UNDERSTANDING THE TRADEOFF BETWEEEN MAXIMUM PASSENGER THROUGHPUT AND AIRLINE EQUITY IN ALLOCATING CAPACITY UNDER SEVERE WEATHER CONDITIONS

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science

by

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August 2016

ABSTRACT

When the capacity at an airport is reduced as a result of weather conditions, a Ground Delay Program (GDP) is implemented to resolve the discrepancy between demand for arrival slots and the available arrival slots on a given day. Currently, GDP ration the available arrival slots via the proportion of arrivals that exist in the schedule by airline (this is termed Ration by Schedule or RBS) with an emphasis on equity among the airlines. Current rationing schemes do not explicitly consider the number of passengers delayed.

This thesis examines the passenger impacts of a focus on airline equity in contrast to a focus on seat throughput in reduced capacity conditions for a GDP at a single airport. An optimization model is developed using the number of seats available in an aircraft as a proxy for number of passengers and an equity term to estimate airline equity implications. A comparison of the current GDP rationing scheme with one focused on seat delay identifies that with no change in the total flight delay time periods, passenger throughput can be improved with a threshold placed on equity. The tradeoffs between airline equity and passenger throughput, and the implications of these results are discussed.

BIOGRAPHICAL SKETCH

Ever since Harika Jayam stumbled upon Mega Structures, a famous show on National Geographic Channel she decided she wanted to pursue a career in civil engineering and one day appear on the show proudly representing her work. With immense passion she worked hard to gain admission to one of the prestigious private universities in India. She graduated top of her class from Vellore Institute of Technology with a Bachelor of Science in Civil Engineering in May 2014. She was also the first female Vice-President representing School of Mechanical and Building Sciences (SMBS) to serve at the Students' Council.

From her experiences pursuing research project in the field of transportation during study abroad in Australia in her senior year of undergrad, she has decided that her passion now lies in solving complex problems in the field of transportation systems and hence went on to pursue her Masters at Cornell University. She was involved in extracurricular activities while at Cornell and served as a co-chair for CEE Graduate Research Symposium.

She has successfully completed her Masters in Transportations Systems Engineering and has accepted a position as Entry Level Planner at Stantec Consulting Services, New York City. With a burning desire to learn and grow as an individual she promises continuing to work hard and make her Alma matter and family proud.

To

The loving memory of my father,

Without whom I would not be who I am today.

ACKNOWLEDGMENTS

I would like to thank my advisor and my inspiration, Prof. Linda Nozick, for her constant support and advice. I attribute the completion of my master's degree and thesis to her mentorship and encouragement. She has taught me what dedication and focus is and has always encouraged me to pursue things out of my comfort zone. I am truly thankful for all the wonderful advice I have received from her. I would also like to thank my minor advisor Prof. Peter Jackson, who has always been a smiling and supporting mentor. I consider myself lucky to have been among one of your last advisee's during your career at Cornell. Your encouragement and warm words have always motivated me to strive for the best.

I would next like to thank all my friends and classmates at Cornell who have supported me during all the hardships in my life. I would particularly like to thank Krista Sandercock for helping me in my roadblocks and for always being an inspiration. I would also like to mention my gratitude to my classmates Sijia Wang and Qingyuan Zhao for being there for me whenever I needed support. I am grateful to my housemate Belac for always believing in me and providing words of wisdom.

I would probably not be here if not for the support and encouragement from my Family. My deepest gratitude to my Mom, my elder sister Harini and my Uncle for taking care of me and never make me realize the burden on their shoulders to let me pursue my dreams. I would like to reminiscence my late father, whom I loved to the

moon and back. I miss you, Dad. I hope I have made you proud, because without your words of wisdom and unconditional love I would not have been the person I am today. Your memories will always be with me.

TABLE OF CONTENTS

Biographical Sketch ………………………………………………………… iii

Dedication ………………………………………………………………...... iv

Acknowledgements ……………………………………………………….. v

Table of Contents ………………………………………………………… vii

List of Figures ……………………………………………………………….. viii

List of Tables …………………………………………………………………. ix

1. Introduction **1**

2. Problem Definition and Formulation **5**

2.1. Notation 5

2.2. Model 7

2.3. Case Study : Chicago O'Hare (ORD) 9

2.4. Results and Discussion 11

3. Conclusions and Future Work **17**

LIST OF FIGURES

1. Capacity Profile under Instrument Weather ……………………………… 10
2. Comparison between Distribution of Delay and Flight Share by Carriers …. 12
3. Total Number of Seats Delayed Vs P ……………………………………… 14
4. Cumulative Number of Seats Delayed …………………………………….. 16
5. Percentage of Flights Delayed by Carrier ………………………………….. 16

LIST OF TABLES

1. Range of P_c with Different Relative Importance, β Placed on Equity… 15

CHAPTER 1

INTRODUCTION

Passenger and cargo demand for air transportation has been growing steadily after a set back from global economic recession in 2008-2009 and is forecasted to grow at an average rate of 2.1% annually over the next 20 years (FAA forecast, 2016). The growth of air transportation capacity to meet this demand is lacking especially in major hub airports (FACT 3, FAA 2015). The most congested airports such as Newark (EWR) or Chicago O'Hare (ORD) cannot expand due to land and environmental pressures (Howe et.al. 2003). Moreover, the capacity improvement benefits of the Next Generation air traffic control (ATC) system also known as NextGen are not expected to be operational before 2025.

