1974, and 1980, as well as to better capitalize on market opportunities, relative to competitors at the

time. Another well-known example is that of the Anglo-American Corporation, a global mining and natural resource group, that conducted a major scenario planning exercise in 1984 to explore the economic and political evolution of various regions of interest around the globe, and which had particular impact on the debate over political action in South Africa. Although evidence on the effect that scenario-based strategic planning has had on corporate performance is relatively limited, and depends on whether internal or external factors are used to assess corporate performance improvements, published literature has shown positive results for a number of industrial and service sectors.[264, 140]

Some notable examples include the aluminum manufacturing and processing industry for which a 1985-2000 study was conducted on a worldwide scale, electric power providers such as Electricite de France (EDF), information technology, and large insurance firms.([142], Ch. 6,7) Scenario-based planning was also successfully implemented at a marketing and ad agency to examine the soundness and economical viability of the global agency business model in the context of this industry's evolution over the second half of the 20th century, particularly in lieu of the numerous takeovers and mergers during the late 1980's as well as the emergence of new business models and technologies in this sector.[264]

Significant efforts to incorporate scenario-based planning into product and service development have been made in recent years, recognizing that factors like globalization, the fast pace of technological development, and the awareness of environmental issues, have changed business paradigm. New products and services not only need to bring forth a solid business and market case, but should also be technologically feasible, and comply with social interests such as safety and environmental impact. The scenario-based approach in product and service development leverages on key factors of change to identify consumer needs and preferences, develop concepts that directly address them, and guide strategic allocation of resources such R&D investments. Though scenarios and concept development activities have been extensively studied and matured over the past decades, a systematic usage of scenario-based futures in concept development is yet to be observed.[211]

Applications of scenario-based strategic planning are also abundantly found in the public sector, where corporate performance objectives are replaced with ones whose scope

is broader and where the boundaries between social, economic, security, environmental, and regulatory factors, among others, are easily blurred. Local governments have successfully used scenarios for long term regional planning and development, policy formulation, and regulation of critical infrastructure sectors such as utilities service providers and telecommunications.([142] Ch. 5) Transportation is a noteworthy example where the importance of contextual forces, the uncertainty associated with them, and the broad range of stakeholders and objectives, make the scenario-based paradigm well suited for implementation of regional critical infrastructure planning efforts. Although this observation is generally applicable to all modes of transportation, scenario-based planning is particularly well suited for airports, terminal areas, and civil aviation applications at the local, regional, and national scale.

For instance, a scenario-based strategic planning study was conducted for the greater Parisian metropolitan area for the 1995-2030 time frame. This study sought to determine the need for an additional airport serving air travel for this region, and support the selection of potential sites. The study incorporated considerations for regional economic development and environmental constraints.([142] Ch. 7)

In the U.S., NASA has progressively adopted the scenario-based paradigm to "more completely understand the potential environments in which NASA research will operate [...] and to design and construct solutions that work for a range of conditions."[302] For instance, in 1996 NASA's Office of Aeronautics sought the involvement of the National Research Council (NRC) to assist in its strategic planning efforts for the next 15 to 25 years. The NRC conducted a workshop involving subject matter experts from the Office of Aeronautics, as well as corporate strategic planning consultants from industry. The workshop sought to identify issues and items of key importance to aeronautics, the potential for evolutionary and revolutionary technology developments, and the role that NASA could play to address these issues by adequately allocating its resources on relevant technology development programs. To do so, the workshop produced a set of five global scenarios based on economic, policy, social, and technological development factors. [9] Some years later, in 2003, a similar study conducted for NASA by the Logistics Management Institute (LMI)

focused on characterizing the context in which operational concepts and NAS technologies proposed by NASA would be implemented, thus providing guidance on their formulation and definition, and enabling more accurate assessments of the overall societal benefits they can provide. To do so, the study focused on the interdependencies between top-level economic drivers, the role of air transportation and its economic impact, and the impact of ATM solutions for the NAS proposed by NASA. This required the review of models for economic aspects such as supply and demand, transportation mode choice, population and demographics, and a range of economic impacts. A set of operational-level scenarios was produced by this study, incorporating considerations for economic conditions, national security, health of the transportation infrastructure, political environment, and airport and airspace capacity among others, and mapping these high-level conditions to effects on volume and distribution of air travel demand. The scenarios that resulted encapsulate interdependencies among key driving factors, offer an operational-level characterization of demand within the greater economic context, and describe a variety of potential conditions in which air travel might operate so that unique needs can be identified and NAS solutions can be evaluated against these different conditions.[302] Other noteworthy efforts by NASA have focused on the integration of scenario generation tools with air traffic simulation platforms, so that researchers can efficiently generate and assess operational scenarios by manipulating relevant data structures that can be directly passed on to the simulation engine.[266]

The scenario-based paradigm has also been adopted by the JPDO, whose vision, formulation, and implementation of NextGen prescribes a profound understanding of the dynamics and interactions among key contextual driving factors, as well as a strong strategic perspective to identify goals and address needs over the long term. This strategic perspective is readily evident in the JPDO's document products, of which the Integrated Work Plan [194], the Concept of Operations [192], and the Enterprise Architecture [193] for the next generation air transportation system, are of particular importance. Additionally, in 2004 the JPDO's Futures Working Group (FWG) conducted a scenario-based planning effort from which five main global scenarios were produced "*with the intent of crafting air transportation strategies that would prove effective across the range of postulated future worlds.*"([197],

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p. iii)

The scenario-based approach has also gained widespread acceptance within global policy development efforts, such as those conducted by the IPCC in regards to world-wide environmental impact and climate change. The IPCC first developed long-term global emission scenarios in 1990 to assess the possible impact on climate change under a variety of socio-economic, demographic, and technological development conditions, among others, as well as the different options to mitigate this impact on the environment. As understanding about the driving forces of anthropogenic emissions and their impact on the climate change phenomenon have grown, these scenarios and the analytical models behind them have been revised a number of times. The 2000 IPCC update report features 40 scenarios stemming from four major storylines and spanning a long term scope of 100 years.[167] Other efforts in environmental systems analysis have also recently implemented a scenario-based approach, and examined the relationship between different types of scenarios and established environmental systems analysis tools.[156] Scenario planning has been notably underutilized in ecology and conservation sciences, though it has been vigorously adopted in the past decade to investigate the "ecological dynamics of alternative futures"[33]. Currently it is actively used by scientists to study interacting social and ecological processes, and in turn to better inform decision-makers responsible for ecological policy development.

8.4 Scenario Generation, Evaluation, and Selection for Strategic Planning

8.4.1 Types and Uses of Scenarios

The purpose, scope, and focus of the strategic planning effort are inherently captured in the way that scenarios are constructed and used. Thus, recognizing the different types and uses of scenarios is a good first step in revealing the variety of ways in which the strategic planning process, and the scenario generation process within it, can be implemented.

Strategic planning efforts can be generally described as quantitative or qualitative, depending on the extent to which numerical data and mathematical constructs are used. The qualitative or quantitative nature of the strategic planning process extends to the generation and use of scenarios. *Quantitative* scenario planning incorporates quantitative elements

such as numerical data to characterize scenario factors and drivers, mathematical relationships that relate scenario factors, and numerical techniques such as scenario probabilization or decision-making mechanisms. It often includes numerical models or simulations for the characterization of contextual conditions, characterization of system performance, and/or the evaluation of different strategies. Software applications are key enablers of quantitative scenario planning and represent an important element of its analytical capabilities. On the other hand, *qualitative* scenario planning is more heavily reliant on people's perception of factors, both external and internal to the organization, how these factors interact with each other, and on their intuition about to how those factors may evolve in the future. It therefore heavily stresses on the participatory aspects of scenario planning, and relies on individual's creativity and expertise for analytical purposes.[44] However, as the number of factors and their interactions grow, and the behavior of the organization/system, or its environment, become more complex, the need for quantitative models becomes more prevalent.

Probability-based scenarios are related to *quantitative* scenarios in the sense that their foundation is a mathematical treatment of scenario variables and their relationships, which can be exploited in a variety of ways to explore or manage uncertainty. Consequently, this type of scenarios rely on numerical models and computational capabilities as fundamental enablers. A common approach for scenario probabilization makes use of a cross-impact matrix that lists major drivers and contains the likelihood and impact of each variable combination. A column (or row) sum reveals a total likelihood for each scenario that allows the selection of the most likely conditions. *Probability-based* scenarios are most commonly used by engineering firms and utilities providers, but have had minimal adoption for corporate planning efforts.[280]

Scenarios can also be classified as normative or explorative. A *normative* scenario is one where the future state is first defined, and using that future state as a starting point the analyst works backward in time to the present to develop the path or storyline for that scenario. This approach is sometimes referred to as *back-casting*. In this approach, strategies can be formulated by investigating what actions need to be made at different decision points so that the prescribed end state occurs.([142] p. 122) On the other hand,

an *explorative* scenario begins from the present state and explores the myriad of possible decisions and outcomes, revealing the end state that would result thereof.

Scenarios can also be characterized by key factors of change. Change factors can be categorized as political, economic, social, technological, and ecological, or *PESTE*. For concept development, scenarios can be formulated as *market-driven*, *technology-driven*, or *society-driven*, based on how available data about change factors is purposely filtered to create scenarios. For example, scenarios that depict the U.S., Asia, or the European Union as world leaders are considered to be society-driven. Scenarios that focus on how consumer values and preferences change over time are market-driven. Technology-driven scenarios focus on how the emergence of some technologies in fields like biomedicine or information dramatically change various aspects of life. [211] An *event-driven* scenario focuses on a specific event, whether real or notional, as a key factor of change, as well as on the impact that such an event can have on an organization so that specific strategic implications can be identified.[280]

Scenarios have also been classified in terms of their purpose or intended use within a strategic effort. In fact, misunderstandings within an organization's leadership about how scenarios will be used and what role will play in the planning task has often led to failure. *Decision-driven scenarios* are used to inform and support the development of sufficiently specified strategic choices. These scenarios focus on the specific uncertainties directly affecting a strategic choice which is often confined to the short or medium term, such as the launch of a new product or service. The scenario generation and planning effort is heavily reliant on quantitative data and analyses, as well a on internal industry expertise, and use scenarios to test strategic options and evaluate them relative to one another. In contrast, *vision-driven scenarios* are more abstract and are built on broad, large scale drivers usually in the context of long-term time horizons. These scenarios are used as an educational tool for top and middle management and seek to instil a collectively perception of possible futures, the potential need for change, and to develop strategic ideas. Since the emphasis is on broad perspectives and divergent thinking, an organization rarely has the internal expertise to generate these scenarios, and relies on external resources.[61]

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Although scenarios reveal an uncertain environment beyond that of forecasts, historical trends are sometimes purposely incorporated into scenarios. A *trend-based* scenario is one that, much like a traditional forecast, uses existing trends of the past and extrapolates them into the future. A common perception is that trend-based scenarios describe futures that are most likely to occur, perhaps because they closely follow patterns that have been observed in the past and carry the implicit assumption that these patterns can be expected for the future. However, it has been recognized that trend-based scenarios are more likely only whenever the contextual evolutionary rate is sufficiently slow, making the continuation of past and current trends more plausible. However, contextual changes may occur more dramatically and more frequently, making trend disruptions, rather than trend continuity, more likely.([142] p. 121)

For the most part, these general characterizations of scenario types and uses are *not* mutually exclusive, and should not be interpreted as a rigid classification scheme. On the contrary, analysts must draw from this pool of scenario types and adequately combine features that are best suited for the particular purpose, scope, focus, and resource limitations/requirements of the strategic planning effort. In this sense, it is valuable to identify the key features of the terminal area strategic planning problem, so that scenarios can be constructed accordingly.

It is easy to observe that strategic planning for terminal areas, particularly for operational-environmental performance, can be best classified as a *decision-driven* effort. This problem deals with the selection and implementation of terminal area solutions such as additional runways, a variety of new taxiway additions and modifications, a wealth of operational and environmentally-oriented modifications to arrival and departure procedures, and multiple operational improvements in aircraft movement accuracy and throughput, among several others. The portfolio of possible strategic choices, while abundant, is nonetheless well defined and features long development and implementation cycles as a common trait across all choices. In turn, the temporal scope is naturally placed on the medium term, rarely spanning more than 30-40 years. Given that this planning effort ultimately centers around the justification of strategic choices, the evaluation of terminal area solutions must be well documented

and *quantitative* in nature. For this reason, and also based on the well known complexity of airport performance and its contextual factors, the evaluation of strategic solutions prescribes the use adequate modeling and simulation capabilities, imposing requirements on the availability of quantitative data, and benefiting from internal industry/operator expertise, though the latter may be *qualitative* in nature. Given its dependence on contextual factors and the adoption of a medium term scope, the terminal area planning problem also places special attention on key uncertainties of interest such as the evolution of demand factors, shifts in domestic policy stance, and possible changes in regulation.

Some important *vision-driven* features must be also be recognized, and adequately incorporated, into the strategic planning for terminal areas. For instance, the attention placed on large-scale drivers is paramount in developing internally consistent views of the world on medium and long term term scope. Thus, they can be accounted for and, if possible, mapped to lower-level factors that carry uncertainties is of interest.

Recognizing that terminal area operations are to a great extent shaped by the values and preferences of the traveling public, planning may have a *market-driven* focus, at least to the extent to which the characterization and modeling of the relationship between demand factors and operations is deemed necessary. On the other hand, the clear emphasis placed on terminal area solutions that enable operational and environmental improvements prescribe a strong *technology-driven* focus.

8.4.2 Formulations of the Development Process for Decision-Driven Scenario Sets

Having recognized that scenarios for the strategic planning of airports and terminal areas are primarily *decision-driven*, the question that logically follows is "how are scenarios, particularly decision-driven scenarios, generated?" A survey of published literature helps answer this question, and reveals a wide variety of scenario development processes that have been formulated and documented since Kahn's original inception of scenario-based strategic planning. Each of them leverages on new methodologies and techniques, advances in analytical and computational capabilities, and lessons learned from practical applications, seeking to address key issues and shortcomings identified in alternative approaches

while tailoring to specific a purpose, scope, and focus of interest.

To understand why there is such a wealth of scenario development formulations it is crucial to recognize the nature of this practice for what it is. As Coates points out, answering the question "How are scenarios created?" is comparable to answering a question like "How do you paint a portrait?" or "How do you write a poem?" Someone can receive training, study previous works known to be of good quality or possessing desirable traits, and then practice while implementing the general guidelines and rules learned. However, and recognizing the inherent redundancy of this argument, the only way to create a scenario, or to generate an art piece, is to actually do it. Moreover, the only way to create a *good* scenario set, or a *good* art piece, is to have the talent and the skills to do it. In other words, guidance and instruction received about basic techniques or a general process is an important part of scenario generation, but just as important is having the skill or the "feel" to create good scenarios that comes with practice and experience.[49]

With this observation in mind, it is easy to appreciate that different experts and authors have created their own formulation of the scenario development process based on their own experience. As will become evident later in this section, there is abundant similarity among scenario development process formulations proposed by noteworthy authors in the field, particularly in terms of fundamental steps or components of the process. In fact, the French futures school *La Prospective* identifies three fundamental steps in scenario development that have been widely recognized through the field: ([143] p. 22)

1. The definition and identification of dependent and independent variables of interest.

2. The analysis of stakeholders and actors, particularly in terms of their roles and strategies.

3. The generation of internally consistent or plausible scenarios based on assumptions about the relationships between variables.

These steps are readily recognizable in some form or another within many of the proposed approaches reviewed in section , and are particularly evident in the work of students of *La Prospective* such as Godet.

The term 'development' appropriately captures the nature of the process whereby scenarios are created, downselected, tested, and refined. On the other hand, there are also differences among formulations that collectively embody complementary approaches of particular relevance to the strategic planning problem of terminal areas. Thus, the purpose of this section is not to provide an exhaustive survey of all scenario development formulations, but rather to illustrate the fundamental steps and unique features of formulations found to be of particular relevance to this thesis and proposed by noteworthy figures in the field.

After the publication of Kahn's work in the early 1960's, a variety of formal methods related to scenario development were actively researched and documented, particularly by the RAND Corporation. Some of the early work focused on scenario generation as an expert-based artifact where reaching stable agreement among experts and supporting structured decision-making was identified as a major challenge. Efforts in this area yielded the Delphi method, a formalized and structured approach for expert opinion elicitation pioneered by Dalkey, Helmer [67], and Brown [35], in the 1960's and 1970's, that has since been continuously implemented and documented. Another well-known body of work addresses the study of interactions among contextual factors in scenarios, and the techniques with which these interactions can be efficiently characterized and measured. The cross-impact method developed by Gordon, Hayward,[145] and Helmer [154] in the late part of the 1960's and throughout the 1970's, laid the foundation for the development of formalized methods of scenario probabilization and other quantitative techniques that have been subject of continuing research and implementation. Seminal work was also conducted during the 1970's at Royal Dutch / Shell, particularly by Wack and Newland [294] who pioneered qualitatively-driven to scenario development, formalized as the intuitive logics approach, and which was effectively implemented and vastly documented during that decade.

Since then the scenario-based planning paradigm has grown into an entire field of its own, overlapping significantly with older disciplines such as forecasting and futures studies. The advent of computer-based applications and the maturation of the scenario development toolbox has enabled very complete and exhaustive formulations such as that by Godet, illustrated earlier in in Figure 40, where a number of well structured tools and techniques

are associated with each step in the scenario development process, and implemented based on the unique conditions and features of the scenario planning effort.

A noteworthy approach proposed by Courtney focuses on decision-driven scenarios and is based on the tenet that the effective management of uncertainty in strategic planning is one of the fundamental reasons (if not *the* fundamental reason) for adopting the scenario-based paradigm, and thus that the way in which scenario sets are constructed should logically reflect the level of uncertainty observed. Since uncertainty can be manifested in varying levels, Courtney argues that "*there is no one-size-fits-all approach for developing effective decision-driven scenarios.*"[61]

In this formulation, strategically relevant information can be readily available, unknown but attainable through appropriate analyses and resource allocation, or unknowable. Uncertainty associated with this unknowable information, referred to as *residual uncertainty*, can be classified into four main categories which prescribe particular approaches for scenario development. *Level 1* residual uncertainty is negligible and can be considered irrelevant for strategic planning. Instances of *Level 1* uncertainty are very uncommon, but when they occur, the available information is sufficient and well suited for a forecast-based planning effort. On the opposite extreme is *Level 4* uncertainty, where uncertainty is prevalent across a multitude of dimensions which interact and coalesce to generate completely ambiguous and uncertain environment where any strategically relevant aspect is impossible to assess. Much like *Level 1*, *Level 4* efforts are extremely rare, and often times evolve over time into *Level 2* or *Level 3*.[62, 61]

In instances of *Level 2* uncertainty the future can be characterized by a relatively small number of *discrete scenarios*, resulting from the mutually-consistent combinations of distinct and sufficiently defined outcomes of interest. These scenario sets are said to be Mutually Exclusive, Collectively Exhaustive (MECE). Whereas each discrete scenario can be readily characterized, planners are unable to determine which of these scenarios will play out. This level of uncertainty typically occurs whenever major decisions with distinct alternatives will take place beyond the control of the organization. Consider for example air transport service providers facing the prospect of a government decision about whether or not to implement

regulatory measures such as environmental levies, a carbon cap-and-trade system, or the use of alternative fuels. Once scenarios are identified an evolutionary path of events for each scenario is described along with the implications that each scenario brings to the organization. Traditional risk assessment techniques can be readily implemented to the *Level 2* set of discrete scenarios, combining the valuation and likelihood estimation of each scenario into a risk index. Similarly, game theoretic techniques can be implemented if scenarios depend on competitor's strategy or actions. The evaluation of strategies with a *Level 2* set of discrete scenarios also requires that planners consider how implementing those strategies may affect the probability of occurrence of that scenario.[62, 61]

Level 3 uncertainty is observed whenever there is a number of major contextual factors characterized by variables whose values lie within continuous ranges. Common drivers of change captured by these variables include economic indicators, demand fluctuations, technology adoption rates, or performance levels of future assets, among others. *Level 3* uncertainty can be observed in cases where demand levels are uncertain such as new markets, whenever key economic variables such as fuel price are particularly volatile, or in industries subject to continuous technological refresh. Due to the continuous nature of key variables, a discrete set of scenarios does not occur naturally and thus a finite all-inclusive list of scenarios cannot be generated. Consequently, the development of a relevant and meaningful scenario set is particularly intensive and challenging. In fact, Courtney recognizes that "*since there are no other natural discrete scenarios in Level 3, deciding which possible outcomes should be fully developed into alternative scenarios is a real art.*"[62] In the absence of a formalized process for the construction and selection of *Level 3* scenarios, the following general rules and guidelines are provided. The first and most obvious issue is that the continuum of the scenario space must be discretized so that a finite set of scenarios can be generated. The level of granularity achieved with this discretization is contingent on the number of scenario variables and the resources available for the planning effort, recognizing that higher discretization granularity will yield an exponentially growing number of scenarios. Courtney indicates that the final set of scenarios should contain no more than four or five, as greater numbers of scenarios easily hinder decision making and compromise

expert participation. The scenario set should also be representative of the entire continuum of possible outcomes, adequately bounding the scenario space. Achieving this quality is particularly difficult because "*scenarios that describe the extreme points of in the range of possible outcomes are often relatively easy to develop, but rarely provide much concrete guidance for current strategic decision.*"[62] Courtney also notes that these extreme cases are also usually the least plausible, and thus the final scenario set must collectively account for the range of probable futures. To attain an adequately representative, and sufficiently small sample of the probable range of outcomes in the continuous scenario space, the handful of scenarios chosen should be sufficiently distinct and avoid redundancy that can obfuscate unique implications for strategic decision making.[62, 61] These guidelines are valuable in the sense that they identify the features that the final set of scenarios should have, but as noted earlier, a formalized technique for discretized and sampling the continuous scenario space to construct scenarios is not provided. Moreover, there are no considerations for the possibility of generating a large set of scenarios and conducting a downselection process via adequate evaluation and ranking mechanisms.

