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**Title of Design:** Dynamic Collaborative Gate Allocation

**Design Challenge Addressed:** Airport Management and Planning

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**Executive Summary**

***Title:*** Dynamic Collaborative Gate Allocation

***Team:*** Six undergraduate students from the departments of Civil and Environmental Engineering in the College of Engineering, Operations Research and Management Science in the College of Letters and Science, and Business Administration in the Haas School of Business.

***University:*** University of California, Berkeley

***Summary:*** At U.S. airports, most aircraft-gate allocations are optimized within each airline without considering a system (i.e. airport) level approach. Even when gate sharing exists, gate allocation is done statically. We develop a dynamic stochastic optimization model that helps airlines and airports collaboratively determine gate usage. The objectives of collaboration are to find the best gate-sharing policy and tactical gate assignments during peak demand periods or other ad hoc situations. Denver International Airport's Terminal A is used as a real-world case study to test validity of the proposed Dynamic Collaborative Gate Allocation (DCGA) program. We find that through DCGA, airports can increase capacity without additional infrastructure and airlines can experience decreased delays, fuel usage, and other costs. Along with Collaborative Decision Making (CDM) and Airport Surface Operations Management (ASOM), DCGA improves efficiency and moves airports toward global system optimization.

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## I. Problem Statement and Background

As insufficient airport infrastructure and land constraints reduce efficiency of the gate-to-gate operations, additional delays are caused, particularly on landside operations. Extreme weather, increased traffic demand, mechanical issues, and runway operations all have a significant impact on the timelines of operations, but even once a flight has cleared these obstacles, punctuality is not guaranteed. Occasionally a flight will land before its planned gate is available. Even if this can be predicted before arrival, there is often very little the airline can do to mitigate the projected gate delay. This problem is exacerbated during peak hours when most or all of the airline's gates are occupied constantly. Delays on the tarmac are particularly costly to all participants, as the engines continue to burn fuel, the time and comfort of the passengers is compromised, and delayed aircraft occupy valuable space on the tarmac (Figure 1-1). This results in costs to the airline, the airport (Shortle et al 2009), the passengers, and the community.

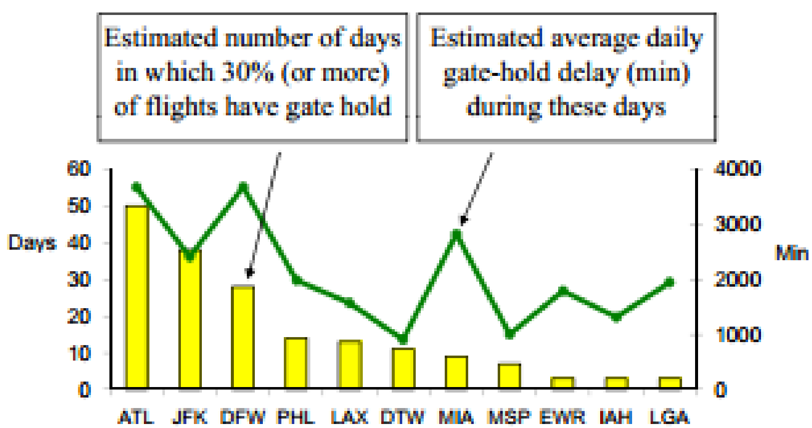


*Figure 1-1: OEP Airports Gate Delays (Ref: Shortle et al, 2009)*

To date, collaborative decision making (Ball et al., 2000) and airport surface traffic management (Jung et al. 2011) initiatives have produced significant operational improvements at airports. Under the collaborative decision making (CDM) concept, improvements are made in the ground delay program (GDP) domain, as well as in maximizing utilization of the available arrival capacity in the presence of delays and flight cancellations. Substitution (intra-airline slot exchange) and compression (inter-airline slot exchange) concepts of slot-trading have significantly reduced ground delays, improved airlines' on-time performance and minimized passenger delay costs. Under the airport surface management initiatives, Spot and Runway Departure Advisor (SARDA) was developed to reduce taxi delays and achieve maximum taxiway throughput.

Both CDM and SARDA have made breakthroughs in the area of Air Traffic Flow Management (ATFM). However, as we look at airport operations more holistically, we notice that the concept of aircraft gate assignments (i.e., gate management) is not integrated with the existing ATFM concepts, and is lacking information exchange between airlines and Air Traffic Control (ATC) while managing flights. In case of SARDA, gate management was not included because the scope of the program was limited to the control functions of today's Tower controllers, excluding airlines' inputs. In case of CDM, arriving aircraft are routed to predetermined gates assigned by the airlines months in advance. Thus, ATC assigns aircraft to gates without considering real-time gate availability and utilization. We believe that a new concept of *collaborative gate management*, and more specifically *dynamic collaborative gate management*, *is* a logical extension of CDM and SARDA, representing a step towards further reductions in ground delays.