Delay increases nonlinearly as demand approaches capacity of an airport (NEXTOR, TDI report, 2010). Growing delays threaten the competitiveness of the US in the world economy by limiting the ability of the air transport system to serve the needs of the US economy. In 2010, 18% of all flights in the US were delayed by more than 15 minutes (FAA, 2012) and recent studies estimated the cost of delays to the US economy in 2007 ranging from $32.9 Billion (NEXTOR,2010) to $41 Billion (JEC,2008). These delays not only have financial costs but also have environmental and climate change implications (Miller and Clarke, 2003).

To resolve the daily demand-capacity imbalances at an airport several Traffic Flow Management (TFM) initiatives have been implemented. One of the initiatives which is collaborative with the airlines to manage the scheduled arrival flow into an airport consistent with its arrival capacity is the Ground Delay Program (GDP). The current GDP rations the arrival slots according to the scheduled (RBS) arrival time of the flights. Each airport where a GDP is being implemented has a defined scope of operation and the rationing scheme excludes long distance flights or international flights which are beyond the scope. The rationing scheme is also adjusted to more equitably allocate arrival slots between airlines to ensure that one airline is not excessively penalized by allocating slots proportional to the number of operations of an airline.

Previous research has examined alternative rationing schemes : (i) equitable distribution of delay on per flight basis using integer programming (Barnhart et al, 2012) (ii) rationing rules on aircraft size and airline equity via an iterative algorithm (Manley and Sherry, 2008), (iii) maximize throughput while preserving equity amongst airlines via Ration by Distance (RBD) allocation (Hoffman, 2007), (iv) improve airline fairness by fair slot allocation (Vossen, 2002) , and (v) improve airline efficiency by trading departure and arrival slots (Hall, 1999, 2002).

This thesis builds an optimization model based on the ideas in Manley and Sherry (2008) and compares the passenger impacts of a focus on airline equity in contrast to a focus on passenger (seat) throughput in a GDP. When allocating the limited capacity, one argument as to how to do that fairly is to allocate capacity proportional to the number of flights an airline has. Translating this concept into delay argues that for a perfectly equitable delay distribution, an airline's share of the total delay should be similar to its share of the total number of flights at an airport. Notice that this argument does not consider the number of seats on a flight and therefore the number of passengers that see a disruption in their itinerary. An alternative argument would allocate delay based on the total number of seats (as a proxy for the number of passenger's inconvenienced) an airline provides in comparison to the total number of seats handled at the airport during periods of reduced capacity. In the current implementation of GDP using RBS there is evidence that carriers with both small and large aircraft do pass the delays received by the FAA down to their smaller scheduled flights likely in an attempt to disrupt as few passenger itineraries as possible (Bureau of Transportation Statistics (BTS) and Wall Street Journal, 2014). This thesis essentially examines the impact of extending this practice.

For the remainder of this thesis, we focus on seat delay as a proxy for passenger delay. This is a reasonable approximation because in practice the load factors in the airline industry are very high and are forecasted to be high (FAA Aerospace forecast, 2016-2036). Also, in the context of a GDP it is important that only readily available data are needed so the effort required to assemble the data is more modest.

The cost functions for delaying aircrafts on the ground and in the air are assumed to be linear. The reasons a linear approximation of the cost functions is reasonable are associated with the operational characteristics of the Air Traffic Control (ATC) system as set forth in Richetta and Odoni (1993). First, when an aircraft is already airborne, they are sequenced by ATC in an approximately First-scheduled, First-served (FSFS) and there is no need to distinguish among various classes of aircrafts. Second, within reasonable airborne delay levels (i.e. within the largest airborne delays observed in practice which are in the order of one hour) delay cost functions are approximately "linear" since non-linearities caused by other factors such as safety does not set in yet.

The remainder of this thesis is organized as follows. The next section gives the problem formulation. The third section presents a realistic case study of the model at Chicago, O'Hare airport, using CPLEX Studio IDE, version 12.6.2. The final section gives conclusions and opportunities for future research.