Although the scenario generation approach is considerably different from that of *Level 2* uncertainty, the way in which scenarios are *used* for strategy evaluation is the same in practice. However, unlike *Level 2* scenarios, this formulation only allow for the definition of bounds to the continuous ranges of values, but does not allow for the probabilization of representative scenarios. Nonetheless Courtney notes that it is possible for planners to evaluate how strategies may affect the likelihood of some points along the continuum of values.[62, 61]

Based on these characterizations of the varying levels of uncertainty, the operational-environmental tradeoff of terminal areas can be best described as being a *Level 3* problem, dominated by major change drivers that are described by continuous variables for which range bounds can be defined. However, as is often the case, some elements from the other levels of uncertainty may be observable and even desirable. For instance, since air transportation is largely driven by a regulatory body, it is not unlikely that it would face discrete

scenario options based on regulatory decisions with discrete outcomes. Also, the risk assessments available to *Level 2* scenario sets leverage on established techniques of probability applications and valuation techniques. A risk assessment for *Level 3* scenarios is highly desirable but but impossible according to Courtney's categorization. Thus, attention is turned to *Level 3* decision-driven scenarios, observing that *Level 2* techniques of probabilization and valuation may be applicable if properly modified or reformulated, and recognizing the inherent complexity in the construction, evaluation, and selection of representative scenarios for which many methods lack detail. In fact, the strategic planning community has recognized the complexity of the scenario generation process, especially when incorporating the probabilization of competing scenarios, as well as the vital role that computational and software capabilities play in it.([20], p. 59)

With this in mind, a formulation of particular relevance is proposed by Schoemaker, which illustrates the fundamental components of the scenario development process and offers some important guidelines for its effective implementation. This process begins with a definition of the scope of the planning effort. This includes the entities and organizations, their different aspects and issues, and the time frame of interest. Major stakeholders are then identified with a special emphasis in who has an interest in the issues at hand, who can affect them, and who can be affected by them. Schoemaker argues that the mismanagement of uncertainty results in the overprediction of change whenever unknowable information is not properly bound, or in the underprediction of change whenever unknowable information is neglected and planners are biased towards knowable information such as historical trends. Seeking to access a middle ground between the two and avoid both mistakes, basic trends and key uncertainties believed to affect elements within the scope of interest are identified and researched to addressing known and unknowable information respectively. As an archetypal example, consider the continuing trends expected in government policies within a presidential term, and the uncertainties associated with the outcome of the following election. However, it is important to note that stakeholders and actors with a greater level of control can influence trends that would otherwise be perceived as external and unchanging. Moreover, uncertainties about stakeholders or other contextual

factors can interact with factors believed to be known, resulting in significant changes on trend extrapolations.[263, 264]

This body of information constitutes the building blocks of scenarios. Several approaches can be considered for scenario construction, such as identifying extreme cases characterized by all positive or all negative trends and outcomes of unknown events. Alternatively, scenarios can be defined according to a thematic characterization such as high or low degree of continuity, turmoil, preparedness, etc. Schoemaker also suggests using the top two uncertainties and crossing them to identify discrete combinations, but warns that this approach is only applicable when some uncertainties are clearly more important than others. Regardless of the approach taken, a general principle in formulation is that it is more important to circumscribe all possibilities than to explicitly account for all them. Thus, scenario planners benefit from choosing representative low-medium-high settings for contextual factors instead of an innumerable number of them within the range of interest.[263, 264]

Once scenarios have been built, they are checked for consistency and plausibility, checking that combinations of trends are compatible with the time frame of interest, that combinations of uncertain outcomes do indeed make sense together, and that major stakeholders are not misplaced in positions or where they are not likely to allow themselves to be in, or not likely to stay in for too long. In turn, many of scenarios are discarded from the initial set due to implausibility, internal inconsistency, or lack of relevance to the strategic scope. Those that remain will embody strategically relevant themes, and are given a title that encapsulates the story told by that scenario. Schoemaker calls these *learning scenarios* because the serve as a focal point from which further research is conducted regarding trends, uncertainties, and understanding of stakeholder behavior. In this next step of additional research expert opinion for all elements outside the areas of competence of the organization is likely required. Quantitative models can then be considered to formalize interactions, capture sufficiently known behaviors, and bound uncertainties to prevent scenarios from straying into the implausible. Thus, learning scenarios are synthesized into *decision scenarios* by iterating through all the steps to check that the final set addresses the real issues faced by the organization. As a final test for the selection of decision scenarios, Schoemaker

suggests that analysts review each of the against the following criteria: relevance, internal consistency, archetypal differentiation (i.e. all decision scenarios are generically different futures rather than variations on one theme), and stability of the final state (i.e. decision scenarios should not have a highly transient end state). However, Schoemaker offers evidence that participants in scenario development tasks commonly assume intercorrelations between uncertainties that are inconsistent, and that may prevail within scenarios despite a final internal consistency test [263, 264]

This formulation for the scenario development process readily reveals fundamental components that can be easily recognized in most other formulations, and that is well aligned with the three basic steps of *La Prospective* previously mentioned:

- First, the scope of the strategic planning effort is used to define the *scenario space*, which contains all known and unknowable factors of interest as well as interrelationships among them, comprising the building blocks for scenario construction.

- Next, a primary or preliminary set of scenarios is constructed, encompassing the breadth of the scenario space, and revealing its edges and limiting conditions.

- Based on the size of the preliminary scenario set, a secondary set of scenarios can be downselected from the first one. This process makes use of evaluation criteria against which all scenarios are evaluated, and potentially ranked.

- Once defined, the secondary set of scenarios is further researched and refined for strategy formulation and evaluation in subsequent phases of the strategic planning process.

These fundamental components of scenario development provide a procedural roadmap well suited for the assessment of specific formulations and the identification of methodological strengths and weaknesses. Schoemaker's formulation provides a comprehensive description of major elements in the planning scope that can be used as building blocks for scenarios, and effectively relates these factors back to the planning scope during the downselection process. The differentiation between known and unknowable information is

also very beneficial in structuring the definition of the scenario space, and guiding the focus of planners to trends and key uncertainties. However, there is little guidance on how known and unknowable factors should be treated. For instance, the process does not provide any indication about the number of variables that should be carried, whether factors should be carried as continuous or discreet variables, or about the appropriate number of settings for discreet variables. Also, the techniques suggested for scenario construction, such as the exploration of extreme cases, thematic characterization, or cross-combination of discreet settings in primary uncertainties, are somewhat lacking in methodological rigor. For instance, extreme cases can be identified for ordinal factors, but not for uncertainties associated with multiple categorical settings. On the other hand, the use of thematic characterization for scenario construction can easily become unmanageable as the degrees of freedom, introduced with every additional factor, grows rapidly. The idea of cross-relating uncertainties is instrumental in scenario construction or in scenario downselection, and as will be shown later is recurrent across several other formulations. However, this cross-relation should ideally be conducted for all uncertainties. Limiting this exercise to the two most important uncertainties not only prescribes that they exist and can be readily identified as such, but more importantly reveals that this formulation lacks a technique to rigorously explore cross-relations among all uncertainties in a way that is manageable and justifiable in terms of resource commitment. Finally, Schoemaker identifies plausibility and consistency as the main evaluation criteria for the downselection process. The the use of consistency as an evaluation criteria follows logically from the necessary internal consistency condition inherent in the definition of a scenario. Plausibility may be an intuitive choice of evaluation criteria in the sense that it can help avert the allocation of resources to the development of a scenario that is so unlikely that it is considered to be outside the scope of interest. However, eliminating highly unlikely scenarios may prove to be unwise, particularly when recognizing that history is plagued with dramatic and unexpected events once considered implausible, and that the scenario-based paradigm attempts to account precisely for such instances. This formulation is unclear about how consistency and plausibility are measured, whether a qualitative assessment suffices or whether a more rigorous technique is beneficial

or necessary. In a similar fashion, Schoemaker suggest using relevance, internal consistency, archetypal differentiation, and end-state stability, as criteria in a final test to confirm or refine downselection of decision scenarios, but offers no indication on how they ought to be measured, nor how assessments across all criteria should be combined in the evaluation of scenarios. More importantly, Schoemaker does not provide any guidance on the number of scenarios that should be developed, or the relationship between the number of scenarios, the availability of resources, and the scope of the planning effort.

Many of these issues and questions are explicitly addressed in alternative formulations. Chief among them are those proposed by Coates [49] and Godet [142]. Coates' formulation of the scenario development process begins with the identification and definition of the scope of interest, or what he refers to as the *universe of concern*. Relevant variables are then identified, noting that no values need to be assigned at this point. Contextual factors commonly used as variables include cost data, environmental concerns, market size, and demographics. Coates notes that this activity is resource intensive as it often involves continuous rearrangement of variables within a hierarchical structure to focus on a working list of variables at an adequate level of abstraction and detail. From a practical perspective, the number of variables used to develop complex scenarios can range approximately between 6 and 20, depending on the availability of resources and the scope of the planning effort.[49]

Similarly, Godet suggests that scenarios be comprised of four to six hypotheses, following his treatment of scenarios as sets of hypotheses, rather than sets of variables, where a hypothesis embodies a given contextual factor. However, this treatment of contextual factors as hypotheses leads to a binary construct where either the hypothesis H is true or that the complement hypothesis H' is true. Thus, Godet notes that using only two hypotheses yields a set of four possible scenarios that oversimplifies the problem, whereas using more than six hypotheses results in a combinatorial space with a very large number of scenarios for which it is generally difficult to attain subject matter expert participation([142] pp. 111-112) A similar assessment is provided by Berkhout and Hertin who additionally recommend against the use of three scenarios because it "*often leads to the identification of one 'best guess'.*"[30]

Scenario themes illustrating possible futures of particular interest to the organization are then identified. Theme identification is a highly judgemental and creative process that, according to Coates, does not follow specific rules and is heavily dependent on scenario building experience. As a general guideline, however, each theme uses one or two variables as primary or dominant characteristics. For instance, a scenario theme can be "An Environmentally Conscious World", where technology development, policy, and regulatory factors are geared towards environmental stewardship. It is common to find between 4 and 6 themes in scenario building efforts. Scenarios are then constructed by taking each theme and identifying adequate values for each variable.[49] Consequently, scenario sets will usually contain 4 to 6 scenarios, although multiple scenarios may sometimes be desirable for a given theme and can be developed as relatively small perturbations in some of the variables. This approach is illustrated in the IPCC scenario set, where a total of 40 scenarios were generated from four major storylines.[167] It is also worth noting that in Coates' formulation the downselection process occurs with scenario themes, and not with the actual scenarios as in Schoemaker's, and thus a preliminary scenario set is not formally defined. Similarly, the use of themes to identify variable values in the construction of scenarios is slightly different between these approaches, featuring a a more formal definition and more instrumental role of themes in Coates' approach.

Variables can be quantitative or qualitative, but the values chosen must be in common agreement with each other. In other words, the internal consistency of the scenario is achieved by selecting variable values that are plausible as a collective. In fact, Schoemaker recognizes that each scenario illustrates how different elements might interact, and that when these interactions can be captured and formalized in a mathematical form then quantitative models can be created, or at least used to check for the internal consistency of each scenario.[264] The scenario construction task also reveals whether certain variables are irrelevant to all themes and can be dropped, or unimportant in only for some themes, in which case they can be treated neutrally.[49]

Godet indicates that *morphological analysis* has been shown to be a valuable tool for the generation of both scenarios and strategies.([142] pp. 124-125) Morphological analysis is an

exploratory tool developed in the late 1960's by Fritz Zwicky, where a morphological space is generated by means of morphological matrix, also referred to as a matrix of alternatives, and a cross-consistency matrix. The matrix of alternatives is a hierarchical construct that lists elements, components, or general categories, as well as alternatives of interest for each component. Each component constitutes a dimension in the morphological space, and each alternative is a discrete setting along that dimension. The cross-consistency matrix relates all alternatives with each other on a pairwise basis and documents whether two alternatives can occur together, or are consistent with each other. In this way, a complete configuration can be defined by a combination of component alternatives with one component alternative chosen for each morphological component. Internally consistent configurations are those for which all selected component alternatives are consistent with each other. These two matrix constructs of morphological analysis are notionally illustrated in Figure 41. Given its exploratory nature, morphological analysis stimulates imagination and allows participants to systematically and rigorously investigate the entire space of possibilities.[310, 311, 312] Godet notes that morphological analysis lends itself very well for scenario generation because scenarios can be characterized by a finite number of scenario variables and a finite number of settings for each of them, and because scenarios are subject to an internal consistency condition. However, the total number of configurations grows very quickly with the number of components and the number of alternatives. In other words, the total number of scenarios grows very quickly with the number of scenario variables and the number of settings in the variables. Since the large number of combinations can be overwhelming and may hinder the exploratory process, and limits on the size of the scenario space oversimplifies the problem, planners can incorporate selection criteria such as preference factors, constraints, or exclusion factors.([142] pp 126, 195)

After a scenario has been constructed, a scenario narrative is often written to elaborate and describe it in more detail, and to characterize lower level variables that were not explicitly used in the scenario construction phase. Finally, a review of all scenarios in the set is performed to check for internal consistency and relevance.[49] Similarly, Godet proposes five conditions as evaluation criteria for the quality and usefulness of scenarios:

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Figure 41: Morphological Matrix and Cross-Consistency Matrix

relevance coherence, plausibility, importance and transparency.([142] p. 109) As mentioned earlier, Schoemaker also suggests relevance, internal consistency, archetypal differentiation, and end-state stability, as evaluation criteria to test and downselect scenarios.

It is worth noting that despite suggesting these criteria, none of the aforementioned methods is sufficiently explicit about the exact means in which these criteria ought to be measured, leaving the exact mechanism for evaluation open to interpretation, and thus mostly relegated to qualitative assessments. In fact, it has been recognized that relevance and consistency, often treated as plausibility, are key criteria for scenario evaluation continuously mentioned in the literature but never discussed in sufficient detail. The conspicuous absence of a rigorous measurement scheme for these criteria may be explained by the fact that they are generally attributed to the seminal work on scenario development conducted by Wack at Royal Dutch / Shell, which is entirely qualitative. Alternative scenario evaluation criteria have been proposed, but are strictly limited to qualitatively-driven efforts in the vast majority of cases. For instance, Chermack suggests use of 'the six senses', proposed by Daniel Pink's in his 2006 book 'A Whole New Mind'[246], as evaluation criteria for qualitative scenarios. These six criteria are design, story, symphony, empathy, participation/play, and meaning.[44] Despite these contributions, there is no consensus on a formalized method for scenario evaluation, particularly for the quantitative approach to scenario development.

8.4.3 Challenges and Opportunities for Scenario Generation, Evaluation, and Selection

The survey of proposed approaches collectively provides a framework of fundamental steps for scenario development that is notably general and flexible, allowing it to be tailored to the unique features and needs of particular applications. Yet, the general observation is that these process formulations are inevitably ambiguous and nebulous in many procedural respects, and that scenario development has been widely recognized as an art form as much as a discipline, relying heavily on ample experience. On the other hand, this body of work clearly identifies and justifies with adequate specificity the desirable features and characteristics sought after in scenario sets developed for each application. In this sense, there is little or no argument in terms of the approximate number of scenario variables that should be used, the approximate number of scenarios contained in a set, or scenario characteristics such as internal consistency, plausibility, or relevance. Consequently, scenario development methods provide a clear picture of *what* the final scenario should look like, but only offers a generalized framework describing *how* that product should be developed.

The inevitable lack of procedural rigor in scenario development represents important challenges in practice, but also offer opportunities for new research and improvement. Scenarios for strategic planning efforts applications on airports and terminal areas, particularly those related to operational-environmental performance, have been recognized to be primarily decision-driven and pertinent to Level 3 uncertainty. Thus, the following challenges and opportunities are identified:

First, there is a need for a formal method to sample the continuous scenario space under Level 3 uncertainty, once it has been properly discretized, to generate a representative set of scenarios that collectively accounts for the range of probable futures while not exceeding the recommended amount of four to six scenarios. It is crucial to recognize that the combinatorial structure that results from the discretization of the space will produce a substantial amount of scenarios. Suppose for example that, in accordance to scenario development guidelines presented before, a scenario space is defined by only six variables. Additionally, in order to avoid a discretization scheme defined purely with extreme values,

a single 'middle' value is provided as well for all variables. The resulting combinatorial set holds 6^3, or 216 scenarios, from which only four to six will be chosen. Even if many of the scenarios constructed are eliminated based on consistency / plausibility, the issue of implementing an evaluation method with which to assess, rank, and select the final handful of scenarios still remains for the subset of consistent scenarios. The challenge of this task is compounded by the fact that there is yet to be consensus on a set of evaluation criteria for scenarios, and that those that have been proposed are adequate in principle but, for the most part, inadequate in practice because they are inherently qualitative. The need for a quantitative and rigorous method for scenario evaluation is thus revealed.

Within the review of scenario types, uses, and development formulations, a method for quantitatively evaluating and ranking scenarios was identified, namely, the probability-driven approach noted in section 8.4.1. Additionally, Courtney's scenario development formulation is based on the observed level of uncertainty, and identifies probabilization and valuation of discrete scenarios as enabling techniques for risk assessments under *Level 2* uncertainty. Courtney states that this approach is not applicable to *Level 3* uncertainty because it is impossible for planner to identify what regions of the continuous scenario space are more likely than others. If this particular view is challenged, there is an opportunity to apply scenario probabilization and valuation on the discretized space to evaluate, rank, and select scenarios based on their respective quantitative measure of risk. Thus the risk assessment technique that is used to evaluate strategies for a prescribed set of *Level 2* scenarios, can be applied to evaluate and select *Level 3* scenarios.

The choice of risk as a quantitative measure is well suited for scenario evaluation and selection. First, the effective management of uncertainty and risk is a fundamental principle, and the primary incentive, in the use of a scenarios for strategic planning. Thus, its adoption as a scenario evaluation criterion constitutes an ideal alignment with the essential principles of the scenario-based paradigm. Secondly, it leverages on accepted probabilization and valuation practices that have already been abundantly implemented in scenario development, and can leverage on adaptations of the probabilization approach proposed in this thesis. Third, the selection of scenarios based purely on probability is subject to

criticism as it is easily affected by participant bias, often tending to established trends, and neglecting the occurrence of events or conditions commonly perceived to be very unlikely. On the other hand, a selection of scenarios based purely on consequence valuation inherently ignores plausibility, and thus compromises the condition of internal consistency for scenarios that can in turn put in question its relevance within the scope of the strategic planning effort. Given that risk contains a likelihood component and a valuation component, a risk-based evaluation and selection method can concurrently account for scenarios across a range of likelihood values and degrees of consequence.

Another important challenge is the construction of scenarios, recognized as a complex and difficult task even when the scenario space has been properly defined. The identification of variables of interest addresses to a great extent the condition of relevance of scenarios with respect to the scope of the strategic planning efforts. On the other hand, the condition of internal consistency, or plausibility, of scenarios is not directly addressed by the definition of the scenario space, but rather depends on the construction mechanism itself. Inconsistencies among uncertainties and trends were noted to prevail in many occasions, particularly in the absence of a formal method of evaluation for plausibility, even if final tests and revisions are made on the scenario set. However, it was also noted that when interactions among variables can be captured and formalized in a mathematical form, then quantitative models can be created, or at least used to check for the internal consistency of each scenario. This observation is closely related to the discretization of the continuous scenario space for *Level 3* uncertainty, given that scenario construction is directly dependent on the combinatorial structure that results from the discretization process. Thus, the consistency/plausibility condition in the construction of scenarios from a finite set of discrete components is inherently associated with the definition of possible combinations.