The collaborative gate management challenges arise from the fact that in the US, airlines "own" gates (i.e. have a long-term leases from airports), and control their own aircraft-gate assignments. In our study, dynamic collaborative gate allocation is proposed to be (1) a mechanism for better gate utilization and ground delay reduction, and (2) a logical progression towards harmonization of different concepts of delay reductions within different airport/airspace target areas. We believe that a dynamic collaborative gate allocation program is a natural extension of CDM and SARDA where the airport and airline decisions to manage gates become a part of the overall ATFM concept, enabling exchange of information/decisions between (1) airlines and airports, and (2) airlines and ATC.

Most gate assignments at large hub airports in the United States are currently done by leasing gates to individual airlines on an Exclusive Use basis - generally for a long period of time, although this trend is decreasing (Table 1-1). This allows airlines to personalize (brand) their space and run operations as they see fit, abilities they see tied to a necessary competitive advantage in this highly competitive industry. Common Use Gates that all airlines can access equally are becoming more widespread, but progress in this direction is halted by the competing interests of all stakeholders and a general resistance to change. Some airports (e.g. Las Vegas/LAS) are beginning to allocate up to 100% of their gates under common use agreements, but even when airlines are willing to comply, airports still face the challenge of providing compatible gate side infrastructure, so CGA is much more easily implementable at new terminals designed specifically with CGA in mind.

**Summary of Gate Usage Practices of Top 10, OEP 35, and Rest of Airports**

| 2003 | Number of Airports | Exclusive Use Gates | Preferential Use Gates | Common Use Gates | 2003 Total |
|---|---|---|---|---|---|
| Top 10 Busiest | 10 | 803<br>62.1% | 296<br>22.9% | 194<br>15.0% | 1293<br>100.0% |
| OEP 35 | 35 | 1621<br>48.5% | 1108<br>33.2% | 612<br>18.3% | 3341<br>100.0% |
| Rest of Airports | 77 | 405<br>34.6% | 543<br>46.4% | 221<br>18.9% | 1169<br>100.0% |
| All Airports | 112 | 2026<br>44.9% | 1651<br>36.6% | 833<br>18.5% | 4510<br>100.0% |

*Table 1-1: Summary of Gate Usage Practices (Ref: ACI-NA, 2003)*

Further advancements into CGA are possible, and previous studies have been done to enumerate the resultant delay reduction and overall cost savings CGA could provide in order to help incentivize airlines and airports to participate. Our study expands upon this cost-benefit analysis using a computer model, and observes the change in variance the airline experiences due to the additional confidence they can place in knowing a gate can be immediately available upon arrival. Decreases in variance allow airlines to further improve their schedules and maximize aircraft usage, thus maximizing profit and thereby incentivizing participation in CGA.

The proposed model is designed to test a variety of scenarios, and results are considered relative to the feasibility of each. Since sharing gates across terminals is generally not practical due to the inconvenience to transferring passengers, the analysis first covers separate terminals individually in order to remain realistic (i.e. within real world constraints). The model has been designed so that input data from any airport can be optimized, but for the purpose of this study we have evaluated Denver International Airport (DEN) as a representative example (Figure 1-2).