CHAPTER 2

PROBLEM DEFINITION AND FORMULATION

2.1 Notation

Consider a set of ordered time periods $T = \{1 \ldots t\}$. For instance T can be a set of 96 time periods of 15 minutes each, amounting to a time horizon of 24 hours. Consider a set of flight-carrier combinations for departing flights from an airport $F_{\mathrm{d}} = \{< f_d, c >\}$, where f_d denotes a departing flight and c denotes its corresponding carrier. Similarly consider a set of flight-carrier combinations for arriving flights to an airport $F_{\mathrm{a}} = \{< f_a, c >\}$, where f_a denotes an arriving flight and c denotes its corresponding carrier. $F_d^{'} = \{< f_d^{'}, c >\}$ and $F_a^{'} = \{< f_a^{'}, c >\}$, where $f_d^{'}, f_a^{'}$ are the same aircraft i.e. they have the same tail number and perform multiple legs of arrivals and departures to different destinations and c is the carrier. Consider a set $N_c = \{1 \ldots. n_c\}$ containing the total number of flights of each carrier during the time horizon T.

For each flight-carrier combination $(f_d, c) \in F_{\mathrm{d}}$ and flight-carrier combination $(f_a, c) \in F_{\mathrm{a}}$, the following data are assumed to be known: $d_{(f_d,c)} \in T$, the scheduled departure time, $S_{(f_d,c)}$ number of seats, $C^g_{(f_d,c)}$ the ground delay cost rate of (f_d, c) (per unit ground delay of (f_d, c) in time periods) $a_{(f_a,c)} \in T$, the scheduled arrival time, $\gamma_{(f_a,c)} \in T$, the ground delay of (f_a, c) at its origin airport, $S_{(f_a,c)}$ number of seats and $C^a_{(f_a,c)}$ the airborne delay cost rate of (f_a, c) (per unit airborne delay of (f_a, c) in time periods). The departure capacity $D(t)$, arrival capacity $A(t)$ and the combined capacity $C(t)$ of an airport (in number of flights) are also known. Since we consider a *deterministic* version of the ground delay program, these capacities are considered fixed and known rather than random variables.

We define decision variables $\Delta^{g}_{(f_d,c)}$, $(f_d, c) \in F_d$ equal to the number of time periods that the flight- carrier combination (f_d, c) is held on the ground before being allowed to take-off, and the decision variable $\Delta^{a}_{(f_a,c)}$, $(f_a, c) \in F_a$ equal to the number of time periods a flight is further held in air before being allowed to land. Decision variable P is defined across all airlines as the maximum ratio of an airline carrier's total delay divided by its total number of flights, as a measure of airline equity. We define assignment decision variables $X_{(f_d,c),t}$, defined to be 1 if flight-carrier combination (f_d, c) is assigned to take-off at time period t and 0 otherwise, and $Y_{(f_a,c),t}$, defined to be 1 if the flight-carrier combination (f_a, c) is assigned to land at time period t and 0 otherwise. Using the assignment decision variables defined above, we derive expressions for the delay decision variables as:

$$\Delta^{g}_{(f_d,c)} = \sum_{t \in T} tX_{(f_d,c),t} - d_{(f_d,c)} , \qquad (f_d, c) \in F_d \tag{1}$$

$$\Delta^{a}_{(f_a,c)} = \sum_{t \in T} tY_{(f_a,c),t} - a_{(f_a,c)} - \gamma_{(f_a,c)} , \quad (f_a, c) \in F_a \tag{2}$$

$\Delta^{g}_{(f_d,c)}$, $\Delta^{a}_{(f_a,c)}$ are the ground delay and air delay decision variables, in time periods respectively. Following similar definitions made by Vranas et al (1993), we define a linear optimization model for the deterministic single airport ground holding problem considering size of the aircrafts and airline equity, with β as the trade-off parameter.

2.2 Model

Minimize $\sum_{(f_d,c)\in F_d} S_{(f_d,c)}[C^g_{(f_d,c)}\Delta^g_{(f_d,c)}] + \sum_{(f_a,c)\in F_a} S_{(f_a,c)}[C^a_{(f_a,c)}\Delta^a_{(f_a,c)}] + \beta P$ (3)