Morphological analysis directly and explicitly addresses the need for a systematic and rigorous mechanism whereby the scenario space is adequately structured, and a consistency or plausibility assessment is embedded in the construction process of scenarios as unique combinations. Moreover, the plausibility of scenarios can be directly related to a measure of probability, for which the probability-driven scenario approach discussed in section 8.4.1

exists. Given that probability-driven scenario generation makes use of a cross-impact matrix akin to the cross-consistency matrix of morphological analysis, there is a significant opportunity in the integration of both approaches to quantitatively assess and enforce scenario plausibility in the construction process. Furthermore, the use of probability in the morphological treatment of scenario plausibility is synergistic with the option of using risk as a scenario evaluation criterion.

With these challenges and opportunities for methodological improvements under consideration, the following sections discuss morphological analysis in more detail, and examine the applicability of probabilization for scenario consistency and risk for scenario evaluation within morphological analysis framework.

8.5 Proposed Improvements for Morphological Scenario Generation

8.5.1 Morphological Analysis in Scenario Planning

Since its inception, morphological analysis has been used abundantly across a wide range of applications and has matured significantly. In particular, it has been continuously implemented for configuration exploration and selection in systems design applications, and has been been recognized as fundamental component in the systems design toolbox.[185] Noteworthy applications include design studies for numerous aircraft concepts such as next generation regional air vehicles [10] and supersonic transports [187, 148], where vehicle taxonomy is tightly coupled with design requirements and is likely to deviate from trends observed on existing platforms.

To a great extent, the evolution and maturation of morphological analysis practice is rooted in the development of software applications and its implementation on a wealth of computer-based tools. For instance, morphological analysis has been successfully used to support optimization techniques suitable for discrete spaces, such as genetic algorithms [185, 187, 148]. Software applications such as the Interactive Reconfigurable Matrix of Alternatives (IRMA) have also been developed to support collaborative system configuration selection studies. The IRMA leverages on its interactive visual interface and on dynamic data structures that enable immediate matrix reconfigurability. This software application

also stores values for component alternative attributes such as cost or technology readiness, and uses these values to implement dynamic filters that capture stakeholder preferences and eliminate certain choices to facilitate the downselection process.[81] As noted earlier in section 8.4.2, Godet recognizes that filtering capabilities such as these are particularly valuable for downselection exercises as the total number of configurations in a morphological space grows very quickly and can easily become unacceptably large.

Implementations of morphological analysis for scenario exercises have have matured and become increasingly common in recent years.[255] Some noteworthy scenario studies using the morphological approach have focused on the development of preparedness and response strategies pertinent to diverse natural disasters and homeland security. Examples include response preparedness assessments for hazardous materials incidents [257], sabotage and attacks to nuclear power infrastructure [183, 254], assessment of disasters and extraordinary societal events [214], development of strategies for multi-hazard disaster mitigation [256], and protection of critical infrastructure segments such as airports and other operational resources of the air transportation system.[189] Similar to system configuration selection studies, the practice of scenario development using morphological analysis has also leveraged significantly on computer-based applications.[82]

For the most part, a morphological approach to scenario construction uses the matrix of alternatives to identify the various scenario variables that will be used, and the discrete settings or values that each scenario variable can have. Thus, each scenario variable is a dimension of the morphological space, and the values for each variable correspond to values along that dimension. In turn, the cross-consistency matrix identifies what variable settings are compatible or incompatible on a pairwise basis. Internally consistent scenarios are thus readily identified from the entire combinatorial set of possible scenarios.

In the vast majority of implementations the cross-consistency matrix documents pairwise consistency relationships via a binary scheme, namely a [0, 1] scale to denote 'consistent' or 'inconsistent', or alternatively 'plausible' or 'implausible'. For each unique scenario, the pairwise consistency values are combined to generate a single aggregate consistency value. This approach is logical and intuitive in principle, but it also results in an important

practical difficulty. Recalling that even moderately sized morphological scenario spaces produce a considerably large number of scenarios, or configurations, the scenario planner is still left with an unmanageable number of internally consistent scenarios, even when a large portion of all possible scenarios are discarded due to inconsistency. While this process is necessary to ensure plausibility, it fails to address the matter of selecting a handful of representative and carefully chosen scenarios. Moreover, published work on morphological scenario generation generally fails to identify any methods, techniques, or procedures by which the final scenario set is selected from the subset of consistent choices.

Consequently, while the use of a binary scale is sufficient to implement the consistency condition in the scenario construction process, and it is found to constitute common practice for scenario generation, it is also hereby recognized to be insufficient for scenario evaluation and downselection.

8.5.2 Higher Resolution Scales for Cross-Consistency

To address the downselection challenge it is important to recognize that the segmentation of scenarios into two subsets, namely a 'consistent' and an 'inconsistent' subset, is insufficient, and that a higher degree of differentiation between scenarios is desired. Thus, the key question that must be addressed is *how can the complete combinatorial set of scenarios be stratified with more than two categories?* The binary stratification of scenarios can be logically traced to the binary scheme for assessing pairwise cross-consistency. Consequently, using a scale in the cross-consistency matrix with more than two distinct values is logically expected to result in more than two scenario subsets, enabling a higher degree of resolution for scenario evaluation and ranking.

This specific concept is discussed and demonstrated by Jimenez, Stults, and Mavris, whose work illustrated the implementation of a four-value likelihood scale in the cross-consistency matrix for the generation and evaluation of scenarios relevant to terrorist attacks on air transportation infrastructure. The scale was composed of values [0, 1, 3, 9], based on a ratio scale augmented with the zero value, to represent qualitative likelihood assessments

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for scenario element pairs.[189][2] This work is of paramount relevance to this thesis because it illustrates how higher resolution scales for cross-consistency enable likelihood assessments, identified in the previous section as a promising methodological opportunity. Furthermore, it also illustrates how said augmentations to the cross-consistency scale readily result in a sufficiently differentiated stratification of the combinatorial scenario set, explicitly conducive to evaluation and ranking.

However, the aforementioned formulation does not treat probability in a mathematically rigorous form, but rather uses a basic scale to capture qualitative assessments of likelihood provided by experts and participants in the scenario development exercise. In order to produce a single consistency value for each scenario using this four-value scale, the approach proposes a product function to aggregate all the pairwise likelihood values associated with each distinct scenario.

$$L_{Total} = \prod_{i=1}^{j=i+1} \prod_{j=i+1}^{n} L_{i,j} \tag{8}$$

where L_{Total} is the aggregate likelihood value for a given scenario, $L_{i,j}$ is the [0, 1, 3, 9] pairwise likelihood value for scenario variable alternatives i and j, and n is the total number of scenario variable alternatives.

This approach reveals the need for the definition of an adequate aggregate function that will synthesize cross-consistency data documented with any level of resolution, binary or otherwise. The use of a binary cross-consistency scale made the aggregation of consistency values across scenario element pairs trivial, and thus it has remained implicit in the common practice of morphological analysis lacking an explicit treatment. Note however that an aggregate function *must* exist for the binary scale, and that in fact the function shown in Equation 8 is directly applicable. If all [0, 1] pairwise consistency values for a given scenario are aggregated as a product, the result can only have a value of zero or a value of one. If the aggregate value is zero, then the scenario is internally inconsistent. Conversely, if the value is one the scenario meets the condition of internal consistency.

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[2]Other than the work by Jimenez, Stults, and Mavris [189], there are very few examples of higher resolution scales for cross-consistency. One approach augments the traditional binary scale with a third option to denote "*these two conditions can co-exist, but are highly unlikely or uninteresting*"[256], and does not exploit the higher degree of resolution to rank scenarios.

The formulation of morphological analysis must thus be revised to account for any degree of scale resolution in the cross-consistency matrix, as well as to account for the need of an aggregate consistency function. This revised formulation can then be used to test whether scenario probabilization can be used within the morphological approach as a means to implement the consistency condition, and to test whether probabilization and valuation can be similarly used to implement a risk-based evaluation of scenarios to support ranking and selection.

8.5.3 A Revised Formulation of Morphological Analysis

The formulation of morphological analysis hereby presented does *not* constitute a variation of the methodology in any way, but rather expresses its fundamental tenets in different terms, broadening its scope to explicitly address the need for an aggregate function and to account for any level of resolution in the cross-consistency value scale.

The *morphological space* is an $n - dimensional$ hyperspace, defined by n components C_1 to C_n. Each component C_i has m_i alternatives a_1^i to $a_{m_i}^i$. The morphological space thus has a total number of component alternatives given by

$$\hat{n} = \sum_{i=1}^{n} m_i \tag{9}$$

A *morphological configuration* is defined by a unique vector of component alternatives

$$\overline{a} = [a_{g_1}^1 \dots a_{g_n}^n] \tag{10}$$

such that there is only one component alternative $a_{g_i}^i$, where $1 \leq g \leq m_i$, for each component C_i.

Relational information between all component alternatives is captured via a quantitative attribute, and expressed through the parameter H. The H parameter is a single scalar quantity defined for each morphological configuration that characterizes the collective relationship among its n morphological component alternatives. Hence, the H parameter for any morphological configuration in an n-dimensional space is said to be of nth order and is denoted as H^n.

By virtue of its order, relational information captured by a single value of H^n can also be expressed through and appropriate number of lower order H^k values, where $k < n$. Analogous to H^n, values for H^k are scalar quantities characterizing relational data between k component alternatives, and are said to be of kth order. Since the information quantified by the parameter H is relational by definition, the lowest order that H can assume is 2, where H^2 is a pairwise relationship between two component alternatives. H^2 values can be encoded in a triangular H *matrix* with $T_{(n-1)}$ pairwise relations.[3] Conversely, H^n can be calculated by means of an *aggregate function* f_a whose arguments are lower order values of H, H^k.

$$H^n = f_a(H^{k_1}, H^{k_2}, ...) \tag{11}$$

such that $2 \le k_i < n$ for all i.

Based on this definition, an attribute characterizing relational information between component alternatives can be used in morphological analysis to construct morphological configurations *if and only if* this attribute is an H parameter. The H parameter test can be expressed as follows:

An attribute J is an H parameter for an n-dimensional morphological space if

1. for each and all morphological configurations, J can be expressed as a single scalar value H^n characterizing the $n^t h$ order relational information.

2. for each and all morphological configurations, J can be expressed as scalar values H^k characterizing $k^t h$ order relational information, where $2 \le k < n$.

3. There exists an aggregate function f_a such that the nth order value of J can be expressed as a function of lower order values of J, such that that $H^n = f_a(H^{k_1}, H^{k_2}, ...)$, where $2 \le k_i < n$ for all i.

8.5.4 Test of Probability as an H Parameter

The H parameter test provides a means to examine whether probability can be used in its rigorous mathematical form within the morphological analysis framework to capture

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[3]The triangular number T_n is the sum of all natural numbers from 1 to n, and is the additive analogue of the factorial number.

relational data for scenario construction. Furthermore, if probability is shown to be an H parameter, and if sufficient numerical resolution is used quantify pairwise (H^2) probability values, then the resulting aggregate probability values (H^n) provide sufficient differentiation and stratification to allow for scenario evaluation and ranking. Note that since probability values have limitless numerical resolution, that is, can assume any value in the continuum of the range [0, 1], the issue of using sufficient resolution is trivial. Consequently, it is only necessary to test whether probability is an H parameter.

In more formal terms, clauses of the H parameter definition are used to test the following hypothesis:

- *Hypothesis 5*: Probability is an H parameter.

A survey of previous work on scenario construction and ranking using probability reveals some noteworthy formulations of particular relevance to the test of *Hypothesis 5*. Duperrin and Godet [80] developed a method that leverages on the use of the cross-impacts approach to incorporate the opinions of participants and explicitly account for the interdependencies between scenario factors expressed in those opinions. This work recognizes that the probability values elicited from participants are generally inconsistent with each other, and fail to conform with basic relationships of probability theory such as

$$0 \leq P(i) \leq 1 \tag{12}$$

$$P(i|j)P(j) = P(j|i)P(i) = P(ij) \tag{13}$$

$$P(i|j)P(j(+P(i|j)P(j) = P(i) \tag{14}$$

In turn, mathematical routines are required to revise these 'raw' probabilities into a finished set that is internally consistent. However, many of these mathematical routines are found to be convergent but fail to guarantee internal consistency. The method proposed by Duperrin and Godet is designed to ensure scenario consistency by minimizing an objective function that quantifies the differences between conditional probability values provided by participants and theoretical ones generated from the aforementioned probability definitions.

Additionally, the minimization is made subject to the following linear constraints enforcing the condition of total probability:

$$\sum_{k=1}^{r} \Pi_k = 1 \tag{15}$$

$$\Pi_k \geq 0 \tag{16}$$

This approach is very appealing because of it offers simplicity and mathematical formality, and because it yields optimal approximations of internally consistent probability values with respect to 'raw' values provided by participants. However, a major shortcoming of this method is that scenario components are defined as *events*, with the ith event denoted by e_i, for which only two options exist: the event occurs (e_i) or it does not ($\overline{e_i}$). Thus, this approach cannot be directly applied if contextual variables, rather than events, are used as scenario components, particularly if more than two settings are used to avoid constructing scenarios in terms of trivial extreme conditions.

A number of related efforts have been documented where the the problem of correcting for internal consistency the probability values produced by participants using the cross-impact method has been approached in different ways. Some have focused on the definition of appropriate statistical conditions that cross-impact probabilities must satisfy (e.g. [260]), whereas others have focused on the development of mathematical methods that more explicitly incorporate expert opinion to implement the probability adjustments in question (e.g. [79]). However, the general observation is that in order to facilitate mathematical development of probability relations, scenario components are defined as events for which the only two possible alternatives are: the event occurs with a probability $P(i)$, *or*, the event does *not* occur with probability $P(\bar{i})$.

More recent efforts have proposed the use of traditional morphological analysis to generate Bayesian networks so that the probability of scenarios can be determined from probabilistic causal relations identified for scenario component alternatives. In this approach the cross-consistency matrix is used to investigate and document the existence of these causal relationships, which depends on the assessment conducted by experts and scenario planning participants. Then, a directed acyclic graph is constructed based on the causal

relationships identified, where the nodes of the graph represent the finite set of scenario variable states, and the directed edges of the graph represent an existing causal relationship linking a variable state with its 'parent' variable state. Finally, conditional probabilities are elicited from participants and documented in tables so that a necessary probability values are assigned to each edge of the graph./citedeWaal2007 This method is a very appealing approach and particularly relevant to the testing of *Hypothesis 5*, but has two important issues. First, the use of causality as a relational attribute for scenario components can lead to difficulties when eliciting opinions from participants, particularly because causality is much more difficult to demonstrate than the concurrent occupance of two conditions. Secondly, the presence of causality is documented in the cross-consistency matrix with a binary scale, which requires the development of separate tables for probability values. Thus, scenario construction only accounts for plausibility to the extent that a causal relationship may be found to exist between scenario variables, whereas the evaluation of scenario probability occurs separately with the Bayesian network and the tables of conditional probability.

It would be beneficial to directly encode probability data in the cross-consistency matrix to explicitly use it as a relational parameter for scenario construction. Additionally, this would leverage the use of matrix operations to test for and comply with fundamental probability definitions. In this sense, the relational data in the cross-consistency matrix would constitute the a series of discrete second order joint probability distributions, akin to the probability tables of the approach previously mentioned. However, such an approach requires an aggregate function that yields an n-dimensional discrete probability distribution form a series of second order distributions.

This aggregate function requirement is explicitly addressed in the seminal work by Chow and Liu in information theory.[45] They propose a method for optimally approximating an n-dimensional discrete probability distribution from a series of second order distributions. First they recognize that an n-dimensional distribution can be approximated as a product of lower order distributions. The approach focuses on product approximations that only

Figure 42: Sample Dependence Tree for Probability Distribution Product Approximation (Reproduced from [45])

$$P(X) = P(X_1)\,P(X_2|X_1)\,P(X_3|X_2)\,P(X_4|X_2)\,P(X_5|X_2)\,P(X_6|X_5)$$
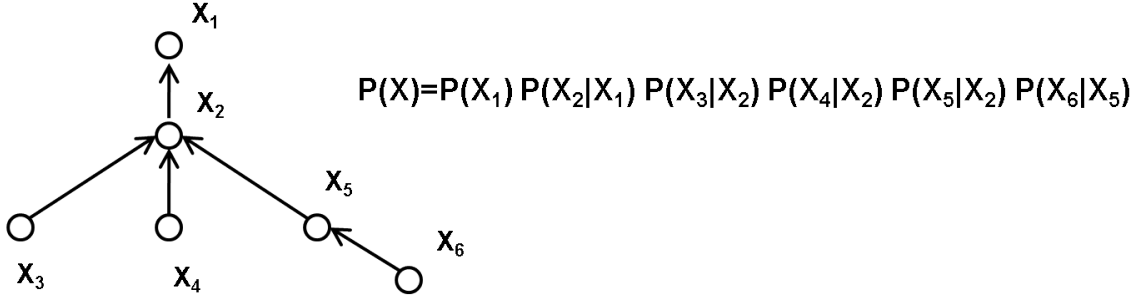
include second order distributions, as follows:

$$P_t(x) = \prod_{i=1}^{n} P(x_{m_i}|x_{m_{j(i)}}), 0 \leq j(i) < i \tag{17}$$

where $(m_1, ..., m_n)$ is an unknown permutation of the integers 1 through n, $P(x_i|x_0)$ is equivalent to $P(x_i)$, and the mapping $j(i)$ represents a dependence tree, as illustrated in Figure 42.

Note that this type of product approximation can use at most $(n-1)$ second order distributions from a total of $n(n-1)/2$. The accuracy of the approximation is measured by the *closeness of approximation I* between an n-dimensional discrete distribution $P(x)$ and an approximation of that distribution $P_A(x)$,

$$I(P, P_A) = \sum_{x} P(x) log \frac{P(x)}{P_A(x)} \tag{18}$$

The closeness of approximation is positive if the two distributions are different, with larger values resulting from greater differences, and equal to zero if the two are identical. The minimization of $I(P, P_A)$ thus results in an optimal approximation of the n-dimensional distribution. However, there are n^{n-2} distinct tree structures with n vertices, and a plethora of possible probability distribution permutations for each distinct tree structure, resulting in a total number of dependence trees so vast, even for moderate values of n, that an exhaustive search approach is clearly prohibitive. As an alternative approach, a quantity

of *mutual information* between two variables is defined as

$$I(x_i, x_j) = \sum_{x_i, x_j} P(x_i, x_j) log \left(\frac{P(x_i, x_j)}{P(x_i)P(x_j)} \right) \tag{19}$$

based on the concept of closeness of approximation. The quantity of mutual information is non-negative and can be assigned as a weight to the branch of the dependence tree connecting variables x_i and x_j. Chow and Liu demonstrate that the minimization problem of closeness of approximation I, is equivalent to the maximization of total branch weight, such that the optimal approximation for the n-dimensional distribution is given by the maximum weight dependence tree. Since the branch weights are additive the maximum weight dependence tree can be constructed branch by branch, thus averting the need for a computationally expensive exhaustive search. This procedure is quite simple, and involves the calculation of mutual information for all possible dependence tree branches, namely for all distinct variable pairs, followed by an ordering of branches according to their mutual information value. Branches are then chosen in order, starting with that of highest mutual information, only discarding those that violate the acyclic condition of the dependence tree.

Based on this survey of methods it is possible to test *Hypothesis 5* using each of the conditions of the H parameter test. The first condition states:

For each and all morphological configurations, an H parameter can be expressed as a single scalar value H^n characterizing the $n^t h$ order relational information.

By definition, an n-dimensional probability distribution $P(X_1, ... X_n)$ provides a scalar probability value $P(X_1 = x_1, ... X_n = x_n)$ for each possible vector of values $[x_1, ... x_n]$. Moreover, this n-dimensional probability value is readily identified as an instance of $n^t h$ order relational information. Thus, probability meets the first condition of the H parameter test.

The second condition states:

For each and all morphological configurations, an H parameter can be expressed as scalar values H^k characterizing $k^t h$ order relational information, where $2 \leq k < n$.

By virtue of the definition of an n-dimensional probability distribution $P(X_1, ... X_n)$ and the law of total probability, the definition of a lower order distribution $P(X_1, ... X_k)$ is

realizable, and commonly observed in practice. Thus, probability meets the second condition of the H parameter test.

The third condition states:

There exists an aggregate function f_a such that the nth order value of the H parameter H^n can be expressed as a function of lower order values of H, so that $H^n = f_a(H^{k_1}, H^{k_2}, ...)$, where $2 \leq k_i < n$ for all i.

The work discussed in this section suggests that n-dimensional discrete probability values can be generated from a product function of $(n-1)$ second order probability values, and that in the absence of an exact solution n-dimensional probability values can be optimally approximated. Thus, probability meets the thid condition of the H parameter test.