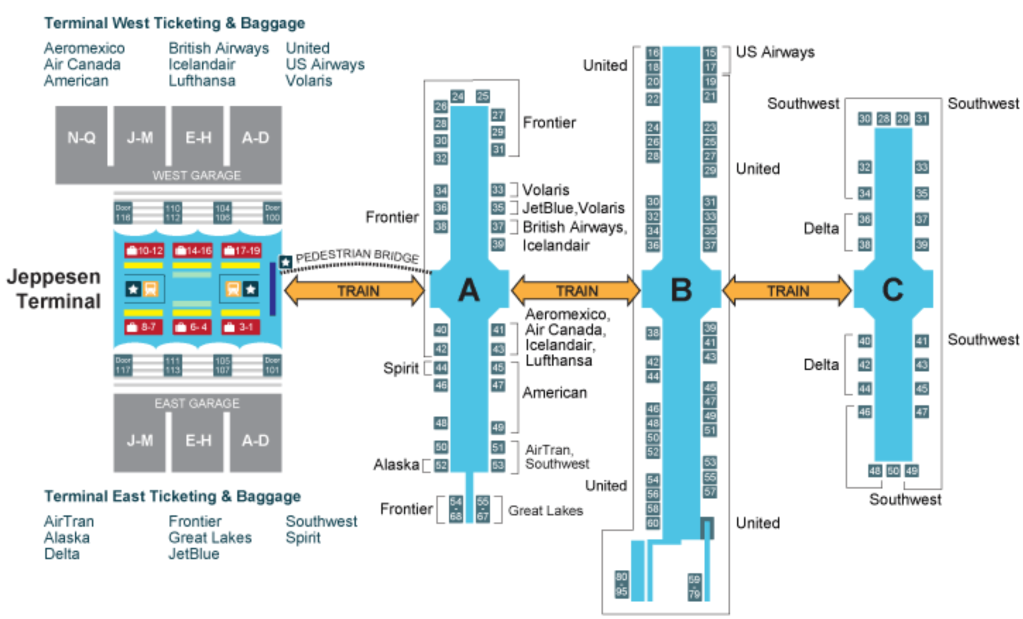


*Figure 1-2: Airport Layout (Ref: Denver International Airport, 2013)*

## II. Summary of Literature Review

### II. a. Introduction

Considering the global economic downturn, energy crisis, and factoring in environmental concerns, it has become necessary to analyze current practices and determine whether modifications are possible to improve our airport system. As more sustainable, "green" systems develop (ACI-NA 2013; Boons et al 2012; CARB 2006; EPA 2013; FAA 2012; LAWA 2008; SAGA 2013), one that is critical to consider is a paradigm shift that moves aircraft gate operations from airline-centric to more airport-centric, in a way that will allow more collaboration and thereby better utilization of scarce resources. The objective of this literature review is to analyze current gate allocation practices, discussing current problems and illuminating opportunities that become available when a system of dynamic collaborative gate allocation is adopted.

### II. b. Current U.S. Gate Sharing Practices

Most airports do not currently offer options for gate sharing but instead lease gates out to airlines on month to yearlong terms, allowing airlines to customize and brand their space but preventing them from using the space of others when theirs is unavailable (SFO, 2011). However, in response to growing concerns about the negative impact of gate delays on customer experience, economic revenue, and the environment, some airports have begun rolling out gate sharing practices to better utilize existing terminal and gate infrastructure (Martinez, 2012). This practice has only been attempted at a low percentage of available gates and on a static model, wherein an airline essentially leases out a weekly time slot rather than an entire gate.

Collaborative Gate Allocation of this variety has been implemented to a certain extent at SFO's International Terminal. This newly built facility was designed for increased common use facilities as all gate equipment is airport-owned instead of airline-owned (Martinez, 2012). Airlines pay fees according to travel volume and do not have to buy this equipment themselves. Ten percent of the gates are also set aside as common use, but on a static model rather than the dynamic one that is proposed in this study. The path is paved for further development into common use gates as the hurdles in this newly built terminal are lower than at most other facilities.

## II. c. European Airport Model

In the United States, local and regional governments own and operate most commercial airports (Table 2-1). In Europe, on the other hand, ownership is much more privatized (ACI-Europe, 2010). Ownership structure is important because it determines who the key stakeholders are and who has the ultimate authority to make decisions, including those concerning whether or not to pursue collaborative gate allocation procedures at a given airport.

**Ownership of Hub and Non-Hub Airports**

| Ownership | Percent of Total |
|---|---|
| City | 40.2 |
| Single County | 14.4 |
| State | 9.3 |
| Port Authority | 4.1 |
| Regional | 22.7 |
| Multi-jurisdictional | 6.2 |
| Other (private, etc.) | 3.1 |
| **Total** | **100.0%** |
| *Source:* Airports Council International-North America, 1997 General Survey. | |

*Table 2-1: Ownership of Hub and Non-Hub Airports (Ref: FAA, 1999)*

Due to the proximity of European countries, most flights originating from E.U. airports (93% at London-Heathrow) are considered international (Heathrow, 2011). Since almost every

European country has at least one flag carrier, exclusive of low cost carriers, there may be over twenty carriers that operate out of a single mid-sized European airport such as Zurich (ZRH) each day. Similar to the manner in which U.S. airports handle gate allocation at international terminals, E.U. airports often employ collaborative (common-use) procedures so that airlines can share gates. This method has proven to be particularly effective in the United States within international terminals when foreign flag carriers may only operate only a handful of flights per day from a given airport (Stellin, 2011). Thus, it is not economical for each carrier to own an entire gate exclusively for servicing its flights. Due to the different time schedules and destinations inherent to international terminals at large airports, other airlines are able to use the same gate, pay lower rent individually, and gain access to the same terminal. Since airports want to maximize rent on their gates and ensure they are efficiently utilized, collaborative procedures are ideal for maximizing international terminal throughput and gate revenue for airports.

Additionally, European airport terminal gates are much more uniform than those in the United States. E.U. airport terminal gate layouts allow for greater flexibility since almost every gate area is nearly identical (e.g. Brussels/BRU) and not much airline-specific branding exists at a given gate. Instead, overhead television monitors display the current airline and flight information and thus designate which particular flight will operate from a particular gate at a particular time. While adopting this strategy at U.S. airports would solve many of the challenges of gate collaboration in the U.S. (U.S. airport gates are not uniform and are often branded), U.S. airlines would no longer be able to brand their gates at their hubs, a major source of value for airlines. This branding creates value for airlines by providing a seamless experience for U.S. airlines' customers and an environment in which airlines can market themselves toward passengers.