Subject to

Equations (1) and (2)

$$\sum_{(f_d,c)} X_{(f_d,c),t} \le D(t), \quad \forall t \in T \tag{4}$$

$$\sum_{(f_a,c)} Y_{(f_a,c),t} \le A(t), \quad \forall t \in T \tag{5}$$

$$\sum_{(f_d,c)} X_{(f_d,c),t} + \sum_{(f_a,c)} Y_{(f_a,c),t} \le C(t), \quad \forall t \in T \tag{6}$$

$$\sum_t tX_{(f_d,c),t} \ge d_{(f_d,c)}, \quad \forall (f_d,c) \in F_d \tag{7}$$

$$\sum_t tY_{(f_a,c),t} \ge [a_{(f_a,c)} + \gamma_{(f_a,c)}], \quad \forall (f_a,c) \in F_a \tag{8}$$

$$\sum_t tX_{(f_d',c),t} \ge \sum_t tY_{(f_a',c),t}, \quad \forall (f_d',c) \in F_d', (f_a',c) \in F_a' \tag{9}$$

$$\sum_t X_{(f_d,c),t} = 1, \quad \forall (f_d,c) \in F_d \tag{10}$$

$$\sum_t Y_{(f_a,c),t} = 1, \quad \forall (f_a,c) \in F_a \tag{11}$$

$$\Delta^a_{(f_a,c)} > 0, \quad \forall (f_a,c) \in F_a \tag{12}$$

$$\frac{[\Delta^g_{(f_d,c)} + \Delta^a_{(f_a,c)}]}{n_c} \le P, \quad \forall c \tag{13}$$

$$X_{(f_d,c),t} \in \{0,1\}, \quad \forall (f_d,c),t \tag{14}$$

$$Y_{(f_a,c),t} \in \{0,1\}. \quad \forall (f_a,c),t \tag{15}$$

Constraints (4) and (5) are the maximum number of departures and arrivals (in number of flights) that can be performed under a capacity profile of an airport, respectively. Constraint (6) is used to allot the combined capacity for departures and arrivals according to the capacity profile of an airport. Constraint (7) is used to ensure a flight does not depart before its scheduled departure time period, avoiding negative delays. Constraint (8) is used to ensure a flight does not land before its scheduled arrival time period and any ground delay time periods it might have encountered at the origin airport, avoiding negative delays. Constraints (9) are the *connecting* constraints: They ensure a unique aircraft (same tail number) cannot depart before it arrives from its previous leg of journey. Constraint (10) ensures that for a given flight-carrier combination for departing flights, only one $X_{(f_d,c),t}$ equals 1 and the rest will be 0. Similarly for arriving flights, constraint (11) makes sure that only one $Y_{(f_a,c),t}$ equals 1. Nonnegativity of $\Delta^g_{(f_d,c)}$ is ensured by (1), whereas nonnegativity of $\Delta^a_{(f_a,c)}$ is not ensured and hence constraint (12). Constraint (13) characterizes the balance in delay among the airline carriers at an airport.

Equation (3) gives the objective function; which is composed of three elements. The first element is the seat delay cost for departing flights, second element is the seat delay cost for arriving flights and the last term is for airline equity. First and second elements contain the number of seats in a flight, cost of delaying the flight and the number of time periods the flight is delayed for. β is a constant which reflects the relative importance of airline equity. It is useful to notice that this model can be used to optimize just the total aircraft delay by replacing $S_{(f_d,c)}$ and $S_{(f_a,c)}$ with unity and setting β to 0.

2.3 Case study instrument weather conditions at Chicago O'Hare Airport

Chicago O'Hare is the second busiest airport in the world as measured by the number of takeoffs and landings and is the fourth busiest airport in the world as measured by passenger traffic[1]. Every airport has three distinct operating capacities based on weather conditions: visual, marginal and instrument weather. Instrument weather capacity at O'Hare[2] is as shown in Figure 1. Hourly departures are shown on X axis and hourly arrivals are shown on Y axis. The line parallel to X axis represents the absolute capacity available for arrivals and the line parallel to Y axis represents absolute capacity available for departures and the rest is the capacity available for combined operations. The dotted lines show the expected improvements in the available capacity after future runway additions and extensions. The dots underneath the solid line show the number of hours with given actual traffic counts that occurred under instrument weather capacity profile.

Airport's capacity drops significantly under instrument weather and leads to ground delays for departing flights and airborne and ground delay for arriving flights. Using the On-time Performance[3] database from Bureau of Statistics (BTS), January 1st, 2015 is randomly chosen for further analysis; there were 12 carriers and a total of 1,381 flights representing 692 departures and 683 arrivals. Since international flights are exempt from GDP, we focus on decision-making with respect to only domestic flights. Further, freight and other operations are not considered in this analysis. Hence we scale down the capacity available for domestic flights[4] using the relative percentage of domestic traffic in comparison to the total traffic. Constant marginal costs of delaying a flight on the ground and in the air are obtained from

[1] Airports council international annual traffic data
[2] www.faa.gov O'Hare International (Chicago) (ORD) ,airport capacity profile (2014)
[3] http://www.transtats.bts.gov
[4] www.flychicago.com Air traffic data monthly reports, January 2015

Euro control, converted from pounds to dollars and adjusted for inflation (Euro Air Journal, 1997). The marginal costs of delay in 2014 for ground delay and airborne delay are $530 and$780 per 15 minute time period, respectively.