Consequently, probability is shown to be an H parameter, and thus, *Hypothesis 5* is accepted. In turn, this result suggests that probability can be used for the construction of scenarios in morphological analysis, as well as an evaluation criterion for scenario ranking and selection.

8.5.5 Test of Valuation as an H Parameter

Valuation of alternatives is an inherently qualitative assessment primarily based on judgement and experience. On some occasions quantitative attributes such as monetary cost can be objectively identified. Unlike probability, for which there is a universal and formal mathematical framework, valuation assessment schemes vary widely and among applications, requiring only that the selected scheme be deemed relevant or suitable for the task at hand and that it is used in a consistent manner.

In turn, rather than testing a plethora of existing valuation mechanisms, it is possible to generate one based on the conditions of the H parameter test so that it is recognized as an H parameter by definition. For instance, a three value ratio scale such as [1, 3, 9], or a three value linear scale such as [1, 3, 5], can be used to qualitatively map low, medium, and high levels of perceived consequence or opportunity for pairwise combinations of of scenario variable values. These pairwise values for each scenario can then be aggregated by means of a sum or a product. If deemed necessary all values can then be normalized with respect

to an appropriate reference such as the highest valuation so that all other values are within the range [0, 1], or with respect to the valuation quantity of a reference scenario of interest.

In this sense, the H parameter test for valuation is trivial, and it can be left to the scenario planner to develop an adequate scheme that meets H parameter conditions.

8.6 Formulation of a Scenario Development Process - Probability and Valuation as H Parameters

This final section describes the process for scenario construction, evaluation, and selection, using probability and valuation as H parameters. The process follows the general approach featured in the 2003 NASA scenario study by the LMI, discussed in Section 3.6.2 and later in Section 8.3.4.

Said approach is particularly well suited as a basic procedural framework for many reasons. First, it is very similar thematically and in scope to the strategic airport planning process as has been formulated in this thesis. The LMI study focused on characterizing the context in which operational concepts and NAS technologies proposed by NASA would be implemented, and required the definition of representative schedules of operations that capture top-level demand drivers to implement the appropriate models and simulations. Similarly, the strategic airport planning process requires considerations for top-level demand factors, but ultimately requires the definition of a corresponding schedule of operations to realize quantitative assessment of terminal area solutions under future conditions. Second, the LMI study uses a basic morphological approach to structure demand factors and their respective settings, and then to list out all the possible scenario configurations. Third, it explicitly incorporates internal consistency and plausibility as an evaluation parameter, consistent the approach proposed in this thesis. Finally, it uses probability values assigned to scenarios by experts.[302]

Based on this general formulation, the process for scenario construction, evaluation, and selection is as follows. Top-level demand drivers are structured in a morphological matrix where the alternative settings for each demand driver are specified. Contrary to most applications reviewed in this chapter and in Section 3.6.2, more than two settings can be specified for a demand driver. The selection of demand drivers and alternatives is

realized by the elicitation of expert opinion and judgement, and facilitated by workshops as has been described numerous times in this chapter.

Based on the the number of demand drivers and on the number of alternative settings for each demand driver, an H matrix (cross-consistency matrix) is defined. The H matrix matrix will be used to document probability information, and a different version of it will be used to document valuation information. This probability and valuation information is, once again, provided mostly by experts and scenario planning participants. It is necessary to moderate the generation of probability data so that as each probability value is provided, it is checked against constraints and definitions of probability theory. In a similar fashion, valuation information must observe any possible constraints and definitions provided by the valuation scheme selected.

Once the H matrix for probability and the H matrix for valuation are completed, a list of all scenarios is generated. This exhaustive list results from the complete combinatorial set of morphological configurations defined by the morphological matrix. Then, the H^n values for probability and valuation are determined for each scenario via the appropriate aggregate function. For probability, H^n is the n-dimensional probability value associated with a given scenario. The aggregate function for probability is the dependence tree approximation, whose definition requires the data from the probability H matrix. In a similar fashion, the valuation data is aggregated into the corresponding H^n value for each scenario by means of the aggregate function constructed for the valuation metric.

What results is a list of all possible scenarios, each with a probability and a valuation value associated with it. The list can be ranked according to probability to select the most likely scenarios, or ranked by valuation to select the scenarios with the highest consequence. However, ignoring either aspect of the scenario is highly questionable as discussed in Section 8.4.3. Rather, the two pieces of information are adequately combined to generate risk value. Thus, a risk-based ranking of scenarios accounts for both aspects, an priorities scenarios based on risk, thus facilitating the selection of a final scenario set by planners and participants.

Finally, once scenarios have been selected, a schedule of operations is produced for

each scenario by mens of the appropriate economic modeling tools. These tools map the high-level demand drivers defining the scenario to the lower level tactical and operational descriptors of a schedule.

CHAPTER IX

CONCLUDING REMARKS AND FUTURE WORK

9.1 Recapitulation of Thesis Objectives and Contributions

In the opening chapter of this thesis the operational-environmental tradeoff was briefly introduced in order to reveal that, despite abundant efforts by the community at large, there are still prevalent challenges in the current paradigm. Based on these observations, a series of *thesis objectives* are stated at that point describing what challenges have to be addressed, and ultimately what must be accomplished by this research effort. In this sense, thesis objectives identify the *contributions* that are made by the body of work hereby documented.

The most fundamental challenge, and hence the first to be addressed, is the articulation of the operational-environmental tradeoff. The first thesis objective is thus stated as follows:

Thesis Objective 1: To formulate the operational-environmental tradeoff with ample depth and breadth, highlighting the incentive for a joint solution portfolio and articulating the fundamental relationships at the crux of the problem.

This objective is addressed in Chapter 2, where the elements and issues at the core of the operational-environmental tradeoff are discussed at length, and where the motivation for seeking solutions that concurrently address both aspects of terminal area performance is clearly stated.

The characterization and focusing of the problem, provided in Chapter 3, builds upon the arguments presented in Chapter 2 and identifies the problem as one of strategic airport planning where methodological gaps are readily revealed. The first gap identified pertains to the characterization of terminal area operational-environmental performance for which the following thesis objective is formulated:

Thesis Objective 2: To quantitatively characterize the operational-environmental performance of terminal areas by investigating the interactions between exogenous and/or

exogenous factors, the sensitivity operational and environmental performance metrics to different factors, and the tradeoffs and correlations between operational and/or environmental metrics.

To meet this objective, a proposed methodological approach is discussed in Chapter 4, and stated as the following methodological hypothesis:

- *Methodological Hypothesis 1:* A quantitative characterization of interactions, sensitivities, and tradeoffs for airport operational-environmental performance metrics with respect to *endogenous and exogenous factors* is realized through regression analysis, statistical testing techniques, and interactive visualization of RSE's.

This hypothesis is not directly testable, but rather it is supported by the successful implementation and demonstration of the method it describes, as well as by the testing of more detailed, relevant, testable hypotheses within it the implementation of the method. Chapter 6 presents at length the work related with the aforementioned method implementation, as well as the formulation and testing of relevant hypotheses. *Hypothesis 1* and *Hypothesis 2* refer to the significance of endogenous and exogenous factor effects, whereas *Hypothesis 3* is used to test regional segmentation of operational schedule to characterize airport performance.

The demonstration of this methodological approach illustrates how a systemic perspective of the system enables the analyst to begin characterizing different factors and setting up adequate modeling and analysis tools that must be used to intelligently vary specific input parameters. In doing so, this approach is also shown to help manage computational and analytical resources by means of designs of experiments for which statistical analysis reveals clearly, transparently, and explicitly, the complex behavior of numerous interacting forces within a rigorous mathematical framework.

Moreover, by incorporating adequate interactive visualization schemes, the confirmation of expected behaviors and the discovery of the unknown is realized and facilitated. Such visualization of results facilitate the synthesis of insight and understanding about complex airport performance characteristics that would otherwise be implicit and obfuscated by

inherent systemic complexity.

In this sense, the strategic airport planning process is enhanced and improved by offering decision-makers a more transparent and complete view of the problem, and more specifically a more explicit and understandable characterization of terminal area performance in terms of relevant exogenous and endogenous factors. This increase level of understanding can be expected to roll over on posterior steps of the strategic planning process, for instance, by guiding the generation of more relevant or plausible projections of future conditions, or guiding the generation of more relevant and focused strategic portfolios from which different solutions will be assessed and selected.

The second gap identified for the strategic airport planning process pertains to the complete evaluation of terminal area strategic solutions. The corresponding thesis objective is stated as follows:

Thesis Objective 3: To quantitatively characterize the effect that different solutions, and combinations thereof, have on the operational-environmental behavior of terminal areas, both in terms of solution main effect and their mutual interactions.

To meet this objective, the method proposed is discussed in detail in in Chapter 4, and stated as the following methodological hypothesis:

- *Methodological Hypothesis 2:* A quantitative characterization of interactions, sensitivities, and tradeoffs for airport operational-environmental performance metrics with respect to *terminal area solutions* is realized through regression analysis, statistical testing techniques, and interactive visualization of categorical RSE's.

This hypothesis is not directly testable, but rather it is supported by the successful implementation and demonstration of the method it describes, as well as by the testing of more detailed, relevant, testable hypotheses within it the implementation of the method. Chapter 7 presents at length the work related with the aforementioned method implementation, and includes the formulation and testing of *Hypothesis 4*, divided into 10 components, which are used to confirm or revise qualitative assessments of the expected impact of terminal area solutions on airport performance.

The implementation of statistical discrete regression analysis for this application is instrumental in characterizing in a quantitative and explicit fashion the direct effect of distinct terminal area solutions, the interactions between said solutions, which were proven to be most significant for a variety of operational and environmental metrics, and the statistical significance of all the aforementioned factors. In conduction with these results, the visualization of regression models provide invaluable insight as they readily reveal the sensitivity of different operational and environmental metrics to the solutions under consideration, and most importantly, reveal how these sensitivities are affected by interactions as they become more or less pronounced depending on whether other solutions have been implemented or not.

By leveraging the synthesis of this information, and allowing analysts and decision-makers to accrue insight and clear understanding about these complex relations in the pre-decisional assessment phase, the proposed approach realizes an important improvement to the existing paradigm of strategic airport planning, and represents in itself an tangible contribution.

The third and last gap identified for the strategic airport planning process pertains to the construction, evaluation, and selection of scenarios that capture future conditions under which strategic alternatives are assessed. The corresponding thesis objective is stated as follows:

Thesis Objective 4: To formulate a traceable, repeatable, and rigorous approach for the definition, generation and down-selection of future scenarios in the context of strategic planning.

Chapter 8 presents an extensive review of scenario development, and identifies morphological analysis, scenario probabilization, and risk based selection, as key components for the formulation of an appropriate method that bridges gaps in current practices. The applicability of scenario probabilization to the proposed method is tested via *Hypothesis 5* against a mathematical reformulation of morphological analysis that specifically addresses the noted gaps in current practices. Based on the insight accrued by this test, the process

for scenario evaluation and selection is formulated at the end of Chapter 8.

This propose approach

The final thesis objective prescribes that all the proposed methods be adequately integrated within a unified effort of relevance, as follows:

Thesis Objective 5: : To demonstrate the synergistic and integrated implementation of the proposed methodological approach in a relevant and realistic sample problem

All the work presented throughput this thesis is in itself a demonstration of the methods proposed, for which all components are shown to work synergistically by means of the strategic planning process upon which each component of this thesis was built.

Thus, each of the objectives set forth at the beginning of this theses are explicitly addressed and met, and comprise the different contributions made by this research.

9.2 Future Work

As the different thesis objectives are met to address identified challenges and gaps, new ones are readily revealed and set the path forward for future efforts in this regard. Several key issues were identified throughout this thesis regarding modeling capabilities, methodological considerations, and implementation of the proposed approach.

First, noise modeling capabilities in the AEDT were noted to be appropriate granted that aircraft trajectories provided explicitly account for any path vectoring that takes place in the terminal airspace. Data from radar tracks corresponding to real operations, for instance, capture this path vectoring and provide the explicit trajectories flown by aircraft which have bearing on environmental performance. However, data from terminal area M&S capabilities such as SIMMOD do not explicitly characterize in its output simulation data file the extended trajectories resulting from path vectoring, and as a result the exacerbated environmental impact associated with any variations of nominal trajectories is not captured by the AEDT. Although this shortcoming has been addressed for fuel burn and emissions calculations, it remains to be solved for noise estimates. As the AEDT continues to be developed, path vectoring capabilities must be incorporated so that vectored flight trajectories are explicitly defined in the SIMMOD output data and can be appropriately captured

in the AEDT. Such a M&S capability would provide immense benefits in the assessment of noise reduction resulting from operational improvements that reduce the inefficiencies of the terminal airspace that prompt path vectoring in the first place.

The proposed methodology for the assessment of airport performance under current conditions involves the purposeful variation of exogenous and endogenous parameters in the appropriate M&S environment to explicitly characterize the different factor effects through statistical analysis. In Chapter 6 it was suggested that a regional characterization of operations is a feasible means to segment and describe with further resolution variations in operational demand. Results showed that the specific scheme examined did not provide significance of regression and thus that it was not entirely appropriate for the characterization of terminal area performance. However, it was noted that there is much potential in this approach, and that origin-destination and regional segmentation of operations should be explored further. The process for evaluating the adequacy and applicability of other proposed regional classification schemes has been describe and illustrated in Chapter 6, and thus it is left for future efforts to implement this process in other proposed classification schemes.

The development of operational schedules representative of projections on top-level demand drivers is a very important aspect of airport strategic planning. Although the mechanism for generating operation schedules implemented in this research builds upon previous work, there are still some important considerations that reveal opportunities for improvement. For example, the application of growth factors on specific groups of operations is a direct way of capturing the growth of demand on the system. However, the relationship between the growing number of passengers and the number of operations conducted by different aircraft models is not fully known, and is driven by airline decision-making. The fleet assignment to specific flights depends on the aircraft models available in the airline, the frequency with which flights take place between a given origin-destination pair, and size of that market. Thus, the relationship between aircraft capacity, range, and frequency of flights, known as the frequency-capacity split, must be captured to generate schedules of operations that are more realistic and correspond with a greater level of accuracy to airline

decision-making.

In a similar fashion, it is important to recognize that all terminal area simulations tracked operations on a flight-basis, but not at an aircraft tail number basis. The implications of this modeling assumption are that aircraft swaps and the physical allocation of aircraft are not captured in the model, but should be recognized since they may have a bearing on gate availability, delays, and turn-around time for schedule connection banking, particularly in a major transfer hub airport as ATL. It is not expected that airborne operational and environmental performance would be particularly affected by changes in modeling assumptions or resolution to incorporate tracking of aircraft tail numbers. However, there may be relevant changes in performance characterization for ground operations that warrants further investigation. Hence, future work should involve the characterization of operational-environmental performance for a variety of conditions and terminal area solutions with tail-number tracking, thus providing an additional degree of resolution and enabling a determination of whether trail-number tracking has any significant bearing in performance characterization.

Another important default modeling assumption in SIMMOD related to the aforementioned consideration for aircraft tail number tracking is that departing aircraft are injected into the simulation at the gates, and arrivals are ejected from the simulation at the gates. This modeling assumption has some relevant implications on gate availability, particularly because it does not *explicitly* capture how the same aircraft conducts an arrival operation followed by a departure operation from the same gate. Whereas the effects of taxiway congestion and required airport throughput are properly captured, gate availability may be affected by modifications in this modeling assumption, which in turn may have an impact on gate delay metrics and to a smaller extent on arrival ground fuel burn. Thus, future work should also consider gate availability modeling in more detail, and in conjunction with tail number tracking to provide a higher degree of modeling resolution for gate usage and the effects that it may have on other operational aspects.

Finally, the value of the proposed approach is measured by the level of insight produced by its implementation on a relevant sample problem. Detailed quantitative characterizations

of sensitivities, interactions, and tradeoffs, for ATL have been provided and collectively offer a greater level of understanding about the complexities of terminal area performance for this specific airport. However, future work must consider additional airports for the implementation of the proposed approach so that its applicability and feasibility can be further assessed, as well as to compare how operational-environmental performance varies differently with each airport, both in terms of terminal area solutions and in terms of exogenous and endogenous factors.

APPENDIX A

OPERATIONAL CONSIDERATIONS FOR THE NATIONAL AIRSPACE SYSTEM

A.1 Navigation Aids

There are a variety of navigation aids, often referred to as *navaids*, which operate in different ways and serve a variety of purposes. A *NonDirectional (radio) Beacon* (NDB), one of the earliest and most basic naviads, is a low to medium frequency transmitter of radio signals containing no directional information. Each NDB is identified by Morse callsign containing three letters and broadcasts on a given frequency, allowing pilots to tune on-board equipment to a given NDB signal. An *Automatic Direction Finder* (ADF) onboard an aircraft allows the pilot to determine bearings relative to the NDB source as shown on a *Relative Bearing Indicator* (RBI), thus allowing the pilot to "home" on the NDB so that the aircraft can fly directly towards it, away from it, or fly along a given track. Early air navigation required that aircraft fly from one beacon to another, tuning to the frequency of the next NDB in a series of beacons and homing on it every time the aircraft reached the current station. Original NDB navigation with ADF allowed aircraft to intercept an arbitrary "fix", specified by the intersection of two bearing lines each passing through a given NDB, as notionally illustrated in Figure 43. This concept, often referred to as "triangulation", eliminated the need to fly over beacons along the route between two points, and thus enabled the creation of more direct alternatives. Although this navigation method was fairly common, the advent of directional and distance navaids, explained next, greatly facilitated the use of fixes and has since become the paradigm of air navigation. [127, 123]

The *Very High Frequency (VHF) Omni-directional Range* (VOR) is another type of ground-based navigation aid which also uses unique Morse code callsigns for identification. A VOR uses high frequency radio to transmit a 360 degree azimuth directional signal

Figure 43: Fundamental principles of NDB fix navigation
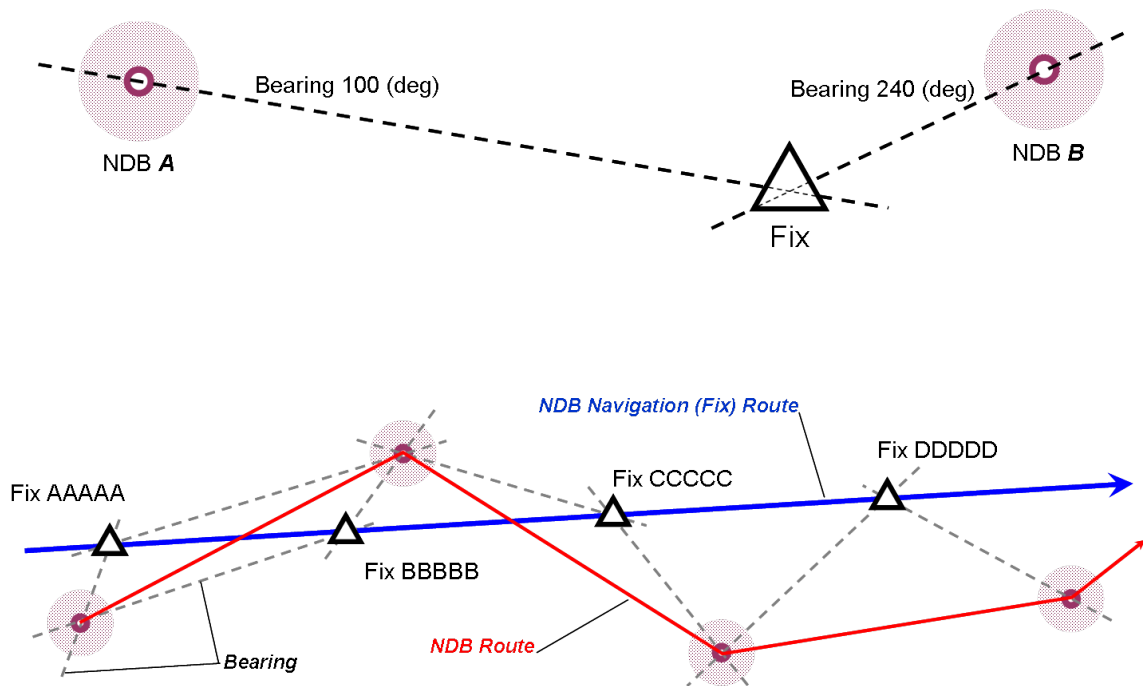
relative to the magnetic north. The accuracy of most VOR stations is +/- 1 degree, resulting in a total of 360 directional bearing signals, or *radials*. Some navigation aid stations are equipped with *Distance Measuring Equipment* (DME), which require that appropriate equipage be present on an aircraft for DME functionality. A DME interrogation signal, consisting of paired pulses with a specific spacing, is first emitted from the aircraft. The ground station, or transponder, receives this signal and transmits back paired pulses at a different frequency. The distance to the station is then estimated by onboard equipment from the total trip time of the signal with an accuracy of half a mile or 3% of the distance. The civil aviation navigation aid system was considered inadequate for miliary applications, which prompted the development of the *Tactical Air Navigation* (TACAN) system to provide directional and range navigation for military and naval forces. Given its analogous functionality to the the civil VOR/DME counterpart the FAA incorporated TACAN facilities into its navigation system, though TACAN's use of *Ultrahigh Frequency* (UHF) signals is not compatible with onboard VOR equipage. Many facilities concurrently provide VOR

Figure 44: Symbols legend of Navaid stations in air navigation charts
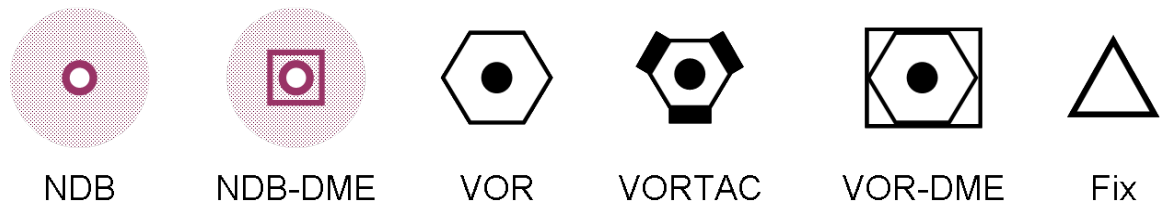
azimuth, TACAN azimuth, and TACAN DME, and are referred to as VORTAC. [127, 123] The legend of symbols used for these navaid stations and fixes in various navigation charts is shown in Figure 44 [6]. As mentioned before, the availability of directional and range measurement navaids greatly facilitates the definition and usage of fixes. Not only are more direct routes generated with fix navigation, but most importantly it is fairly straightforward to generate specific tracks that turn and traverse as needed for a given procedure. The use of fixes defined by VORTAC stations, for instance, is commonplace and readily observable in the definition of *Standard Instrument Departure* (SID) procedures and *Standard Terminal Arrival* (STAR) procedures. Figure 45 [130] shows part of the WHINZ ONE arrival procedure to Hartsfield-Jackson Atlanta International Airport as a representative example. A series of fixes are shown defining the multiple arrival tracks of this procedure, identified with five-letter callsigns: JOINN, AVERY, BEBAD, RUBIE, WHINZ, and VICTU. Also shown are the different navaid stations identified with three-letter callsigns, primarily Montebello VOR-DME (MOL), Foothills VORTAC (ODF), and Atlanta VORTAC (ATL). The chart also identifies the navaid stations that are used to define each fix, as well as the specific directional and range information for each of them. Fix JOINN, for instance, is defined relative to the MOL along radial 233 and at a distance of 78 NM. Fix AVERY is another 105 NM further down radial 233 relative to MOL, even though it is actually defined relative to the ODF 96 NM along radial 45 (R-045). Fix BEBAD is also defined relative to ODF along radial 45, but only at a distance of 42 NM, and is shown to intersect radial 129 of Volunteer VORTAC (VXV).