This consequence also explains why collaborative gate allocation currently seems unattractive to U.S. airlines – since U.S. airport gates are often branded and segmented by carrier, airlines would not want their passengers board and deplane at gates branded by two different airlines since this can be very confusing. This decreases the airline's ability to offer a better experience to its own customers compared to its competitors. Unless U.S. gates become undifferentiated, as they are in the E.U., collaborative gate allocation will continue to appear to be much less attractive than current preferential or exclusive-use procedures that are employed across U.S. domestic terminals. This will hold true until the net benefit an airline experiences from decreases in delays outweighs the inconvenience incurred by both airlines and passengers.

## II. d. Review of Existing Studies

Academic studies and technical reports focusing on benefit-cost analyses for Collaborative Gate Allocation programs in U.S. are sparse.  A previous airport design group at UC Berkeley developed a Sigma Simulation Model to simulate Collaborative Gate Allocation (Leung et al, 2011). Their randomized arrivals and subsequent sensitivity analysis give a sophisticated picture of the aircraft arrival and gate assignment policy under CGA, which we further improve by proposing a fundamentally different approach.  Their cost-benefit analysis was lacking, especially in how they quantified and applied passenger cost to calculations. The passenger cost was defined as the value of time wasted by all passengers in an idling aircraft, but in the real world this varies greatly between business travelers and children, and also between an aircraft that is empty and one that is full. Their model calculates a $54.90 value that is explained to be an average of all these cases, but they do not explain whether this loss is a cost felt by the bottom line of the airline or airport, or if it remains a hypothetical cost to society that no one directly pays for. To avoid this issue we introduce the cost incurred by gate-delays as a time-delay assessment rather than assigning it a monetary value.

A fundamental difference between our proposed model and previous one is in the nature of the gate-sharing policy dynamics. The previous collaborative gate allocation policy is static, meaning that the solution proposed does not modify itself when things in the real world change. Airlines simply chose to share certain gates during certain times up to six months in advance and then remain at this new status quo. This is still an improvement because more options are available to incoming flights, but it does not solve the problem of ungated flights. Unexpected delays will still occur, especially during peak hours when most gates are already being used to their full capacity. Since different airlines have different peak hours, simple collaboration could already bring significant improvements. However, a more dynamic system that features collaboration but can also recalculate scenarios in unpredictable situations could be vital in further decreasing gate-related delays, as well as in improving the air traffic system as a whole.

### II. e. Conclusion

Upon reviewing literature, we found that no dynamic system for gate allocation is currently in place. Such a system could dramatically decrease delays in the time periods where they are most likely to propagate, since only in peak hours do infrastructure constraints become binding. Thus using collaboration to combat these issues would be more efficient than constructing new infrastructure since it would have the same net positive effect in the times that matter most for a much lower upfront cost. Dynamic collaborative gate allocation (DCGA) takes collaborative gate allocation one step further by applying real-time data to a gate assignment algorithm. This allows the algorithm to allocate gates based on a more accurate, realistic picture.

The airlines can thus make more efficient gate allocation decisions and be more responsive to changes and crises.

## III. Problem Solving Approach

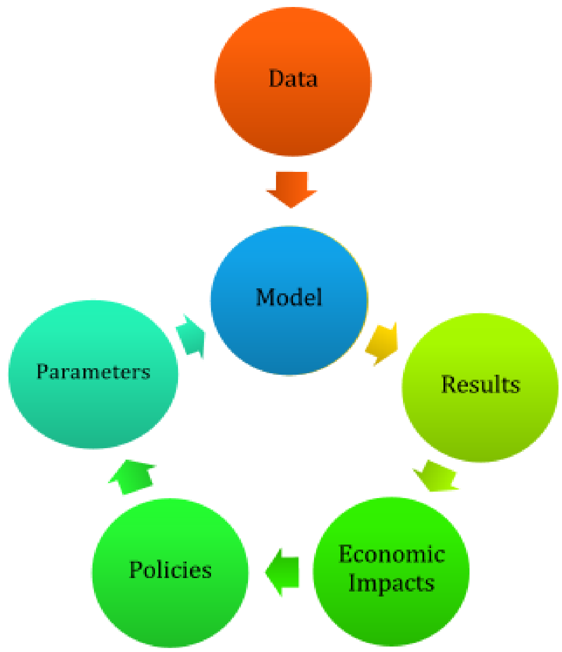


*Figure 3-1: Information flow between different aspects of DCGA model*

Designing and modeling a realistic dynamic collaborative gate allocation scenario requires a multifaceted approach. The three inputs to build our model upon are (1) the state of the current industry, (2) a simulation of gate/airfield operations, and (3) recorded schedule data obtained from airports and airlines. We began with the major obstacle to DCGA, namely the economic incentives required to encourage participation between airlines and airports. By evaluating the impact DCGA would have on the industry, we were able to assess various gate sharing policies, ranging from mandatory sharing of all gates to optional cooperation by small airlines. The various policies became the different sets of parameters we would test by inputting them into our optimization model and running the simulation.