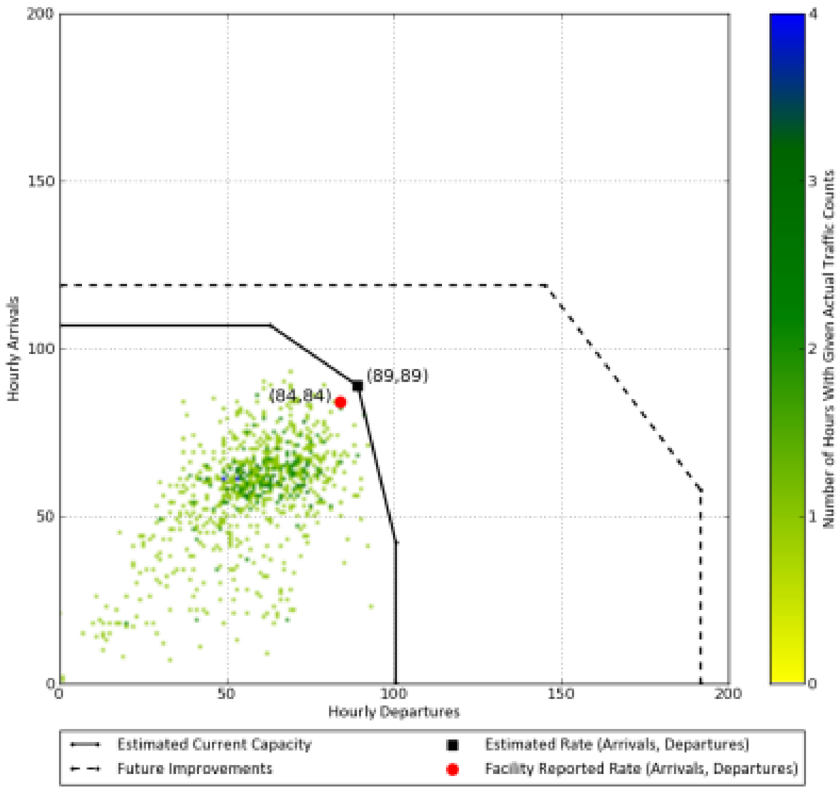

Figure 1: Capacity profile under instrument weather

Capacity per hour is converted to capacity per time period, where each time period is assumed to be 15 minutes. The 12 different carriers operating at O'Hare are: AA-American Airlines, AS-Alaska Airlines, B6-Jet Blue Airways, DL-Delta Airlines, EV-Express Jet, F9-Frontier Airlines, MQ-American Eagle Airlines, NK-Spirit Airlines, OO-SkyWest, UA-United Airlines, US-US Airways, and VX-Virgin America. Regional airlines are considered separate even if they are owned by a common airline, for e.g. American Eagle flights are considered as a separate carrier even though American Airlines owns American Eagle. American Eagle has the highest share of flights at 24.04%, followed by United Airlines at

19.84%, American Airlines at 16.87%, Express Jet at 15.49%, SkyWest at 13.18%, Spirit Airlines at 3.33%, US Airways at 2.46%, Delta Airlines at 1.52%, Frontier Airlines at 1.23%, Alaska Airlines and Jet Blue Airways at 0.72% each and the lowest share of 0.58% by Virgin America.

2.4 Results and Discussion

Figure 2 illustrates how different strategies as to how to allocate the limited capacity as represented in the objective function given in equation (3) assign total delay and seat delay among carriers. The share of total delay (in time periods of ground and air delay) by carrier is compared to the proportion of flights belonging to the carrier. As mentioned earlier, current GDP practice (base case) does not consider the size of an aircraft while assigning arrival or departure slots, the assignment is done solely based on predefined schedule. Since there are many alternative optimal solutions, we select the solution that matches the air carrier penetrations as closely as possible. To do this we modify the formulation slightly. Let ε_c be the difference between the initial proportion of flights δ_c, based on the schedule operated by carrier *c*, and the proportion of the total delay experienced by that carrier where $\varepsilon_c \geq 0$. This concept is reflected in equation (16).

$$\left(\frac{(\Delta^g_{(f_d,c)} + \Delta^a_{(f_a,c)})}{\sum_c \Delta^g_{(f_d,c)} + \sum_c \Delta^a_{(f_a,c)}} \right) - \varepsilon_c \leq \delta_c, \qquad \forall c \tag{16}$$

The objective function is then simply the minimization of total aircraft delay along with the deviations, ε_c as given in Equation (17) below.

$$\sum_{(f_d,c)} C^g_{(f_d,c)} \Delta^g_{(f_d,c)} + \sum_{(f_a,c)} C^a_{(f_a,c)} \Delta^a_{(f_a,c)} + \gamma \sum_c \varepsilon_c \tag{17}$$

For these experiments, we omit Equation (13) and the objective is as given in equation (15) instead of Equation (3). Figure 2 gives the share of flights based on the schedule operated by each carrier as well as the percentage of delay incurred by each carrier when we minimize aircraft delay only (including the tie breaking mechanism for alternative optimal solutions given in Equations (16) and (17).) Notice that this solution essentially assigns delays based on the operations associated with each carrier.