Figure 45: Sample fix navigation with directional and range navaids - STAR WHINZ ONE for ATL

A.2 Approach and Landing Procedures, and Landing Systems

The *Instrument Landing System* (ILS) is a precision instrument approach system comprised of a series of instruments on the runway, with corresponding instrumentation onboard the aircraft, that provide path alignment and descent on final approach to a runway, thus enabling operations during limited visual conditions according to predefined ILS procedures. Guidance information is provided by two instruments, the *localizer* and the *glideslope*. The localizer, whose transmitter is usually placed at the opposite runway end, provides course guidance and is used to align the aircraft with the extended centerline of the runway. The front course of the signal is 700 feet wide at the runway threshold, and has off-course indications at 10 degrees on either side of the extended centerline along and 18 NM radius from the transmitter, as well as 35 degrees on either side of the extended centerline along a 10 NM radius. The glideslope provides vertical, or altitude, guidance for the descent profile, and is used to maintain proper altitudes during the landing procedure. The glideslope transmitter is usually located 750 to 1,250 ft down the runway from the approach end and is offset up to 600 feet to either side of the runway centerline. The beam is emitted in the same direction as the localizer course and has a 1.4 degree vertical width. The *glide path* is the part of the glideslope beam that intercepts the localizer signal, and is adjusted to be at 3 degrees above the terrain horizontal. The glide path denotes the path that an aircraft should follow when performing an ILS landing procedure. Visual information in the ILS is provided by approach lights, touchdown zone lights, centerline lights, and runway lights.[127, 123] A typical runway lighting system is shown in Figure 46 (Adapted from [6], pg 4-36).

Range information on the ILS is provided by a series of marker beacons along the localizer course which emit a signal upward over an elliptical pattern about 4,200 feet tall and 2,400 feet wide, starting at about 1,000 feet above the antenna. Whenever the aircraft flies over a marker beacon ILS instrumentation on board provides a distinct signal to the pilot. The *Outer Marker* (OM) is usually located just over NM from the runway threshold and indicates the point where the aircraft will intercept the glide path if it is flying at the correct altitude, approximately 1,400 feet above runway level. The exact distance from the

Figure 46: Runway lighting for ILS visual information
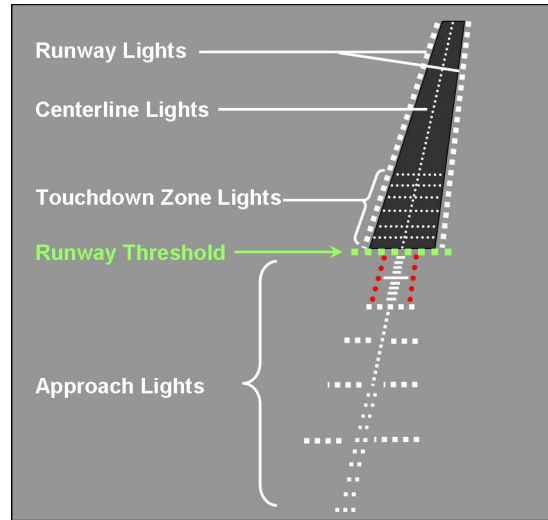
runway threshold to the OM may vary whenever its usual location it is not practical. When flying over the OM a onboard instrumentation will produce a blue light and audio signal with continuous Morse code dashes. The *Middle Marker* (MM) is located approximately at 3,500 ft from the runway threshold and indicates the position where the aircraft should be 200 feet over the runway elevation if following the glide path. The MM is observed with an amber light and audio signal with continuous intervals of Morse code dot-dash.[127, 123] A notional depiction of the basic ILS architecture and functionality is shown in Figure 47 (Adapted from [123]).

Based on the equipment available at a given runway (and on the equipment onboard an aircraft) ILS approach procedures can provide different levels of accuracy which permit operations with varying levels of visual limitations while maintaining appropriate safety margins. A system of ILS categories is used to indicate the different types of procedures available for a given runway based on two key parameters: the *Decision Altitude* (DA) and the *Runway Visual Range* (RVR). The former refers to the "altitude or height (A/H) in the precision approach at which a missed approach must be initiated if the required visual reference to continue the approach has not been established."[127] RVR is "the range over which the pilot of an aircraft on the centerline of a runway can see the runway surface

Figure 47: Basic ILS
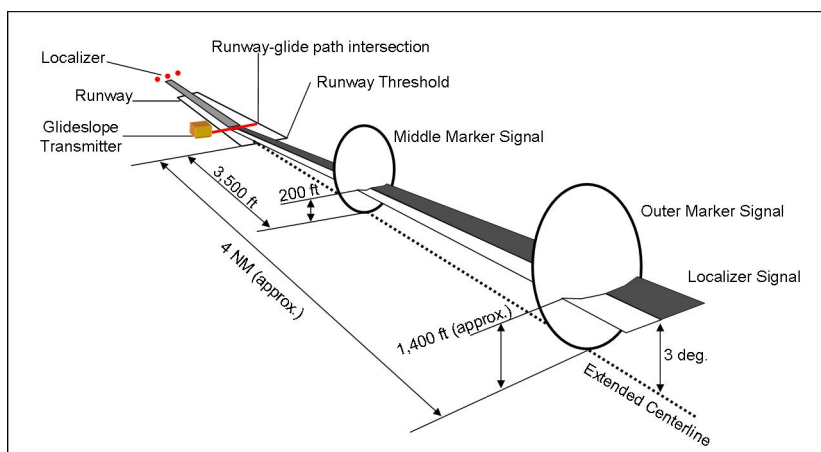
markings or the lights delineating the runway or identifying its centerline."[127]

An ILS Category I approach procedure has a DA of 200 feet or more, and RVR of 1,800 feet or more if centerline and touchdown zone lighting is available, 2,400 feet otherwise. For CAT I ILS the MM indicates the point of DA. CAT I represents the lowest level of accuracy and is the most limited procedure. ILS Category II procedures allow for a DA at or above 100 feet and RVR of 1,200 feet or more. ILS CAT II uses a third marker beacon, namely the *Inner Marker* (IM), located between the MM and the runway threshold to indicate the point of DA on the glide path. The IM is observed by onboard equipment as continuous Morse code dots produced by a white light and an audio signal. An ILS Category IIIA procedures has no DA and limits RVR to 700 feet. Category IIIB has no DA and RVR limited to 150 feet. Finally, Category IIIC procedures are the most accurate and are defined for the most constraining visual conditions: there are no specified DA and RVR, permitting fully instrumented landing operations with no visibility.[127, 123]

Special ILS procedures have been defined for certain situations that require specification of instrument accuracy whenever the procedure involves limiting conditions for safety margins. An ILS *Precision Runway Monitoring* (PRM) approach, for example, is conducted for PRM equipped "parallel runways whose extended centerlines are separated by less than 4,300 feet [permitting] simultaneous independent ILS approaches."[127]

A.3 Aircraft Separation

A.3.1 Separation Responsibility, Flight Conditions, and Airspace

The responsibility of aircraft separation falls on ATC or on the pilot based on the type of flight plan filed for a given aircraft/flight and the clearances that have been requested/granted. In general, ATC is responsible for the separation of all aircraft operating on IFR flight plans. ATC implements aircraft separation in three ways: vertical separation is attained by assigning different altitudes to different flights; longitudinal separation is attained by allowing for time or distance intervals between aircraft on the same course, or on courses that converge or cross; lateral separation is attained by assigning different flight courses/paths. Whenever an ATC facility is equipped with a radar system and offers radar services, all traffic whose separation is controlled by that ATC facility is said to be *radar-controlled*. However, ATC facilities need not have a radar system to provide ATC traffic separation services (see for instance [125] Ch. 6 - Nonradar). For radar-controlled aircraft in the air, time or distance intervals used to generate necessary longitudinal separation between aircraft result from speed adjustment or path deviation instructions issued by ATC. On the other hand, separation for departing aircraft currently on the ground is implemented by appropriately timing takeoff clearances issued by tower controllers. ([123] §4-4-11, 4-4-12, 4-4-13)

Pilots of aircraft flying under a VFR flight plan are responsible for separation, but must still comply with all ATC instructions. It is important to note that a VFR flight can only take place whenever conditions are better than the VMC minima for a given airspace class. This type of separation is referred to as *visual separation*, and is said to take place when a pilot sees other air traffic and maneuvers the aircraft to avoid conflict.[1] Although the responsibility to *see and avoid* always remains with the pilot when flying under VFR and conducting visual separation, ATC may issue instructions or advisories to guide a VFR aircraft away from other traffic. ATC aircraft separation services for non-IFR flights, namely those that filed a VFR or composite IFR/VFR flight plan, varies with airspace classes. For instance, ATC provides service for *all aircraft separation* (IFR/IFR, IFR/VFR, and

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[1]ATC can also exercise *visual separation* if the tower controller sees air traffic and issues necessary introductions to avoid conflict.([123] §4-4-14)

VFR/VFR) in Class B airspace surrounding major airports.[2] This means that ATC provides instructions to all flights regardless of the type of flight plan that has been filed so as to maintain safe traffic separation. However, it is still the responsibility of VFR aircraft pilots to *see and avoid* so as to maintain visual separation. Similarly in Class C airspace surrounding busy but smaller airports, ATC is provides IFR/IFR and IFR/VFR separation, and provides VFR traffic advisories if ATC workload permits it. Said advisories inform pilots of VFR aircraft about traffic in their vicinity, but do not constitute explicit separation instructions. In Class D and Class E airspace ATC only provides IFR/IFR separation services and offers VFR traffic advisories workload permitting. Whenever VMC exist ATC may issue a visual separation clearance to an IFR aircraft, granted that adequate separation has already been established by ATC for the traffic involved. When visual separation for IFR flights is exercised ATC instructs the pilot in one aircraft to follow another. The acceptance of such clearance by the pilot is an acknowledgement of responsibility over aircraft separation, requiring that constant visual surveillance be maintained and that the aircraft be maneuvered as necessary to avoid conflict. Acceptance of visual separation responsibility also includes responsibility for any additional separation due to wake turbulence phenomena, explained in the next section.([123] §4-4-14, [5], Ch. 4D)

Outside airspace classes where ATC is always provides IFR aircraft separation services, flights that have filed an IFR flight plan can request clearance for *VFR-on-top* operations. VFR-on-top is an *"ATC authorization of an IFR aircraft to operate in VFR conditions at any appropriate VFR altitude. [...] A pilot receiving this authorization must comply with the VFR visibility, distance from cloud criteria, and the minimum IFR altitudes [... but] does not relieve controllers of their responsibility to separate aircraft in Class B and Class C airspace or TRSAs[...]."*[127] If VFR-on-top clearance is granted, ATC may still provide some services such as traffic or wake turbulence advisories, but it is the sole responsibility of the pilot to *see and avoid* other traffic.([123] §4-4-11)

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[2]ATC is also responsible for *all aircraft separation* in Class A airspace, though only IFR flights are allowed in it.

A.3.2 General Radar and Wake Turbulence Separation

Radar equipment accuracy makes radar-based aircraft separation contingent on the type of radar equipment available and the distance between the target and the antenna. For most facilities a 3 mile separation minima is used for targets within 40 miles of the antenna, as well as a 5 mile separation minima for targets beyond this range. In addition to these minima, wake turbulence separation is applied to prevent hazardous flight conditions resulting from aircraft flying into the wake turbulence generated by preceding aircraft.([125], §5-5-4)

Wake turbulence has been studied extensively since the late 1960's, and today it is well known turbulence strength is primarily driven by the weight, speed, configuration, and wingspan of the generating aircraft. In general, greater turbulence strength is observed with heavier aircraft flying at low speeds with a clean wing configuration. Wake turbulence separation standards have evolved continuously over the last four decades, driven by a number of research programs and incident/accident reports linked to wake turbulence phenomena. Historically these standards have used aircraft weight as the categorization criterion of choice for aircraft and wake turbulence strength.[3]([150], pg 2.3) Between 1976 and 1996 the wake weight classification scheme for turbulence separation minima was as follows [42]:

Heavy: *Maximum takeoff weight of 300,000 pounds or more.*

Large: *Maximum takeoff weight between 12,500 and 300,000 pounds.*

Small: *Maximum takeoff weight of 12,500 pounds or less.*

During the late 1980's and early 1990's a series of wake-related incidents and accidents were reported involving aircraft following a Boeing 757 during landing approach. These events prompted an investigation aimed to characterize wake turbulence for this aircraft and determine whether it was more dangerous than that of other transports of comparable size and weight. In general studies showed that, relative to larger vehicles such as the

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[3]It is worth noting, however, that no Federal Aviation Regulations addressing wake turbulence separation minima exist for certification or operation purposes, but rather are contained in documents such as the FAA Order 7110.65R: Air Traffic Control [125], and the FAA Aeronautical Information Manual [123]. ([53] pg 15)

Boeing 767, "the wake behaved as would be expected for an aircraft of the size and weight of the 757"[42]. However, measurements for a particular set of weather conditions showed that the wake velocity of the 757 was 50% higher than that of the 767. These controversial measurements were later quoted to support the argument that the 757 should be treated like *Heavy* class aircraft such as the 767 and the 747. Another important factor quoted for this purpose was the 757's relatively low approach speed (125 kts), enabled in part by its low sweep angle, high aspect ratio, and large wing area. These factors are known to exacerbate wake turbulence strength, and more importantly, lead to inadvertently reduced separation with small aircraft immediately behind whose approach speeds are notably higher. Following recommendations by the National Transportation Safety Board (NTSB) the FAA implemented in 1994 revised wake turbulence separation minima for aircraft following a 757. In 1996, and after considerable research efforts and discussions, the FAA revised the weight categorization scheme for wake turbulence separation as well as the separation minima.[42] The weight classification scheme currently in place for wake turbulence separation minima is as follows [127]:

Heavy: *Aircraft capable of takeoff weights of more than 255,000 pounds whether or not they are operating at this weight during a particular phase of flight.*

Large: *Aircraft of more than 41,000 pounds, maximum certificated takeoff weight, up to 255,000 pounds.*

Small: *Aircraft of 41,000 pounds or less maximum certificated takeoff weight.*

Wake turbulence separation minima are defined for all aircraft following directly behind a *Heavy* or *B757* aircraft. In this context *directly behind* refers to an aircraft operating within 2,500 feet of lateral separation relative to the preceding aircraft's flight path, and is at the same altitude or less than 1,000 feet below the preceding aircraft .[4] Current wake turbulence separation minima are shown in Table 24.([125] §5-5-4, [123] §7-3-9)

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[4]The inclusion of a lateral separation restriction in this definition requires that wake turbulence separation for departures from parallel runways less than 2,500 feet apart be treated as if it were a single runway for all departing traffic.

Table 24: Air Traffic Wake Turbulence Separations (NM)

		Heavy	Large	Small
	Heavy	4	5	5
Lead	B757	4	4	5

Additionally, there are wake turbulence separation minima for *Small* aircraft directly behind *Heavy*, *B757*, or *Large* aircraft during arrival procedures. The minima are 6 NM, 5 NM, and 4 NM respectively. This standard applies for landing operations on the same runway or runways that are less than 2,500 feet apart. Wake turbulence separation minima can be incorporated with the general separation standards in a single matrix for all arrival operations as shown in Table 25. The separation matrix also shows that the 3 mile separation standard may be reduced to 2.5 miles. This separation reduction is only authorized for aircraft on final approach course within 10 NM of the runway threshold, granted the leading aircraft's weight class is the same or less than the trailing aircraft, the average runway occupancy time is less than 50 seconds, and the airport is adequately equipped with Certified Tower Radar Display (CTRD).([125] §5-5-4, [123] §7-3-9)

Table 25: Separation Minima for Arrival Operations (NM)

		Heavy	Large	Small
	Heavy	4	5	6
Lead	B757	4	4	5
	Large	3 (2.5)	3 (2.5)	4
	Small	3 (2.5)	3 (2.5)	3 (2.5)

This traffic separation scheme is implemented by ATC over all aircraft for which it has separation responsibility, namely all IFR aircraft, and VFR aircraft within Class B. Wake turbulence separation is considered IFR separation as issued and maintained by ATC. However, as noted in the previous section, a clearance for visual separation may be issued for IFR traffic granted that VMC exist and that separation minima are provided by ATC for traffic prior to clearance issuance. If the pilot of an IFR aircraft accepts a visual separation clearance then separation responsibility is transferred from ATC to the pilot. As

a safety measure, whenever a clearance for visual separation is granted by ATC and a wake turbulence condition exists, ATC issues a *wake turbulence advisory.* ([125] §3-10)

Even though transfer of separation responsibility to pilots of IFR aircraft during VMC is a legal and quite common procedure, data has shown that during these operations actual traffic separation maintained by pilots is reduced relative to the ATC-issued radar separation minima presented in Table 25. As a result of this reduced separation higher traffic volumes are observed and the capacity of the airport in question is effectively increased. Conversely, it is widely recognized that air traffic capacity is reduced during IMC vis-a-vis VMC. Data collected at Chicago O'Hare International Airport (ORD) for same-runway arrivals in the late 1970's suggests that during visual separation operations longitudinal traffic separation maintained by pilots is reduced to approximately 60% to 75% of prescribed separation minima otherwise maintained by ATC during IMC. The data of this study, shown in Table 26, is based on the FAA's previous aircraft classification scheme [5], but none the less illustrates the effect that visual separation has on air traffic operations. Additionally, the VMC separation values presented in this study are representative of the operations observed at ORD, but are not regulatory in nature.([53] pp. 15-18, [159] pp. 157-159, [147])

Table 26: Observed Separation Minima Reduction During VMC / Visual Separation (NM) (Source: [147])

	IFR			VFR			(VFR/IFR)%		
Lead	Heavy	Large	Small	Heavy	Large	Small	Heavy	Large	Small
Heavy	4	5	6	2.7	3.6	4.5	67.5%	72%	75%
Large	3	3	4	1.9	1.9	2.7	63.3%	63.3%	67.5%
Small	3	3	3	1.9	1.9	1.9	63.3%	63.3%	63.3%

A.3.3 Separation in Departure Operations

For departure operations, the control tower is responsible of issuing clearances to departing traffic in such a way that appropriate separation will be maintained for all aircraft departing, arriving, and in transit. After an aircraft has switched communications from ground control

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[5]Previous classification scheme featured *Small* aircraft under 12,500 lb, *Large* between 12,500 lb and 300,000 lb, and *Heavy* over 300,000lb.

to the control tower, the tower issues a series of instructions that aircraft pilots must follow and acknowledge. Among the most important ones are the issuance of a Taxi Into Position and Hold (TIPH) clearance, and takeoff clearance. A TIPH clearance is issued to position aircraft for an imminent departure. Once all other operations impeding takeoff have occurred, a departing aircraft in *hold* is issued a clearance for takeoff. For efficiency reasons ATC is allowed to issue a takeoff clearance if there there is reasonable assurance that adequate separation will exist when the departing aircraft starts its takeoff roll, and is not required to withhold takeoff clearance until prescribed separation exists. ([125] §3-9-4, 3-9-5, 3-9-9)

In general, a departing aircraft should not begin its takeoff roll until the preceding departing aircraft has crossed the runway end or has executed a turn away from the runway centerline, or a preceding landing aircraft is clear off the runway. In cases where distance can be adequately observed along a runway, and only between sunrise and sunset, the preceding aircraft need not have crossed the runway end nor have turned away from its centerline before the following aircraft is cleared for takeoff. Rather, the preceding aircraft need only be airborne if the following distances exist ([125] §3-9-6):

- 3,000 feet between Category I aircraft or if a Category I aircraft is preceded by a Category II aircraft.