By feeding the aircraft landing data into the model, we obtain results that include the overall reduction in delay, schedule variance, fuel usage, and pollution. We are able to assess the benefits of each DCGA scenario compared to a control simulation (in which gate priority takes place on a preferential basis) and quantify the incentives. Contrasting these benefits against the financial costs and resistance to collaborative gate allocation, we are able to distil out which DCGA policies are applicable to the industry and refine them. This iterative process will hopefully lead to policies for DCGA in which all of the participants in the aviation industry are willing to partake.

## III. a. System Optimum

Many decisions in the proposed study are postulated upon the assumption that the system optimum is greater (or at least equal) than the sum of local optimums. This means that the optimal solution to a set of problems (the solution with maximum net profit) is not necessarily the sum of the optimal solutions of the smaller problems. Each sub problem has a local optimum, which in this case is the gate allocation strategy that results in maximum profit for each airline represented at a given airport. If each airline were to maximize its own profit, the net profit of all parties involved (all of the airlines, the airport, and the public) is not necessarily maximized. In order to attain the system optimum it is necessary for some of the parties to not attain maximum profit. In order to compensate for this, there needs to be some sort of economic incentive for the airlines to accept a plan that attempts to approach the system optimum at the expense of their own local optimum. This concept is central to our project and will be discussed.

## III. b. Reduction of Ungated Flights and Variance

An early arriving flight (Figure 3-2), if not dealt with correctly, can have just as many negative consequences as a late arriving flight (Wharff, 2012). Even if the passengers still end up arriving at their destination at the scheduled time, they will be frustrated if they have landed and are not yet allowed to disembark because their gate is not yet available, especially if they can see other empty gates through their window. This causes an airline's reputation to suffer, as they must also pay for the additional fuel the aircraft uses while idling on the tarmac. The stakeholder that suffers the most in such a situation is the airport, as it is simply more congested and running in a suboptimal condition, especially if there are unutilized gates available that this aircraft could potentially use, but is not allowed to due to various outside constraints. All participants value predictability, and situations like this make it hard to predict how a situation will be resolved, even if every part of the aircraft's journey until the taxiing phase has run entirely smoothly.

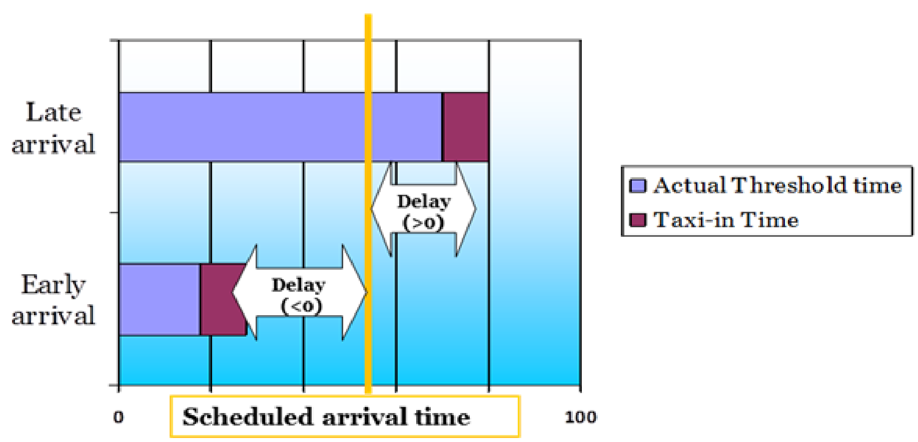


*Figure 3-2: Interpretation of Delays: Early and Late Arrivals (Ref: Rakas et al, 2009)*

Airlines value delay reduction strategies in a large part because of the reduction in variance a reduction in delays brings with it. Less variance means greater predictability (Figures 3-3 and 3-4). If an airline can be more confident in the variance of delays their flights will experience at a certain airport, they will be better able to schedule their block-to-block flight times, allowing them to further pack their schedule. This increase in flights means greater revenue for an airline, affecting their bottom line and giving them a strong incentive to participate in DCGA, if it turns out it brings this decrease in variance we are expecting. In our interview with Frank Ketcham, a commercial airline pilot, he emphasized how strongly commercial airlines feel about decreasing block time variance, so we feel this could be a valuable incentive for airlines to participate in DCGA.