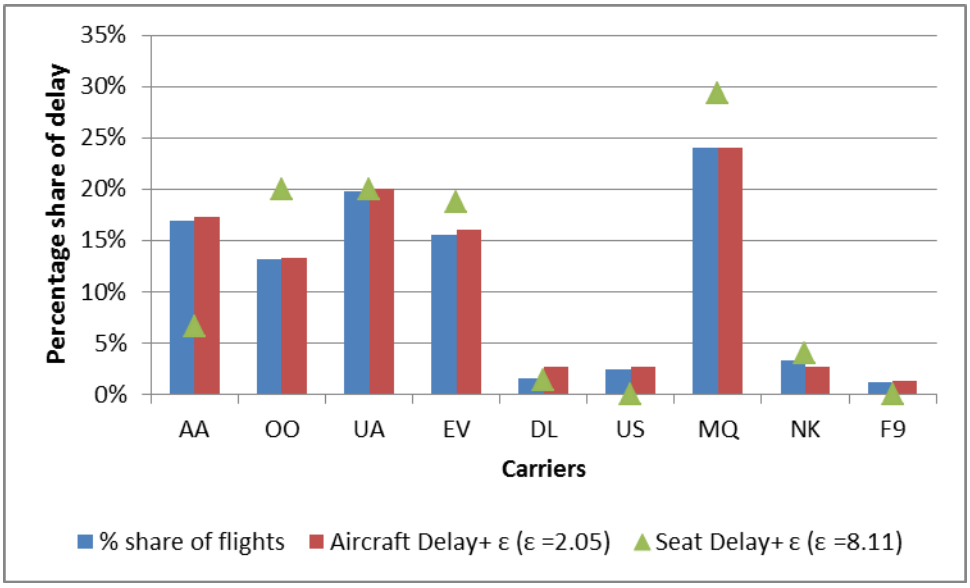

Figure 2: Comparison between distribution of delay and flight share by carriers

As a point of comparison, the optimization is done focusing on seat delay instead of aircraft delay. Hence we revert to including the number of seats in the objective function as given in Equation (3). We retain the penalty term on differences in the allocation of delay across carriers as a tie breaking mechanism only among alternative optimum with respect to seat delay. The total aircraft delay is the same when minimizing seat delay and when only minimizing aircraft delay. However, if the goal is to allocate the aircraft delay consistent with the penetrations of the carriers in the schedule, it is not possible to reach the same minimum value for seat delay as given by the triangles in Figure 2. When the goal is to minimize seat delay with a tie breaker between alternative optimal solutions based on the relative number of flights in the schedule associated with each carrier, larger planes receive less delay than smaller planes. Since some carriers fly relatively more smaller planes, they receive more delay than those carriers flying relatively more larger planes. For example, American Eagle (MQ), a regional carrier operates with a majority of small flights and receives about 29% of the total delay. Other regional carriers such as Express Jet (EV) and SkyWest (OO) each receive around 20% of the delay. It is interesting to note that by delaying smaller planes owned by United (UA), aircraft delays can be approximately matched with its flight share.

Equations (16) and (13) are essentially two different ways of computing equity. Equation (16) focuses on all carriers in the computation of equity whereas Equation (13) focuses on minimizing the maximum inequity. We choose to focus on minimizing the maximum inequity as done in Manley and Sherry (2008) and use Equation (16) as a mechanism to choose between alternative optimal solutions.

Table 1[5] gives the left hand side of Equation (13) for each carrier. Minimum and maximum values of P_c are shown in bold where the maximum value is the value of *P*. Notice that with different relative importance placed on equity, there is a large variation in the range of P_c. Notice that the carrier specific equity as a function of β is consistent with the carrier characteristics associated with Figure 2. With lower relative importance placed on equity, smaller aircrafts owned by different carriers receive delays but there is a wide range of delay across the carriers. With increasing importance placed on equity the share of delay is more evenly distributed among carriers. It is interesting to note that Alaskan Airlines (AS, 10),

[5] The weight shown is of the order $\beta(\times 10^5)$.

JetBlue (B6, 10) and Virgin America (VX, 8) never receive any delay even with highest importance placed on equity due to very low penetrations of these carriers.