- 4,500 feet between Category II aircraft or if the succeeding aircraft is Category II

- 6,000 feet if the preceding or succeeding aircraft is a Category III.

The Same Runway Separation (SRS) categorization scheme is used to determine the distance between two successive departing aircraft. The SRS aircraft categories are as follows:

Category I: Small aircraft weighing 12,500 lbs. or less, with a single propeller driven engine, and all helicopters.

Category II: Small aircraft weighing 12,500 lbs. or less, with propeller driven twin-engines.

Category III: All other aircraft.

Based on the SRS aircraft category descriptions, the vast majority of operations in major Class B airspace airports will involve SRS Category III aircraft.

Wake turbulence considerations also affect the separation, sequencing, and timing of departing aircraft. When using the same runway or a parallel runway less than 2,500 feet apart, all aircraft taking off behind a *Heavy* or *B757* aircraft must be separated by a 2 minute interval starting at the beginning of the *Heavy/B757* takeoff roll. However, the wake turbulence separation minima shown in Table 24 may be used in lieu of the 2 minute interval if radar separation can be guaranteed prior to or when an aircraft becomes airborne. The 2 minute interval is recognized to be in excess of the 4 mile separation indicated in Table 24, and may be requested by the pilots prior to taxiing onto the runway.([125] §3-9-6) For all other aircraft, and unless otherwise specified by the aforementioned SRS rules, the 3 mile radar separation minimum is applied for departures.([125], §5-5-4)

A 2 minute interval is also used for a departure following a *Heavy* or *B757* arrival on the same runway with a displaced threshold, if flight projected paths intersect . Under these circumstances ATC does not issue a takeoff clearance to departing aircraft until this 2 minute interval has been completed. Arrivals following a *Heavy* or *B757* departure on the same runway must also be separated with a 2 minute interval.([125] §3-9-6)

Intersection departures, which constitute any departure initiated from a runway intersection that is not the runway heading/end, are also limited by wake turbulence considerations. A 3 minute interval is enforced for *Small* aircraft conducting an intersection departure, in the same or opposite direction, of a preceding departure on the same runway. This separation standard is extended for *any* aircraft conducting an intersection departure if a preceding *Heavy* or *B757* has taken off in the same or opposite direction from the same runway, a parallel runway less than 2,500 feet apart, or a parallel runway less than 2,500 feet apart with runway thresholds displaced by 500 feet or more.([127],[125] §3-9-7)

Separation standards are also prescribed for departures using intersecting runways, or non-intersecting runways for which flight paths intersect. In general, the clearance for takeoff of a succeeding aircraft is not issued until the preceding departing aircraft has departed and passed the runway intersection while airborne, or has crossed the departure runway while on

takeoff roll, or has turned away from the succeeding aircraft's path at any point. Similarly, takeoff clearance for a succeeding aircraft is not issued until an preceding arriving aircraft has completed the landing roll and has stopped (hold short) of the intersection with the departure runway, or has passed the runway intersection during landing roll, or has crossed over the departure runway while airborne prior to landing. Beyond these considerations, wake turbulence separation is also applied for these types of departures. All departing aircraft succeeding a *Heavy* or *B757* departure must be separated by a 2 minute interval if their projected flight paths cross, whether departures are taking place from intersecting runways, non-intersecting non-parallel runways, or parallel runways separated by 2,500 feet or more. Similarly, all departing aircraft succeeding a *Heavy* or *B757* arrival on a crossing runway must be separated by a 2 minute interval if the departure flight path crosses the arrival flight path.([125] §3-9-8)

Departure and arrival operations in facilities that offer radar services are further subjected to radar separation minima, intended to guarantee that air traffic movement will be adequately captured by the available radar capabilities to ensure safe and efficient operations. Radar separation for successive or simultaneous departures requires that radar identification with all aircraft be established within 1 mile of the takeoff runway and that takeoff courses diverge by at least 15 degrees. As illustrated in Figure 48, departures from a single runway (A) or from runways less than 2,500 feet apart (B) must be separated by no less than 1 mile, measured when the succeeding aircraft crosses the runway end. Simultaneous departures from non-intersecting diverging runways (C) are allowed, granted that the runway headings diverge by more than 15 degrees. For intersecting runways (D) a succeeding departure is allowed immediately after the preceding aircraft has passed the runway crossing. Simultaneous departures are also allowed from parallel runways with more than 2,500 feet separation (E).([125] §5-8-3)

For consecutive departure-arrival operations on parallel or non-intersecting diverging runways radar separation requires that a departing aircraft must be separated from an arriving aircraft on final approach by a minimum of 2 miles, only if this separation will increase to a minimum of 3 miles within 1 minute after takeoff. In other words, departing

Figure 48: Radar Separation Minima for Successive and Simultaneous Departures. ([125] §5-8-3)
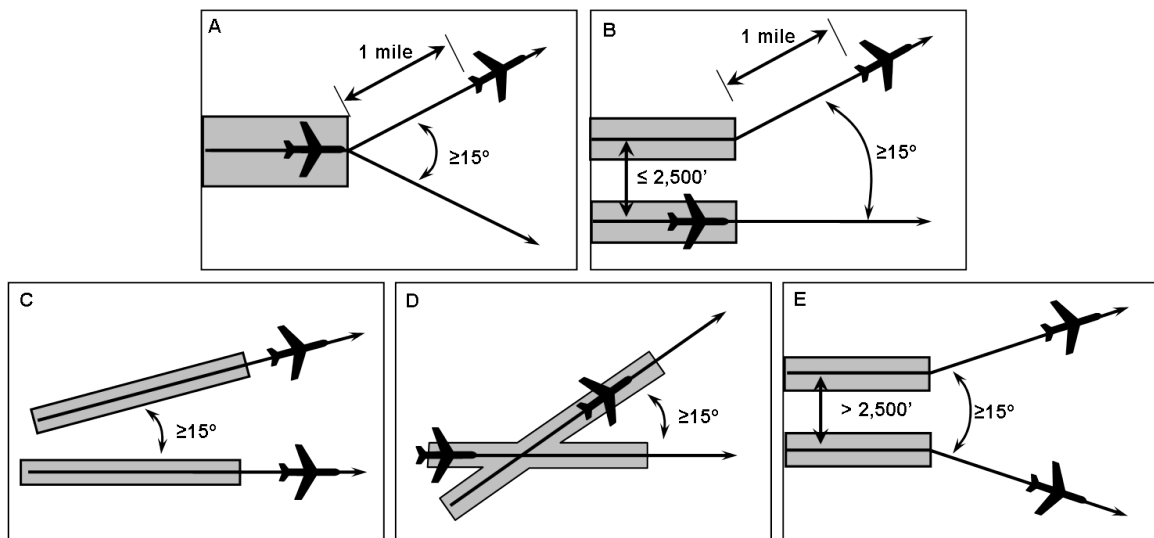
aircraft may be cleared for takeoff if an arriving aircraft is no closer than 2 miles from the runway at the time that the departing aircraft commences the takeoff roll.([125] §5-8-4) The implementation of this separation rule, sometimes referred to as the "*2 increasing to 3 rule*"[186], is readily observed in airports with designated arrival runways in close parallel proximity to designated departure runways, such as ATL (runways 26R and 26L, and 27R and 27L), LAX (ruwnays 24R and 24L, and 25R and 25L), SEA (runways 16L and 16R), or PHX (runways 7L and 7R).

However, radar separation allows for simultaneous arrival and departure operations for parallel runways where the missed landing course and the takeoff course diverge by 30 degrees or more. As illustrated in Figure 49, this operation may take place if parallel runways are separated by more than 2,500 feet and their thresholds are even (A). If runway thresholds are staggered, then simultaneous operations are allowed:

- If the landing aircraft is approaching nearer runway, and parallel runways are at least 1,000 feet apart and landing thresholds are staggered at least 500 feet for every 100 feet less than 2,500 that the runway centerlines are separated (B)

Figure 49: Radar Separation Minima for Parallel and Non-Intersecting Departures-Arrival Operations. ([125] §5-8-5)
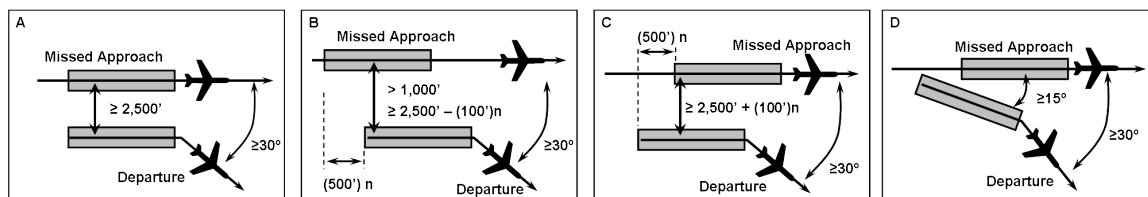
- OR, if the landing aircraft is approaching the farther runway, and parallel runway separation exceeds 2,500 feet by at least 100 feet for each 500 feet of threshold stagger (C)

Simultaneous operations are also permitted for radar-separated operations from non-intersecting diverging runways, as long as runway headings diverge by 15 degrees or more, and missed approach and departure headings diverge by 30 degrees or more (D).([125] §5-8-5)

A.3.4 Separation in Arrival Operations

As with departures, arrival procedures involve a number of communications between aircraft and ATC, whether it is TRACON or the control tower, where ATC issues information and instructions that aircraft must acknowledge and comply with. ATC issues instructions and clearance to land in such a way that the appropriate separation is maintained among all aircraft. ATC may issue clearance in anticipation of future aircraft positions if there is sufficient assurance that prescribed separations will be maintained. ATC is also responsible for instructing arriving traffic what taxiway should be used to exit the runway, and any instructions to hold short of an intersecting runway or taxiway.([125] §3-10-5, 3-10-6, 3-10-9)

For arrivals using the same runway, runway occupancy is a critical factor driving how aircraft separation is implemented. In general, a succeeding arriving aircraft should not cross the runway threshold until the preceding aircraft has landed safely and is clear off the runway. Similarly, a landing aircraft should not cross the runway threshold until a preceding departing aircraft has taken off safely and has crossed the runway end. Wake

turbulence considerations for separation during arrival operations are implemented by ATC as described in Table 25. As with departures, SRS categories are also used to determine reduced separation minima for arrivals following other arrivals and arrivals following departures, granted such operations occur between sunrise and sunset and as long as distances along the runway can be adequately determined. A preceding landing aircraft need not have cleared the runway if the following SRS minima exist ([125] §3-10-3):

- 3,000 feet for Category I aircraft landing behind a Category I or II aircraft

- 4,500 feet for Category II aircraft landing behind a Category I or II aircraft

A preceding departing aircraft need not have crossed the runway end but rather only be airborne if the following SRS minima exist

- 3,000 feet for Category I aircraft landing behind a departing Category I or II aircraft

- 4,500 feet for Category II aircraft landing behind a departing Category I or II aircraft

- 6,000 feet when either aircraft is a Category III

Separation for arrivals on intersecting runways, or non-intersecting runways for which flight paths intersect, are also prescribed. For an arriving aircraft succeeding a departure, the arriving aircraft should not cross the landing runway threshold or the flight path of a departing aircraft until the preceding departing aircraft has crossed the runway/flight path intersection during takeoff roll or is airborne prior to the runway/flight path intersection and has turned to avoid conflict. For an arriving aircraft succeeding another arrival, the succeeding aircraft should not cross the landing runway threshold or the flight path of the preceding aircraft until the preceding aircraft has landed and cleared off the runway, or completed landing roll and held short of the runway/flight path intersection, or passed the runway/flight path intersection. Wake turbulence considerations dictate that any aircraft landing behind a departing *Heavy* or *B757* aircraft on a crossing runway must be separated by a 2 minute interval if the landing aircraft will fly through the airborne path of the departure. Additionally, wake turbulence advisories are issued by ATC to any landing

aircraft if it will fly through, or traverse through during landing ground roll, the takeoff ground roll path of a preceding *Heavy* or *B757* departure.([125] §3-10-4)

Arrival procedures in facilities providing radar services are also subjected to radar separation minima. The controller in charge of radar arrivals is responsible for giving instructions to aircraft so as to maintain adequate separation, *unless the control tower authorizes visual separation.* Different radar separation minima exist for different types of approaches. For single runway approaches in-trail separation dictated by radar and wake turbulence minima, as depicted in Table 25, must be maintained. Aircraft performing *dependent* ILS/Microwave Landing System (MLS) arrivals to parallel runways must have a minimum vertical separation of 1,000 feet, or 3 miles radar separation, during turn-on to final approach, whether they are landing on the same or on different runways. During final approach, there must be at least 1.5 miles diagonal separation between successive arriving aircraft on the adjacent final approach paths if extended runway centerlines are between 2,500 and 4,300 feet, and at least 2 miles diagonal separation if extended runway centerlines are between 4,300 feet and 9,000 feet. Aircraft on the same final approach course must observe radar separation and wake turbulence separation minima as presented in Table 25.([125] §5-9-5, 5-9-6)

Independent dual and triple ILS/MLS arrivals are permitted based on prescribed runway separation minima. Independent dual arrivals are permitted whenever runway separation is no less than 4,300. Independent triple arrivals are permitted whenever runways separation is no less than 5,000 feet and the field elevation is not greater than 1,000 feet MSL. Independent triple arrivals at airports where field elevation is over 1,000 feet MSL and/or where runway separation is less than 5,000 feet but greater than 4,300 feet are allowed granted that ATC approach control is equipped with high-resolution color monitors. Dual and triple independent arrivals require that traffic have a minimum vertical separation of 1,000 feet, or 3 miles radar separation, during turn-on to final approach. More specifically for triple parallel approaches, all aircraft simultaneously executing turn-on to final approach must be assigned *different* altitudes so that there is a minimum vertical separation of 1,000 feet from each other, for instance 4,000, 5,000, and 6,000 feet. After turn-on to final approach course double and triple approaches must have at least 1 mile of straight flight prior to

intercepting the glide slope to allow for dissipation of excess speed. Said approaches must also be *straight-in* landings and must have a No Transgression Zone (NTZ) at least 2,000 feet wide equidistantly located between extended runway approach courses. For all dual and triple independent approach procedures aircraft on the same final approach course, radar and wake turbulence minima is applied. ([125] §5-9-7)

The runway separation minimum for simultaneous dual ILS/MLS operations can be reduced, effectively becoming *simultaneous close parallel ILS Precision Runway Monitor (PRM) approaches*. The runway separation may be reduced to to 3,000 feet if the facility is equipped with a 1-second (high-rate) update radar system and one of the localizers is offset by 2.5 degrees, effectively diverging the corresponding final approach course by that same amount. Alternatively, the separation minimum can be reduced to 3,400 feet if the facility is equipped with 2.4 second or less update radar. Use of Simultaneous Offset Instrument Approach (SOIA) procedures also enables the reduction of the runway separation minima, enabling simultaneous dual arrivals for runways less than 3,000 feet but at least 750 feet apart.([125] §5-9-8, 5-9-9)

APPENDIX B

REVIEW OF DEMAND MANAGEMENT SOLUTIONS

Different forms of demand management have been generally applied to a vast number of service industries across the entire economy such as telephone and communications , tourism and lodging, and restaurants. Transportation is also subjected to strong variations in demand and has also been the subject of demand management studies, most notably for road vehicle traffic and civil aviation.([284] Ch1,2) In the context of air transport operations, demand management refers to "the collection of strategic, administrative, and economic policies designed to ensure that demand for access to some element of the ATM system is kept at a manageable level".[84] These options have some attractive features relative to capacity enhancement alternatives, such as shorter implementation times and seemingly lower upfront costs.[205]

A common form of demand management is the implementation of *slots*. This regulatory scheme, developed by IATA, limits access to highly congested airports by allowing only those operators who own or hold slots to take off and land. Airports that implement a slotting system, referred to as *fully coordinated* airports, determine the number of slots for a given time period based on the airport's capacity and the conditions under which safety margins are maintained. Although more than 140 airports worldwide operate under slot allocation practices, including most of Europe's busiest, only four in the U.S. are fully coordinated: New York LaGuardia (LGA), New York John F. Kennedy (JFK), Chicago O'Hare (ORD), and Washington DC Reagan National (DCA). This measure has been severely criticized, as it is said to allow anti-competitive and monopolistic behavior, contradicting the deregulation policies that embody the current paradigm.[84] The 2000 Wendell H. Ford Aviation Investment and Reform Act for the Twenty-first Century, commonly referred to as *AIR 21*, called for the elimination of of slot allocation in any US airport who had previously implemented it within 5 years of the issuance of the Act.[58] However, mostly due to lack

of consensus between stakeholders regarding the design of a permanent slot system, the temporary scheme was still in place at LaGuardia by the end of 2007. The most controversial aspect of slot allocation concerns the allocation mechanism. Airlines that wish to penetrate a high-demand market favor allocation schemes that offer opportunities for entrant competitors. Incumbent airlines favor schemes that enable them to keep a tight hold of slots. The new slot auctioning system proposed in 2007 for LaGuardia sought continue capping operations, make slots available for new competitors, and channel revenues from the auctioning to finance air traffic control infrastructure. Airlines currently holding slots at this airport strongly opposed the proposal and continue to do so to date.[296]

Another common demand management measure is operations *de-peaking*, or *schedule smoothing*, where the time-of-day distribution of (demand for) landings and takeoffs is spread out more evenly relative to the traditional instance where a high number of flights are scheduled to depart or arrive in certain morning and afternoon time periods. Rather than artificially reducing or capping demand levels through regulatory measures such as a slot system, de-peaking seeks to re-allocate existing demand. Research has demonstrated and quantified the effectiveness of airport de-peaking. In a simulation study, daily delay at congested airports was shown to be potentially reduced by 40% during peak evening hours and by 20% during peak morning hours, relative to actual operations and schedules for August 2001. However, only airports facing high operational demand in isolated portions of the day can effectively address delays through de-peaking without having to resort to demand reduction. For airfields that face demand levels close or beyond VFR limits on a continuous basis, demand reduction measures such as slot allocation are necessary and de-peaking is rendered utterly useless. [84] It has also been observed that airport operators airlines are able to better spread the workload of their personnel by de-peaking, but that that the benefits of delay reduction are offset by prolonged connection times and that passengers are unlikely to agree to a premium in exchange for more connection alternatives.[220]

Slot auctioning has been studied as an allocation mechanism for de-peaking. It employs basic market rules rather than administrative/regulatory ones. In this approach the slots of high-demand periods are assigned increasingly higher prices until only those carriers whose

willingness to pay the growing market price for the slot, and for which demand is greatest, remain.[1][207] However there are important challenges, as well as hidden costs and losses, in de-peaking. For instance, schedule smoothing implies changes in the hub and spoke operational concept, which would degrade benefits associated with increased connectivity, more flight options for the traveling public, and economies of scale for airlines.[205]

Other demand management schemes include flight relocation to alternate airports and policy options for aircraft size minima. A recent study on the effect that different combinations of demand management systems have on the reduction of demand have enabled the quantification of their benefits. However, only the combination of all demand management options was shown to accommodate forecasted increases in demand with acceptably low levels of delay. Moreover, the study notes that these measures "require significant changes in airline scheduling and fleet purchase strategies"[205], making them very impractical and unfeasible.