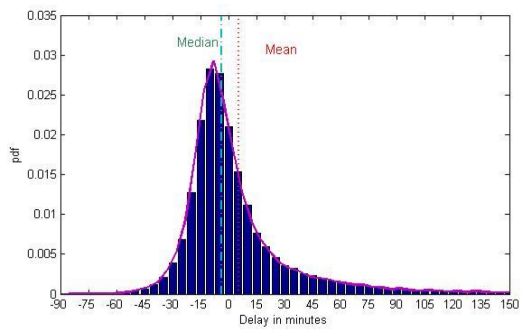


*Figure 3-3: Empirical distribution of the Delays at SFO Airport (Ref: Rakas, 2009)*

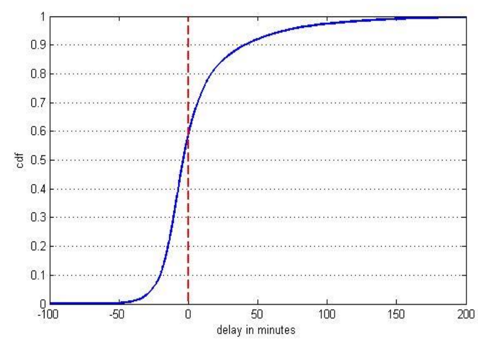


*Figure 3-4: Empirical cumulative distribution function of delays, SFO (Ref: Rakas, 2009)*

| | Number of flights | Mean (in min.) | Standard deviation (min.) | Median (min.) |
|---|---|---|---|---|
| Global | 30 395 | 5.15 | 34.34 | -3.70 |
| | | | | |
| Domestic | 26 076 | 5.40 | 34.28 | -3.77 |
| International | 4 319 | 3.91 | 34.18 | -2.87 |
| | | | | |
| 19L | 3 260 | 27.48 | 44.07 | 12.33 |
| 19R | 955 | 20.29 | 37.07 | 6.91 |
| 28L | 10 961 | **1.10** | 29.32 | -5.73 |
| 28R | 14 991 | **2.22** | 32.81 | -5.25 |
| | | | | |
| Wide body | 4 348 | **1.05** | 31.39 | -3.73 |
| Narrow body | 26 047 | 5.83 | 34.76 | -3.70 |
| | | | | |
| Off peak hour | 20361 | 4.16 | 29.46 | -3.4 |
| Peak hour | 10034 | 6.98 | 36.5 | -2.86 |

| | Number of flights | Mean (in min.) | Standard deviation (in min.) | Median (min.) |
|---|---|---|---|---|
| AAL | 2 661 | **1.88** | 32.13 | -4.78 |
| ACA | 534 | 5.78 | 33.78 | -0.89 |
| ASA | 1 756 | 7.00 | 37.34 | -5.72 |
| AWE | 1 082 | 5.60 | 28.31 | -1.84 |
| BAW | 179 | 3,83 | 30,72 | 0,93 |
| COA | 811 | **0.81** | 27.70 | -3.43 |
| DAL | 1 182 | **1.15** | 32.22 | -4.28 |
| JAL | 91 | 23.07 | 32.65 | 18.05 |
| KLM | 78 | 3.96 | 33.01 | -3.96 |
| MXA | 195 | 11.72 | 24.88 | 10.48 |
| NWA | 883 | 3.83 | 35.82 | -2.70 |
| SKW | 8 779 | 10.78 | 35.97 | -1.73 |
| TAI | 117 | **-3.84** | 28.03 | -10.75 |
| UAL | 10 030 | 1.86 | 32.98 | -5.64 |
| USA | 643 | 2.90 | 38.77 | -5.57 |

*Table 3-1: Characteristics of the empirical distributions of delays (Ref: Rakas, 2009)*

## III. c. Increased Airport Capacity without Additional Infrastructure

Air transportation, like all modes of public transportation, requires large capital investment to be made possible and, generally, to be made better. US airports spend roughly 30% of their annual budget for capital improvements on terminal developments. Though some of this is for renovations, much of this budget is spent on the construction of new terminals and gates to increase the capacity of the airport. Over the past 4 years, this has amounted to $28 trillion worth of investment (Table 3-2, Airport Investments From 2009-2013). Though DCGA not permanently remove the need for this investment and will require some capital as the system is installed and integrated, this cost is relatively small compared to the price of constructing new terminals, and will increase the benefit derived from such investments in the future. Furthermore, DCGA also spares the airport valuable real estate that would be required for a new terminal, as well as the logistics involved in placing the aforementioned facility.

**ACI-NA Total Costs by Project Type**

Millions of Current Year Dollars

| Airport Type | Safety | Sec. | Recon | Stnds. | Env. | Cap. | Term. | Access | New Airports | Other | Total | Percent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Large Hub | $651 | $2,102 | $3,830 | $268 | $1,892 | $13,778 | $23,019 | $ 9,034 | $ 34 | $664 | $55,273 | 58.6% |
| Medium Hub | 327 | 438 | 1,498 | 671 | 646 | 2,948 | 4,680 | 2,066 | 0 | 0 | 13,273 | 14.1% |
| Small Hub | 253 | 227 | 1,229 | 235 | 178 | 1,395 | 840 | 931 | 303 | 209 | 5,800 | 6.2% |
| Nonhub | 724 | 69 | 1,422 | 1,843 | 208 | 198 | 706 | 130 | 0 | 35 | 5,335 | 5.6% |
| Commercial Service | 48 | 23 | 384 | 470 | 1 | 17 | 52 | 28 | 0 | 12 | 1,035 | 1.1% |
| Reliever | 68 | 45 | 902 | 1,929 | 7 | 433 | 30 | 115 | 0 | 24 | 3,636 | 3.9% |
| GA | 168 | 234 | 2,553 | 5,981 | 129 | 479 | 152 | 191 | 0 | 64 | 9,953 | 10.5% |
| Total | 2,239 | 3,138 | 11,820 | 11,396 | 3,060 | 19,247 | 29,479 | 12,496 | 337 | 1,007 | 94,305 | 100% |
| Percent | 2.4% | 3.3% | 12.5% | 12.1% | 3.2% | 20.4% | 31.3% | 13.3% | 0.4% | 1.1% | 100.0% | - |