Figure 3 gives the relationship between total number of seats delayed and equity as measured using Equation (13) under three different scenarios for capacity reduction: instrument weather, 10% and 20% reduction beyond instrument weather. Notice that with increasing importance placed on equity, seat delay increases. Again, this occurs because the percentage of flights using smaller planes differs substantially across the carriers. It is useful to notice that increased equity comes at a small price as measured in seat delay up to a point. Beyond that point, the costs (as measured in seat delay) escalate quickly. Also, notice that equity threshold is reached more quickly as capacity declines.

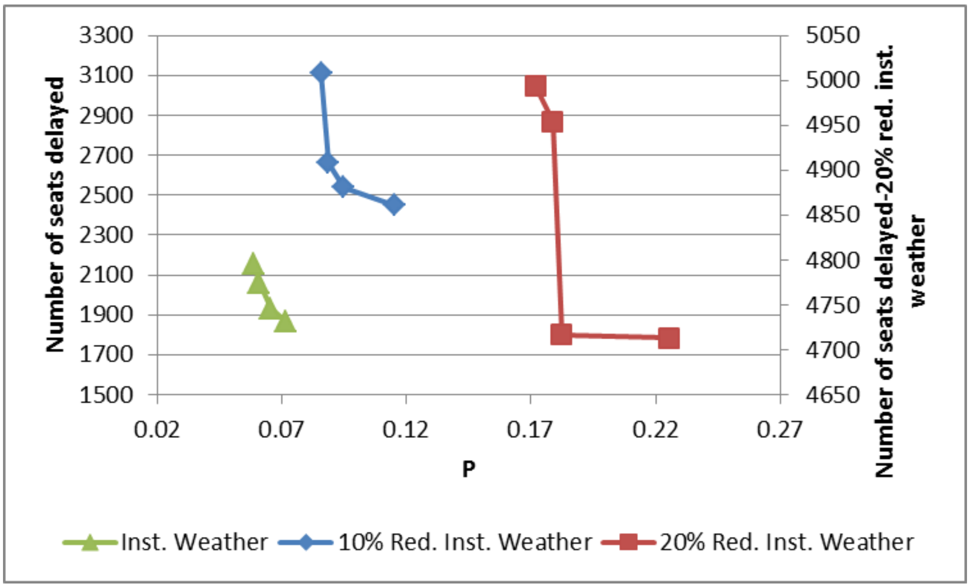

Figure 3: Total number of seats delayed Vs P

Table 1: Range of P_c with different relative importance, β placed on equity

Carrier	$\beta = 10^{-5}$	$\beta = 35$	$\beta = 120$	$\beta = 350$
AA	**0.021**	**0.025**	0.038	0.051
OO	**0.071**	**0.066**	0.060	0.055
UA	0.062	0.062	0.058	0.058
EV	0.070	0.065	**0.061**	0.056
DL	0.047	0.047	0.047	0.047
US	0.000	0.000	0.058	**0.058**
MQ	0.060	0.063	0.060	0.057
NK	0.065	0.065	0.043	**0.043**
F9	0.058	0.058	0.058	**0.058**
AS	0.000	0.000	0.000	0.000
B6	0.000	0.000	0.000	0.000
VX	0.000	0.000	0.000	0.000

Figure 4 gives the cumulative number of seats delayed under three different scenarios for airport capacity and whether the optimization focused on seat delay or aircraft delay. For instrument weather, when the optimization focused on seat delay in contrast to aircraft delay, the percentage of seats that were delayed between 1 and 6 time periods increased from 1.32% to 3.15% of total seats. However, when the available capacity was 20% less than that under instrumented weather, the percentage of seats delayed increased from 3.33% to 6.17%. Figure 4 illustrates that optimizing the use of remaining capacity focusing on seats provides much better service for the flying public by delaying smaller planes with less number of passenger on them.

Figure 5 gives the percent of aircrafts delayed by carrier for the 6 solutions illustrated in Figure 4. Notice that the percentage share of delay is more or less even among carriers under instrument weather when the focus is to minimize either aircraft delay or seat delay. With further reductions in instrument weather capacity, the share of delay among carriers is more equitable when the focus is to minimize seat delay in contrast to aircraft delay. Since most carriers operate a few smaller aircrafts, by considering the size of aircraft and minimizing seat delay results in these smaller aircrafts receiving the delay. When the focus is to minimize aircraft delay, delay is assigned to aircrafts irrespective of the size and hence few larger aircrafts also end up receiving a portion of the total delay.