Demand management options have also been considered for the mitigation of environmental impact. For instance, taxes and charges in the form of *environmental levies* represent economic, market-based, and regulatory measures that exploit market rules to curb demand for air travel by artificially increasing its price. In general, environmental levies assign an operating cost that is proportional to the amount and form of emissions generated by a given air traffic operation. A slightly different approach has been considered for reductions in road traffic emissions by making use of congestion-based pricing, namely increasing the cost of road usage as a function of road congestion. The idea behind this approach is that curbing the demand for road access in otherwise congested times not only would reduce emissions by reducing the traffic volume, but would do so as well by enabling more favorable operating conditions where vehicles move more and generate less emissions.[146] For civil air transportation different schemes detailing how charges could be determined as a

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[1]Market rules are also used by carriers to adjust fares following seasonal variations in demand. Access to tickets in high seasons such as summer, winter holidays and the thanksgiving weekend, is limited to those willing to pay for the higher prices. Schedule smoothing on a daily basis also uses market rules as a demand management scheme. Just as slots auctioning is the means for airports to limit access to those airlines most willing to pay for it, increases in fares is the means by which airlines manage the demand for flights in highly desirable times during the day.

function of emissions and noise have been proposed, but there is still lack of agreement on appropriate mechanisms for a full-scale implementation in civil aviation. Uncertainty about carrier behavior, price elasticity of demand for air travel, and underlying regulatory functions, further complicate the analysis and obfuscate the task identifying the implications of implementing environmental levies. What has been recognized with some confidence is that to be effective, such a measure would necessitate implementation on an international scale. Not only does this represent a very large policy challenge but moreover it stands at odds with the incentive of promoting the growth of air transport and meeting its growing demand as was articulated in the previous chapter.([243], Ch. 10)

In general, well designed demand management schemes can effectively address mismatches with capacity and help reduce environmental impact. However, the variability in demand that they address is confined to short or medium time frames, spanning from hourly to monthly variations. In turn, it has been recognized that the benefits of demand management exist only within a limited time horizon. A focus on demand management solutions to address delay within a short time frame results in a narrow view of the operational problem, and deemphasizes the matter of capacity enhancement as the enabler of sustained growth in air transportation over the long term.[205] Even suboptimal demand management schemes can be shown to be effective, but should only be considered as temporary measures.[84] The formulation of the operational-environmental problem is best presented in the context of a long term horizon, strongly suggesting that demand management is a necessary approach but insufficient if not properly complemented with capacity enhancement. Moreover, the incentive articulated in the previous chapter is to meet growing demand with necessary capacity, not to cap it. Schemes like slot allocation are inherently plagued with stakeholder conflict and contradict the deregulation and liberalization policies that have allowed the air transport to grow and prosper. They also hide many policy problems, costs, and losses, making them fairly unpopular with key players.[205]

APPENDIX C

KEY ENTITIES AND STAKEHOLDERS OF THE AIR TRANSPORTATION SYSTEM

C.1   The International Civil Aviation Organization

The International Civil Aviation Organization (ICAO) is a United Nations (UN) specialized agency [176] that serves as the main regulatory body for international civil aviation and acts as the "permanent body charged with the administration of the principles laid out in the [1944 Chicago Convention on Civil Aviation]."[170]. Said convention sought to lay out the guiding principles and agreements among signing governments so that "*international civil aviation may be developed in a safe and orderly manner and that international air transport services may be established on the basis of equality and opportunity and operated soundly and economically.*"[173] The convention served as a discussion forum on post-war civil aviation between the United States and 52 other allied and neutral countries. It produced a 96-article document outlining the privileges and responsibilities of the contracting states and providing for the creation of Standards and Recommended Practices (SARP). The ratification of these articles by 26 signatory states resulted in the official creation of ICAO in April 4th 1947, a number which has since grown to over 160 ratifying states.[22] When SARPs are adopted by ICAO they are included in the annexes to the Chicago Convention. Currently there are 18 such annexes which cover key aspects of civil aviation such as "Rules of the Air" (Annex 2), "Aeronautical Charts" (Annex 4), "Operation of Aircraft" (Annex 6), "Airworthiness of Aircraft" (Annex 8), "Air Traffic Services" (Annex 11), "Aerodromes" (Annex 14), and "Environmental Protection" (Annex 16).[170]

In 1997 ICAO adopted a Strategic Action Plan where it sought to adapt the framework embodied by the principles and structure of the convention so that it could effectively respond to the present-day challenges and needs of signatory nations. The Strategic Action

Plan is composed of eight objectives that that guide the yearly work plan and the allocation of resources for its numerous initiatives. The plan is a live document that is reviewed and updated as necessary to remain flexible and adapt to the fast-changing environment of civil aviation.[170] ICAO is divided into five bureaux, including the Air Navigation Bureau and the Air Transport Bureau.[171] The former is charged with providing technical studies and recommendations for the development of SARP's, and is intimately related with the technical content of sixteen of the eighteen annexes of the convention.[169] The latter is charged with the implementation of security, environmental protection, efficiency and continuity strategic objectives, and thus fulfills a number of functions within ICAO. A notable example is the provision of economic advice to a number of ICAO bodies such as the Air Navigation Bureau and the Committee on Aviation Environmental Protection (CAEP), which exists under the Air Transport Bureau Environmental Unit (ENV).[180] CAEP was created in 1983 to undertake the majority of ICAO's environmental efforts, superseding the Committee on Aircraft Noise (CAN)Committee on Aircraft Noise and the Committee on Aircraft Engine Emissions (CAFE).[172]

C.2   The Federal Aviation Administration

The Federal Aviation Administration (FAA) is the prime U.S. governmental entity responsible for civil aviation. It operates under the U.S. DoT executing functions of air commerce regulation and safety, control of airspace usage, installation and operation of air navigation facilities, development and operation of air traffic control and navigation, direction and guidance of research and development, and regulation of civil aviation environmental impact among others.[1][22, 114] As the primary regulatory body of aviation in the U.S. the FAA maintains a series of Federal Aviation Regulations (FAR) where all relevant rules to which parties must abide in order to legally hold and operate an aircraft. FAR incorporate standards and accepted practices that whose purpose is to ensure the safe and orderly operation of aircraft under a wide variety of conditions.

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[1]The FAA was originally created under the name Federal Aviation Agency by the Federal Aviation Act of 1958. The current name of the FAA was adopted when it was officially absorbed by the U.S. Department of Transportation in the Department of Transportation Act of 1967 [22, 114]

Leadership and oversight of the FAA is charged to the Administrator, who directly interacts with FAA key officials such as the Deputy Administrator, the Chief of Staff, the Chief Operating Officer of the ATO, and leaders of other bodies outside the FAA such as the Joint Planning and Development Office (JPDO). The ATO is the branch of the FAA responsible for the safe and efficient movement of air traffic across the nation by providing services through controllers, engineers and supporting personnel.[124] The FAA is divided into a series of Assistant or Associate Administrations that operate under the direction of the FAA Deputy Administrator. Examples include those for Regions and Center Operations (ARC), for Aviation Policy, Planning and Environment (AEP), for Airports (ARP), and for Aviation Safety (AVS), among others. In turn, each of these units oversees a number of offices responsible for specific activities and functions within the FAA. For instance, the Associate Administration for Airports hosts the Office of Airport Safety and Standards, and the Office of Airport Planning and Programming.[120]

C.3 The National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA) is a the primary government body responsible for research efforts dedicated to "space exploration, scientific discovery and aeronautics research."[229] NASA's predecessor was the National Advisory Council for Aeronautics (NACA), created in 1915 for the study of aeronautical sciences and engineering. The council was formed in a time when significant technological advances were taking place and incentive existed for a center of aeronautical research, motivated in part by the role that aviation had begun to demonstrate for military applications in World War I. Over the next few decades advances in propulsion, aerodynamics and rocketry among others expanded the scope of the council. These factors, along with the beginning of the space race and the need for an American space program, led to the creation of NASA through the National Aeronautics and Space Act of 1958.[31, 54]

Currently, NASA's structure features four mission directorates responsible for the primary areas of research: Aeronautics, Exploration Systems, Science, and Space Operations. The work of the Aeronautics Research Mission Directorate (ARMD), of particular relevance

to this thesis, is divided into four major programs. The Fundamental Aeronautics Program, which contains projects for subsonic, supersonic, rotary wing and hypersonic vehicles, seeks to address current challenges in air transportation by developing "focused technological capabilities, starting with the most basic knowledge of underlying phenomena through validation and verification of advanced concepts and technologies."[231] The Airspace Systems Program focuses its efforts on the transformation of the NAS from an operational perspective as well as from that relating to the aircraft in it. Similarly, the Aviation Safety Program focuses on the safe movement and operation of aircraft in the system and its associated challenges, while the Aeronautics Test Program provides a vast pool of testing resources and facilities. Through a series of partnerships the ARMD continuously works with other government bodies such as the U.S. Army, the U.S. DoD, the FAA, the White House Office of Science and Technology Policy (OSTP), and the JPDO. [229, 226, 231, 230, 232]

C.4 The Joint Planning and Development Office

The Joint Planning and Development Office (JPDO) was established in 2003 by the Vision 100 - Century of Aviation Reauthorization Act [56] as the primary entity in charge of coordinating a multi-agency partnership between government and private bodies to design an air transportation concept meeting the needs of the nation, and to deploy it by the year 2025. The vision of this system was originally called the NGATS, but has since be renamed Next-Gen. The transformation of the air transportation system is enacted through the JPDO joint initiative which includes NASA, OSTP, FAA, DoT, DoC, and the DHS.[192, 190]

The JPDO is divided into six divisions in charge of multiple technical and supporting functions: Systems Modeling and Analysis, Enterprise Architecture and Engineering, Policy, Portfolio Management, Partnership Management, and Business Management. Additionally, the JPDO contained a set of eight Integrated Product Teams responsible for specific areas of interest. In 2007 these were superseded by nine Working Groups that serve the same core purpose: Aircraft, Air Navigation Services, Airport, Environment, Safety, Security, Net-Centric Operations, Global Harmonization, and Weather.[195, 196]

C.5 The Transportation Research Board of the National Academies

Originally established as the National Advisory Board on Highway Research in 1920, today the Transportation Research Board (TRB) is one of six units of the National Research Council, which serves as the primary operating arm of the National Academy of Sciences, the national Academy of Engineering, and the Institute of Medicine, collectively known as the National Academies. The mission of the TRB is stimulate, coordinate, and manage research initiatives in matters of transportation, as well as to publish and disseminate the findings of said research, and in many cases, promoting their practical implementation beyond the research realm. In turn, the TRB is responsible for conducting a series of policy analyses and studies on key transportation issues, often times at the request of Congress or executive-branch entities. The TRB is supported by the DoT through modal administrators (aviation, freight, public transport, rail, and marine), by state level departments of transportation, and by other government bodies with special interests in specific programs such as the FAA-sponsored Airport Cooperative Research Program.[285, 286]

C.6 Operators and Service Providers

There is a variety operators and service providers responsible for the plethora of functions involved in air transportation. Many of these entities are organized into representation groups, usually through a membership system, so that their collective interests can be voiced and their relationships with other key players can be managed in a unified fashion. As such, these special interest organizations have a strong bearing on decisions about the development of the air transportation system.

Players of paramount importance in this thesis are airport operators. These are the bodies and individuals "responsible for enabling passenger, flight, and cargo operations conducted within an airport with consideration for safety, efficiency, resource limitations, and local environmental issues."[192] Airports also host a spectrum of tenants who offer supporting services such as fueling or catering, as well as security providers who are responsible for homeland security and law enforcement functions. The Airports Council International (ACI) is an entity comprised of airport operators from around the world

founded in 1991 to represent their common interests and voice the views of its members on key issues while fostering cooperation with other players in the air transportation system. The ACI resulted from the merging of the Airport Operators Council International and the International Civil Airports Association which represented primarily U.S. and European members respectively. Among its multiple relationships with other industry representatives the ACI maintains a strong and continuous partnership with ICAO where it defends the position of airport operators and provides expert opinion in the development of SARPs and relevant regulations.[192, 22, 15]

Also of key relevance are flight operators, in charge of planning and executing a flights schedule with a given aircraft fleet. In this thesis flight operators refers primarily to commercial aviation, namely airlines and their personnel such as flight crews and Flight Operations Center (FOC) staff. The International Air Transport Association (IATA) is an international and non-governmental body whose core mission is to represent and serve the airline industry. With over 235 member airlines, IATA seeks to foster interest in matters of civil aviation, leverage the creation of standard practices in the airline industry, and provide a space to share the industry's views and interests. To do so IATA partners with key air transport players such as airport operators, aircraft manufacturers, and the fuel industry among others.[192, 168, 22]

There are many other service providers who operate separate from, but often in collaboration with, airport and flight operators. For instance, weather service providers dispense relevant meteorological information to flight and airport operators, and Air Navigation Service Providers (ANSPs) procure ATC and ATM services for flight operators.[192]

Within each of these major player categories there is an abundance of professions and trades whose collective interests are the responsibility of labor unions. Notable example include the Air Line Pilots Association (ALPA), which represents commercial aviation pilots in the U.S. and Canada and is the world's largest pilots' union, or the National Air Traffic Controllers Association (NATCA).[11, 234]

C.7   Civil Aerospace and Manufacturers

The civil aerospace sector and all its manufacturing entities are responsible for the procurement of products and equipment necessary for flight operations.[192] This includes:

- Airframe manufacturers such as Boeing, Airbus, Bombardier, Embraer, and Gulfstream

- Engine manufacturers such as Rolls Royce, Pratt & Whitney, and General Electric Aircraft Engines

- Manufacturers of avionics and other aircraft systems such as Honeywell Avionics, Dassault Electronique, and Thales Avionics

- Manufacturers of ATC and ATM equipment (e.g. RADARs, antennaes, and ground control systems) such as BAE Systems and L3 Communications

- Manufacturers of navigation aids and ANSP equipment, such as Alenia Marconi Systems, Honeywell Airport Systems, and Thales Navigation

C.8   Airport Communities and the Traveling Public

There are two groups in the general population who play important roles in the air transportation system. One of them are airport communities which, as explained in Chapter 2, are the populated areas in the vicinity of airports. Because of their relative proximity, these communities experience most directly the effect of aviation activity to and from the airport, particularly in terms of environmental impact. As a result they are particularly sensitive to variations in operational activity levels as well to the implementation of solutions to the operational-environmental problem. Airport communities have been significantly successful in organizing themselves and establishing strong relationships with elected officials who, in the interest of satisfying an important segment of their constituent base, represent their interests and take action accordingly in the political and legal arena.

The other group is the traveling public who, along with traders, represent the customers and end users of the air transportation system. This group also experiences the impact of

the operational-environmental problem directly, particularly in terms of delay during air travel. As was shown in section section 2.4.3, shortcomings in the operational capacity of the system during the last two decades or so have resulted in periods of unprecedented delay and the great economic loss associated with it. One such period was the summer of 1999 where excessive delays led to a series of congressional hearings where customers and representatives argued for a Passenger Bill of Rights.[241] Consumer advocacy groups and special interests groups continue to represent the interest of the traveling public and to push for measures that, among other objectives, aim to mitigate the economic loss and inconvenience experienced by passengers due to delay.

APPENDIX D

REVIEW OF RESPONSE SURFACE METHODOLOGY, REGRESSION ANALYSIS, AND ASSOCIATED STATISTICAL TECHNIQUES

D.1 Introduction

This appendix provides a basic overview of response surface methodology, multiple linear regression, statistical hypothesis testing, and other techniques relevant to the analysis of data produced for this thesis. While broadly covering some basic principles and key concepts based on their use and applicability within this dissertation, this purpose of this overview is not to exhaustively cover all the theory associated with them.

D.2 Response Surface Methodology

Response Surface Methodology (RSM) is *"a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes [with] important applications in the design, development, and formulation of new products, as well as in the improvement of existing product designs."*([224], p 1) A fundamental concept at the core of RSM is that the metrics of performance of a product or process are influenced, to lesser or greater extent, by its characterizing parameters. These performance metrics are of interest because they provide a measure of the quality of the product or process in question, whereas the importance of its parameters lies on the fact that they may be controllable and thus can be adjusted to improve quality and value. This relationship of influence is captured by referring to a measure of performance as the *response*, *response variable*, or *dependent variable*. Conversely, characterizing parameters influencing the response are referred to as *input variables* or *independent variables*.

In this sense, an overarching objective in RSM is to explore, analyze, understand, and ultimately model this relationship between the response and its input variables. Since the

exact function describing this relationship is unknown, the basic approach in RSM to model this relationship is to use a data set containing observations of the response and the input variables to fit a function of known mathematical form. This process is referred to as *model fitting*, and it involves the determination coefficient values within the known mathematical function. In RSM the assumed mathematical function is a linear combination of the input variables. The determination of the coefficients can be reduced to a linear system problem solved through a model-fitting technique known as *linear regression*. The model that results once the values of all coefficients are determined is referred to as a *regression model*. If this model has only one input variable, or *regressor variable*, the technique is referred to as a *simple linear regression*, and if it has multiple regressor variables it is referred to as *multiple linear regression*.([224], Ch 1)

D.3 Multiple Linear Regression

Multiple linear regression is concerned with modeling the response variable y as a function of k input variables $x_1, x_2, ..., x_k$), using a data set of n observations. For the ith observation, the response variable y has a value y_i and the input variables have values $x_{1,i}, x_{2,i}..., x_{k,i}$. The response variable y is therefore modeled as a linear combination of input variables

$$y = \beta_0 + \beta_1 x_1 + ... + \beta_k x_k + \epsilon = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \epsilon \tag{20}$$

where ϵ is the error associated with the model. Note that the $beta_0$ is the intercept term in the linear relationship, whereas β_1 thorough β_k are the slope terms for each of the regressor variables. These coefficients are unknown and must be estimated to generate the multiple linear regression model of y. It follows that the value of the response variable y_i is modeled as

$$y_i = \beta_0 + \beta_1 x_{1,i} + ... + \beta_k x_{k,i} + \epsilon_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{j,i} + \epsilon_i \tag{21}$$

The linear nature of this relationship can be extended to one of higher order by expressing some input variables as products of others. For instance, the function $x_2 = x_1^2$ effectively replaces x_2 with the *quadratic* term x_1^2 (product of x_1 with itself), so that the

regression model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \epsilon$$

becomes the 2nd order, or quadratic, regression model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_1^2 + \epsilon$$

In a similar fashion a linear term can be replaced by a *cross product*, or *interaction*, term that captures the product of two (or more) different input variables rather than the product of an input variable with itself. A regression model that includes quadratic and interaction terms for two input variables x_1 and x_2 is known as a *response surface model*, and is expressed via the *Response Surface Equation (RSE)*:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_1^2 + + \beta_3 x_2 + \beta_4 x_2^2 + \beta_5 x_1 x_1 + \epsilon \tag{22}$$

This basic definition of the response surface model only considers two input variables x_1 and x_2, but can be extended to a multiple linear regression model with k input variables resulting in a k-dimensional response surface model for which a general RSE can be expressed as follows:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_{(j)} x_j + \sum_{j=1}^{k} \beta_{(j,j)} x_j^2 + \sum_{j=1}^{k-1} \sum_{h=j+1}^{k} \beta_{(j,h)} x_j x_h + \epsilon \tag{23}$$

Note that Equation 23 is expressed in terms of k input variables but that it contains more than k terms because quadratic and interaction terms were incorporated through variable replacements. More specifically, the RSE contains 1 intercept term, k linear terms, k quadratic terms, $(T_{(k-1)})$ interaction terms, and 1 error term, indicating that there are a total of $K = (2k+T_{(k-1)})$ regressor variables in the equation but that $(k+T_{(k-1)})$ of them are expressed as a function of the k input variables. Accordingly, the multiple linear regression of this model estimates values for the K coefficients $(\beta_1, ... \beta_K)$ and the intercept β_0. The indexing notation of the $n+1$ coefficients in Equation 23 facilitates their identification with the different types of terms, namely linear, quadratic, and cross product, in terms of the k input variables. It is worth noting that an RSE is not limited to be second order and can be further expanded to include cubic terms and corresponding interaction terms.