*Table 3-2: Airport Investments from 2009-2013 (Ref: ACI-NA, 2013)*

One of the main benefits of Dynamic Collaborative Gate Allocation is this lack of such a large, expensive barrier to implementation. DCGA will require research, negotiation, and maintenance, but the time and money required are much lower than with traditional infrastructure changes. At an airport that is gate-constrained, DCGA could still have the same net positive effect on delays and congestion as a much more costly alternative.

## IV. Practicality and Feasibility

Our proposed solution, implementing dynamic collaborative gate allocation, addresses the Airport Management and Planning challenge because it enables airports to maximize capacity without needing to build additional terminal space. DCGA also decreases the variance of delays at airports, dampening the negative ripple effects of delay that can permeate through the entire National Airspace System. Furthermore, implementing DCGA involves increasing existing inter-terminal communication infrastructure, which could potentially help coordinate cross-airline optimization efforts. Our proposal offers a solution to extended delays experienced by aircraft that undergo gate holds. Reducing the issue of gate holds decreases delays, fuel burn, and the time wasted by pilots, flight attendants, and passengers. DCGA offers several advantages while only requiring infrastructure similar to other common-use terminals, yet maintains its attractiveness to competitive airline. These are summarized below in Table 4-1.

| Cost Benefit Analysis of DCGA | |
|---|---|
| **Benefits** | **Costs** |
| • Decreased gate delays<br>• Increased airport capacity without additional terminal space<br>• Increased gate utilization<br>• More cooperation among airlines<br>• Increased inter-terminal communication<br>• More operational flexibility<br>• Decreased fuel burn<br>• Lower $CO_2$ and $N_2O$ emissions<br>• Saves time of pilots, flight attendants, and passengers<br>• Fewer "ungated" flights<br>• Decreased variance of gate delays | • Data transfer and update costs<br>• Inter-terminal communication setup<br>• Decreased operational freedom of airlines<br>• Decreased terminal branding opportunities for airlines<br>• Additional training for airline employees |

*Table 4-1: Cost-Benefit Analysis of DCGA*

## IV. a. Requirements for Implementation

One of the largest advantages of DGCA is the relatively low capital costs required to implement it. The primary requirement for installing DGCA at an airport is cooperation between airlines, in terms of both willingness as well as coordination of systems. Though the competitive environment of the aviation industry has fostered an attitude in which airlines value their exclusive gate lease agreements, the international portion of the industry has long utilized common gates. Many major US airports have recently begun building terminals for collaborative use between airlines, as well. Dynamic Collaborative Gate Allocation presents a more moderate approach of partial sharing of gates, but still needs airlines to cooperate since they own the leases to their gates.

In addition to the willingness to participate of airlines, the more physical aspects of adapting a terminal or airport to DCGA is the coordination of the systems and schedules of participating airlines, as well as the conversion of the gates to common-use. Information on flights, delays, shared gates, and personnel all need to be coordinated and distributed. Additionally, the shared gate control system would need to be integrated into each participating airline's systems. Systems for such cooperation are already in place in airports with common terminals. This infrastructure could be reproduced and combined with computing for the DCGA system to create the improved gate control. The physical aspects of gates such as unique electronics would need to be standardized or removed to the airlines remaining preferential gates. Additionally, airline employees associated with gate operations would need to accommodate these changes as well, requiring that they set up at their assigned gate with less planning than under preferential gate assignment circumstances. Still, none of these requirements impose upon airlines beyond other common use terminals.

## IV. b. Economic Incentives

Since collaborative gate allocation offers advantages to all parties in the air travel industry, but imposes the greatest potential cost on the airlines, the policy must be tailored to offer them increased benefits by adopting the system. This will prioritize financial gain without compromising the efficiency of the system, making DCGA lucrative enough for them to participate. The economic benefits for airlines are linked primarily to the reduction of delay; therefore this must be given the greatest importance in the DCGA system. The other benefits to airlines are derived from the increased degrees of freedom for scheduling. Both of these benefits are dependent on the size of the pooled gates, so a policy with a higher percentage of gates reserved for common use will optimize this effect.