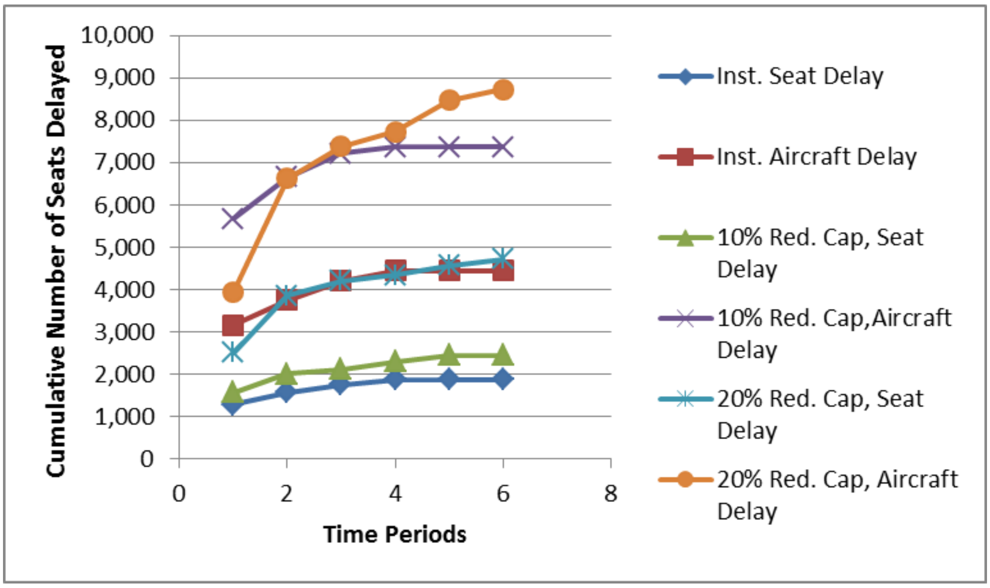

Figure 4: Cumulative number of seats delayed

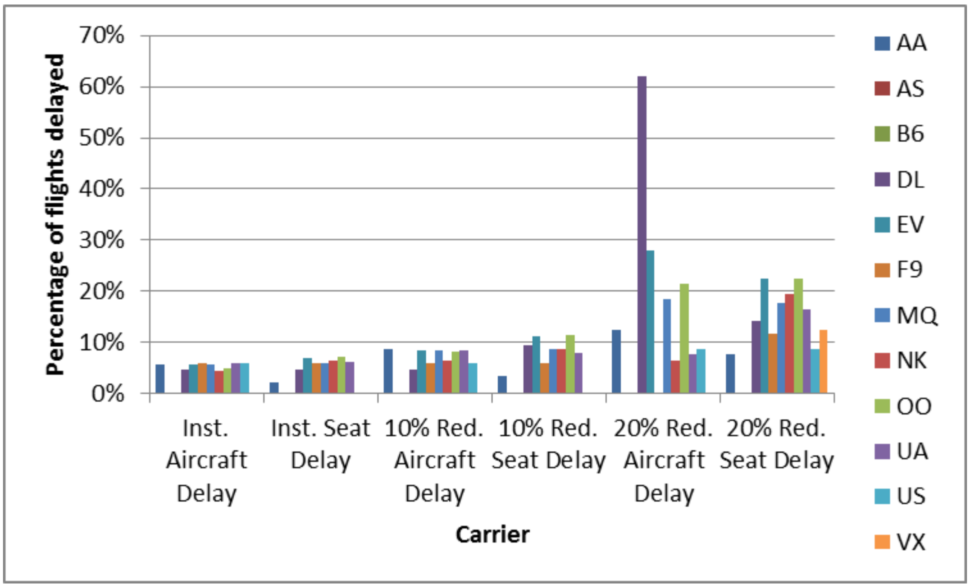

Figure 5: Percentage of flights delayed by carrier

CHAPTER 3

CONCLUSIONS AND FUTURE WORK

This thesis developed an optimization model to implement a GDP by identifying which flights should receive a departure or arrival delay and what the duration of that delay should be. The case study of reduced capacity conditions in Chicago O'Hare (ORD) demonstrates the impact on passengers of focusing on seat delay verses aircraft delay. Optimizing the use of remaining capacity focusing on seats provides better service to the flying public however, if the remaining capacity is relatively small there are likely to be inequities among the carriers. This analysis illustrates that there can be an intrinsic trade-off between carrier equity and passenger waiting time.

This research can be extended in several directions. First, it would be useful to understand how many passengers would miss connections at O'Hare based on optimization of flight delays using seat delay vs. aircraft delay. This analysis used seats as an approximation for passenger delay. It is important to test that seat delay is proportional to passenger delay. Second, this thesis focused on a single airport and did not consider flight connections from that airport to other airports. It is important to consider how the flight delay assignments would interrupt the schedule of other flights in the system due to delay of equipment. Finally, this thesis did not consider dynamic evolution in capacity at an airport from improving or worsening weather conditions.

Dynamic changes in capacity are common in areas like the northeast and often impacts several airports at the same time.

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