The most popular method for estimating the regression coefficients is the *method of least squares.* This method uses a data set with n data points or observations. Each of the n observations includes a value for the response variable y and a value for each of the k input variables $x_1, ... x_k$. Thus, the response value for the ith observation can be modeled as

$$y_i = \beta_0 + \sum_{j=1}^{k} \beta_{(j)} x_{j,i} + \sum_{j=1}^{k} \beta_{(j,j)} x_{j,i}^2 + \sum_{j=1}^{k-1} \sum_{h=j+1}^{k} \beta_{(j,h)} x_{j,i} x_{h,i} + \epsilon_i \tag{24}$$

The method of least squares estimates the values for the coefficients such that the *sum of squares of errors, L,* is minimized. The sum of squares of errors is calculated using Equation 24 as

$$L = \sum_{i=1}^{n} \epsilon_i^2 = \sum_{i=1}^{n} \left(y_i - \beta_0 - \sum_{j=1}^{k} \beta_{(j)} x_{j,i} + \sum_{j=1}^{k} \beta_{(j,j)} x_{j,i}^2 + \sum_{j=1}^{k-1} \sum_{h=j+1}^{k} \beta_{(j,h)} x_{j,i} x_{h,i} \right)^2 \tag{25}$$

To minimize L, its partial derivatives with respect to the intercept and each of the coefficients is equated to zero, resulting in a linear system of $(K+1)$ equations known as the *least squares normal equations.* The solution to this linear system of equations produces *least square coefficient estimates* $(\hat{\beta}_0, \hat{\beta}_1, ... \hat{\beta}_K)$, or in the alternative notation $(\hat{\beta}_0, \hat{\beta}_1, ... \hat{\beta}_k, \hat{\beta}_{1,1}, ..., \hat{\beta}_{k,1}, ..., \hat{\beta}_{k,k},)$.([153] Ch. 13, [224] Ch. 2)

It is important to note that the method of least squares minimizes error, but does not reduce it to zero. There is an inherent amount of error within the model associated with the behavior of the response that it cannot capture in terms of the input variables. There are several sources of model error. For instance, the relationship between an input variable and the response can be misrepresented, or not properly captured, because the data set does not contain enough information about the relationship between them. To address this issue a Design of Experiments (DoE) can be used. A DoE is a carefully selected data set tailored to maximize regression information given a certain number of input variables and settings while observing constraints on the number of observations. Model error can also occur if one or more of the input variables chosen do not influence the response, or if input variables that do influence the response are not included in the data set. The result is a regression model that does not fully capture or explain the underlying behavior of the response in terms of the input variables selected. This can also occur when assuming an

inadequate mathematical form for the regression model, which may ignore or incorrectly include certain terms.

Of particular interest is the realization that studying regression models and their inherent error based on the data set utilized offers important insight about the underlying relationships under consideration. The significance of regression of all or specific regressor variables is fundamental in characterizing the behavior of a response and offers guidance into how it can be modified to improve performance, quality, and value.

D.4 Statistical Hypothesis Testing

The significance of regression of a response to its regressor variables, and the the significance of regressor variables relative to each other, are of fundamental interest in regression analysis and response surface methodology. This measures of significance are tested using *statistical hypothesis testing*, a methodology with which the plausibility of a given hypothesis is assessed. The hypothesis of interest is called the *null hypothesis*, and is denoted as H_0. An alternative hypothesis H_A is used to exhaustively define the opposite of the null hypothesis. There are two types of hypothesis testing problems based on the choice for H_0 and H_A. A *two-sided* problem has the hypotheses

- $H_0 : \mu = \mu_0$

- $H_A : \mu \neq \mu_0$

It is considered to have two sides since H_A includes values of μ that are greater than μ_0 *OR* smaller than μ_0. In similar fashion, a *one-sided* statistical hypothesis testing problem has the hypotheses

- $H_0 : \mu \leq \mu_0$

- $H_A : \mu > \mu_0$

or

- $H_0 : \mu \geq \mu_0$

- $H_A : \mu < \mu_0$

One-sided problems broaden H_0 and use the value of μ_0 as an upper or lower bound.

Statistical hypothesis testing uses the *p-value*, a probability value to measure the plausibility of the null hypothesis. Standard practice considers H_0 as *not* plausible if the p-value is between 0.00 and 0.01, and as plausible if the p-value is between 0.10 and 1.00. P-values between 0.01 and 0.10 are considered to be intermediate, or marginally plausible. If H_0 is not plausible then it is rejected in favor of the alternative hypothesis H_A. Conversely, if H_0 is plausible then it is accepted. However, acceptance of the null hypothesis does *not* mean that it has been proven to be true, only that it has been found to be *plausible*. Since a null hypothesis cannot be proven to be true, but at best it can be rejected by showing it to be implausible, a stronger level of inference is attained when the null hypothesis is rejected. Thus, the standard approach in statistical hypothesis testing is to define the hypothesis of interest as the the alternative hypothesis H_A, testing the null hypothesis H_0, and rejecting it by demonstrating that it is implausible.

The p-value is defined as "the probability of obtaining the data set or worse when the null hypothesis is true."([153], p. 394) In this definition a "worse" data set means one that is in less agreement with the the null hypothesis relative to the data set observed. It is also important to note that the definition of the p-value assumes that H_0 is true. Thus, a large p-value suggests that *if* H_0 is true then it is likely to obtain the data set observed, or one that is at least in as much agreement with H_0, and thus H_0 is plausible and should be accepted. Conversely, a very small p-value means that *if* H_0 is true the probability of obtaining the data set observed, or one that is at least in as much agreement with H_0, is very small. Thus H_0 is implausible and is should be rejected.([153], Ch. 8)

The level of agreement or discrepancy between an observed data set and a given H_0 is often described through a *test statistic*. There are several test statistics, such as the *t-statistic* and the *F-statistic*, applicable to different tests and having prescribed distributions after which the test statistic is named. Thus the definition of the p-value can be modified as "the probability of the test statistic being at least as extreme as the one observed given that the null hypothesis is true"([235], §7.1.3.1)

D.5 Analysis of Variance (ANOVA)

The Analysis of Variance, or *ANOVA*, is a statistical technique that tests the significance of regression of a response variable y to one or more regressor variables x_1 (..., x_k), based on a data set with n observations used to conduct the regression. A *one factor* ANOVA is applied in simple linear regression when only one regressor variable x is used for a response y; when applied to multiple linear regression analysis the ANOVA tests whether there is a linear relationship between the response y and *at least one* of the regressor variables $(x_1, x_2, ..., x_k,)$.

ANOVA follows the method of *statistical hypothesis testing*, and is concerned with supporting the hypothesis that the response y is related *to least one* of the regressor variables $(x_1, x_2, ..., x_k,)$. This hypothesis can also be expressed in terms of the corresponding regressor coefficient(s) $(\beta_1, \beta_2, ..., \beta_k,)$, for which at least one is non-zero. The complement, or opposite if this hypothesis is that the response is not related to any of the regressor variables and hence all regressor coefficients are equal to zero. Following common practice, the hypothesis of interest is accepted by testing and rejecting its opposite. Thus for ANOVA, the null hypothesis H_0 which is explicitly tested, and the alternative hypothesis H_A, are as follows:

- $H_0 : \beta_1 = \beta_2 = ...\beta_k = 0$

- $H_1 : \exists\, \beta_i : \beta_i \neq 0$

If H_0 is rejected then at least one of the regressor variables significantly contributes to the variability of the response. To test H_0, ANOVA makes use of the total sum of squares SST, which is a measure of the *total* variability in the data set.

$$SST = \sum_{i=1}^{n}(y_i - \bar{y})^2 \tag{26}$$

where n is the total number of samples in the data set, y_i is the the ith observation of the response variable in the data set, and $\bar{y}$ is the statistical mean of the response in the data set.

SST has (n-1) degrees of freedom associated with it. As a measure of the total variability of the data set, SST can be decomposed into two components of variability, one associated with the regression and one associated with the error, such that

$$SST = SSR + SSE \tag{27}$$

where SSR is the regression sum of squares SSE is the error sum of squares. Thus, SSR is a measure of the variability of the response *between* the regressor factor levels, and SSE is a measure of variability *within* the regressor variable levels. SSR has has k degrees of freedom associated with it, namely the number of regressor variables, and is calculated as

$$SSR = \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2 \tag{28}$$

where $\hat{y}_i$ is the value of the response variable as estimated by the regression model for the ith observation in the data set. In turn, SSE has (n-k-1) degrees of freedom associated with it, and is calculated as

$$SSE = \sum_{i=1}^{n}(e_i)^2 = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{29}$$

where e_i is the residual for the ith observation in the data set.

Since sum of squares are measures of variability in the data set, SST, and SSR can be combined into a ratio to provide a measure of variability explained by the regression with respect to the total variability of the data set. This ratio, referred to as the *coefficient of determination*, or *coefficient of multiple determination* in the case of multiple linear regression, is a statistic that assumes values between zero and 1 and is often used to quickly assess the significance of a set of regressor parameters.

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \tag{30}$$

However, the value of R^2 is known to depend on the number of regressor terms, and always increases as more factors are added to the model. To address this unwanted dependency the R^2 statistic can be corrected by normalizing each sum of square term with respect to number of degrees of freedom associated with it. Thus, SST is normalized with respect to n-1 total degrees of freedom, SSR is normalized with respect to k regression degrees

of freedom, and SSE is normalized with respect to n-k-1 error degrees of freedom. The resulting adjusted coefficient of determination is

$$R^2_{Adj} = \frac{SSR/(k)}{SST/(n-1)} = 1 - \frac{SSE/(n-k-1)}{SST/(n-1)} = 1 - \frac{n-1}{n-k-1}(1-R^2) \qquad (31)$$

The variance associated with the error is estimated via the *Mean Squared Error (MSE)*, which is calculated by dividing the error sum of squares SSE by the number of degrees of freedom associated with it, or

$$MSE = \frac{SSE}{(n-k-1)} \qquad (32)$$

Similarly, the variance associated with the regression is estimated via the *Mean Squared Regression (MSR)*, which is calculated by dividing the regression sum of squares by the number of degrees of freedom associated with it, or

$$MSR = \frac{SSR}{k} \qquad (33)$$

An adequate measure for significance of regression can be constructed by relating the variance associated with the regression, namely variance that can be explained through the fitted model, to the variance associated with error, namely variance that can *not* be explained through the model. The *F-statistic* is the ratio of MSR to MSE, or in other words the ratio of variance explained by the regression model to that not explained by the model and associated with error. This statistic is used to test regression significance in ANOVA, and can be expressed in terms of R^2 as follows by virtue of the Equation 30

$$F = \frac{MSR}{MSE} = \frac{(n-k-1)R^2}{k(1-R^2)} \qquad (34)$$

Clearly, higher values of F suggest that more variance is explained by the regression relative to the variance due to error; values of F greater than 1.0 indicate that more variance is explained by the regressor variables than by the error, whereas values less than 1.0 indicate that more variance is associated to error than to regressor variables. If the null hypothesis H_0 is true, then the F-statistic is distributed as an $F_{k,n-k-1}$ random variable, that is one that has an F distribution with degrees of freedom k and $n-k-1$.[1] Thus, the plausibility

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[1] A random variable that follows an F distribution with degrees of freedom k and $n-k-1$ is the result of

Figure 50: F-distribution and p-value ([153], p 567)

$F_{k,n-k-1}$ distribution

p-value

F = MDR/MSE
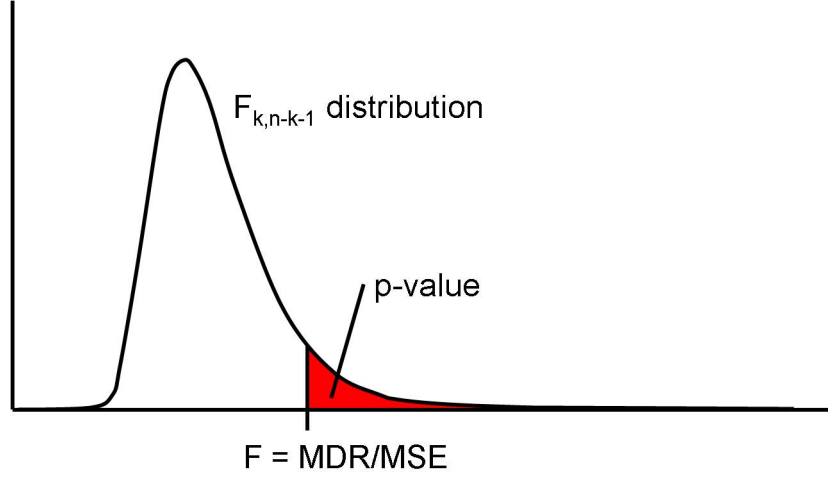
of the null hypothesis is lower when the observed value of the F-statistic is less likely to be an observation from the aforementioned F distribution, that is a value of the F-statistic corresponding to the low-probability extreme of the F distribution. Moreover, given the definition for p-value as the probability of obtaining a test statistic at least as extreme as the one observed if H_0 is true, the p-value for ANOVA becomes the probability of the F distribution greater or equal to the observed F-statistic as follows The p-value can hence be expressed as follows

$$p - value = P(X < F) \tag{35}$$

where X is random variable distributed as an F-distribution with k and $n - k - 1$ degrees of freedom. This is concept is graphically illustrated in Figure 50. Explained in different terms, the p-value for the F-test in ANOVA refers to the "probability [...] of obtaining a greater F-value by chance alone if the specified model fits no better than the overall response mean"[261], that is, if the null hypothesis is true.

Thus, ANOVA produces a value of the F-statistic based on the observed data set, as well as a corresponding p-value for the F-test. The null hypothesis, namely that the response

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a random variable distributed as $(\chi_k^2)/k$ divided by a random variable distributed as $(\chi_{(n-k-1)}^2)/(n-k-1)$, where χ_k^2 is a *chi squared* distribution with k degrees of freedom and $\chi_{(n-k-1)}^2$ is a *chi squared* distribution with $(n-k-1)$ degrees of freedom.

does not depend on any of the regressor variables, is rejected for a sufficiently large F-statistic value that corresponds to a sufficiently small p-value. For practical purposes, ANOVA p-values less than 0.01 suggest that the response has a linear relationship with at least one of the regressor variables in the data set. The estimates produced in ANOVA are summarized in an ANOVA table which has a standard form and is notionally presented in Table 27.([153] Ch. 13, [224] Ch. 2)

Table 27: ANOVA Table

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-statistic	p-value
Regression	k	SSR	MSR = SSR/k	F = MSR/MSE	$P(F_k, n - k - 1 > F)$
Error	n - k - 1	SSE	MSE = SSE/(n-k-1)		
Total	n-1	SST			

D.6 Regression Parameter Estimates - t-Test

The test of significance for *all* regressors conducted in ANOVA can be similarly applied to test the significance of each individual regressor variable, that is, whether each regressor coefficient is non-zero. This test uses the estimates for each regression parameter $(\hat{\beta}_0, \hat{\beta}_1, ..., \hat{\beta}_k)$ and the standard error for the regression parameters $(se(\hat{\beta}_0), se(\hat{\beta}_1), ..., se(\hat{\beta}_k))$. The hypotheses for this test are

- $H_0 : \beta_i = 0$

- $H_1 : \beta_i \neq 0$

In a way similar to how the null hypothesis in ANOVA is tested with the F-statistic and compared to an F-distribution, the parameter estimate null hypothesis is tested with the *t-statistic* and compared against a t-distribution with $n - k - 1$ degrees of freedom. The t-statistic for the ith parameter estimate is calculated as

$$t = \hat{\beta}_i / se(\hat{\beta}_i) \tag{36}$$

where $\hat{\beta}_i$ is the estimate for parameter β_i produced by the model fit, and $se(\hat{\beta}_i)$ is the *standard error* of the estimate $\hat{\beta}_i$. The standard error is simply the standard deviation, or an estimate of the standard deviation, of $\hat{\beta}_i$.

A certain effect is more significant, that is, has a greater impact on the response, if its corresponding parameter β_i has a larger value. However, since β_i is approximated by the estimate $\hat{\beta}_i$ which can inherently contain error, a large value of the estimate $\hat{\beta}_i$ is not sufficient to conclusively determine that that its corresponding effect is significant for a given response. The error of the parameter estimate $\hat{\beta}_i$ must be taken into consideration, and must be determined to be sufficiently small, before the magnitude of the parameter estimate $\hat{\beta}_i$ can be used as an indication that a certain effect is significant. The ratio defined by the *t-statistic* incorporates these two pieces of information, namely the value of the parameter estimate $\hat{\beta}_i$ and the error of the estimate. Thus, for larger values of the *t-statistic* the effect of a regressor factor on a response is greater with respect to the error associated with that regressor factor. Conversely, for smaller values of the *t-statistic* the effect of a regressor factor on a response is smaller with respect to the error associated with that regressor factor, and if sufficiently small, the effect of a regressor factor cannot be distinguished from the error associated with that regressor factor.

The estimate standard error can be calculated as

$$se(\hat{\beta}_i) = \sqrt{\hat{\sigma}^2 C_{ii}} \tag{37}$$

where $\hat{\sigma}^2$ is the unbiased estimator of error variance σ^2, and C_{ii} is the ith diagonal element of the matrix

$$\mathbf{C} = (\mathbf{X'X})^{-1} \tag{38}$$

The matrix $\mathbf{C}$ results from the matrix notation development of the least squares normal equations for multiple linear regression, which is a convenient approach for the solution of that set of linear equations. In this matrix notation, Equation 21 is rewritten as follows

$$y_i = \beta_0 + \beta_1 x_{1,i} + ... + \beta_k x_{k,i} + \epsilon_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{j,i} + \epsilon_i \tag{39a}$$

$$\mathbf{y} = \mathbf{X}\beta + \epsilon \tag{39b}$$

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$$\mathbf{y} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \quad \mathbf{X} = \begin{pmatrix} 1 & x_{1,1} & x_{1,2} & \cdots & x_{1,k} \\ 1 & x_{2,1} & x_{2,2} & \cdots & x_{2,k} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{n,1} & x_{n,2} & \cdots & x_{n,k} \end{pmatrix} \quad \beta = \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{pmatrix} \quad \epsilon = \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{pmatrix} \tag{39c}$$

Accordingly, $\mathbf{X}$ is an $n \times (k+1)$ matrix containing the levels of all independent variables for all observations.

Higher values of the t-statistic suggest lower values of standard error relative to the value of the parameter estimate, and thus indicate greater significance of regression. If the null hypothesis is true, then the t-statistic follows a t-distribution with $n - k - 1$ degrees of freedom. Consequently, the plausibility of the null hypothesis is lower when the the observed value for the t-statistic is less likely to be an observation from said distribution. The t-distribution is symmetric about zero and has diminishing probability at its extremes. Thus, values of the t-statistic that are farther from zero are less likely to be sampled from the t-distribution and make the null hypothesis less plausible. The p-value for this two-sided t-test is therefore given by the probability of obtaining a value from the the t-distribution that is greater than the absolute value of the t-statistic, or one that is less than the negative of the absolute value of the t-statistic. The p-value can hence be expressed as follows

$$p - value = P(X < -|t|) + P(X > |t|) = 2P(X > |t|) \tag{40}$$

where X is random variable distributed as a t-distribution with $n - k - 1$ degrees of freedom. The calculation of the p-value for the two-sided t-statistic test can be simplified as shown in Equation 40 by virtue of the symmetry of the t-distribution. This is concept is graphically illustrated in Figure 51.

Higher values of the t-statistic thus result in lower p-values, which suggest that the null hypothesis is less plausible. If the null hypothesis is rejected then the alternative hypothesis that the regressor coefficient is non-zero is accepted. It is standard practice to provide parameter estimate results as a table that includes parameter estimate $\hat{\beta_i}$, the standard error, the t-statistic, and the p-value, for each parameter.([153] Ch. 11,13, [224] Ch. 2)

Figure 51: t-distribution and p-value ([153], p 396)
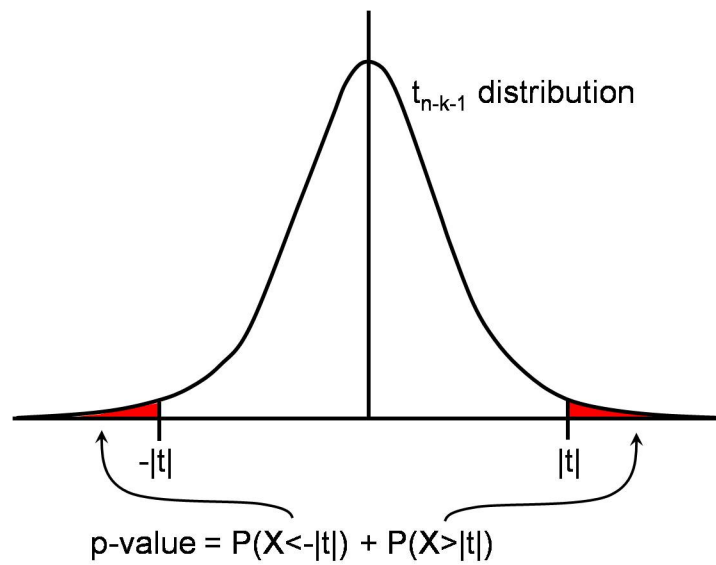
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