The greatest benefit to airlines comes in the form of reduced delays. With the direct operating costs of running a large, commercial jet (including wages of employees and additional fuel) on the order of $100 per minute, reduction of these delays this offers a large incentive to airlines (de Neufville, 2003). Airlines that suffer from delays at airports operating at (or above) their stated capacity experience an average cost per delayed flight in excess of the profit generated by the flight (Figure 4-1). For our simulation case of DEN, this equates to a combined $350,000 in expenses suffered by airlines due to gate-hold delay in a single day, the majority of which can be alleviated by DCGA. The combination of increased capacity, reduced delays, and improved schedule variance provide airlines with ample incentive to encourage their participation.

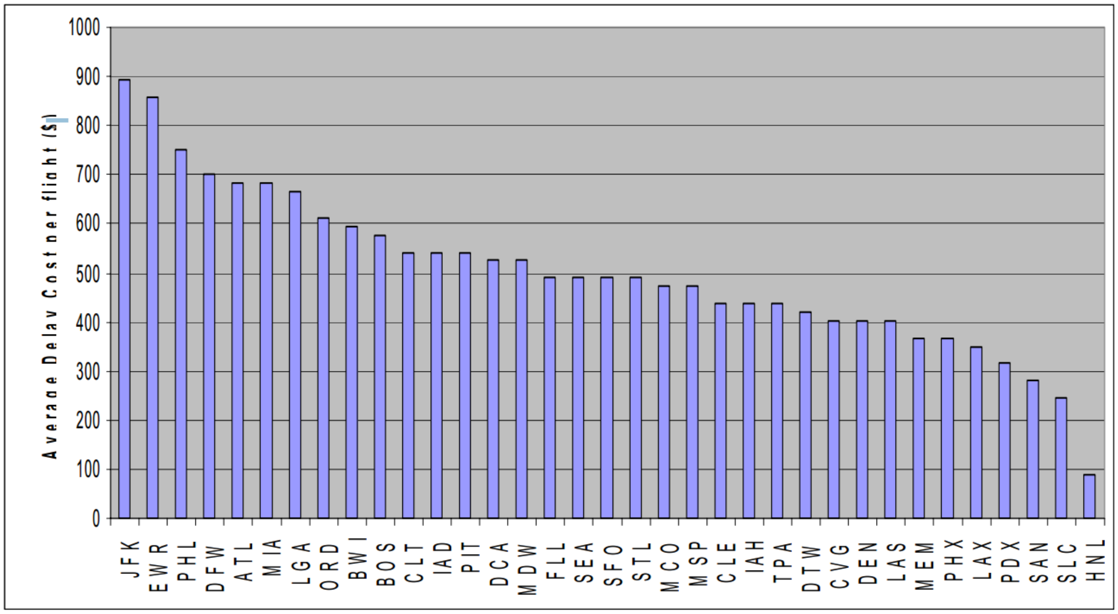


*Figure 4-1: Cost of Delay per Flight at OEP-35 Airports (Ref. FAA 2009)*

From the passengers' perspective, the airport represents a local monopoly, so improved service only marginally increases the attractiveness of air travel as a whole to the consumer. The economic incentives for the airport are all directly derived from increased capacity, leading to heightened throughput of the entire airport system. This saves them capital and land expenses, while supplementing their revenue with additional flights. Therefore, even marginal improvements to capacity, intrinsic to the DCGA system, are sufficient to inspire an airport's cooperation. DCGA presents an opportunity for Airlines and Airports to reach a middle ground and all receive mutual financial benefits through cooperation.

## V. Safety and Risk Management

DCGA is algorithmic and requires changes in the airport's digital communication systems rather than physical structures. Therefore many safety concerns with construction and physical alteration of airports do not apply here.

Here is a look at risk assessment of our design from the SMS Manual Safety Risk Management (SRM) process and the FAA Advisory Circular 150/5200-35 Introduction to Safety Management Systems for Airport Operations Safety Risk Assessment (SRA) points of view.

SMS Manual SRM Process:

A. Document proposed NAS changes regardless of their anticipated safety impact

B. Identify hazards associated with a proposed change

C. Assess and analyze the safety risk of identified hazards

D. Mitigate unacceptable safety risk and reduce the identified risks to the lowest possible level

E. Accept residual risks prior to change implementation

F. Implement the change and track hazards to resolution

G. Assess and monitor the effectiveness of the risk mitigation strategies throughout the lifecycle of the change

H. Reassess change based on the effectiveness of the mitigations

Similarly, the FAA Advisory Circular 150/5200-35 lists these steps below as phases for Safety Risk Management:

Phase 1. Describe the system

Phase 2. Identify the hazards

Phase 3. Determine the risk

Phase 4. Assess and analyze the risk

Phase 5. Treat the risk (i.e., mitigate, monitor and track)

Our project proposes a potential software change, therefore only touching on the software/hardware category. According to the SMS Safety Manual, “When a system includes software and/or hardware, the safety analyses consider possible design errors and the hazards they may create. Systematic design processes are an integral part of detecting and eliminating design errors.” (p 17) These design errors in software should be eliminated in the extensive testing and debugging phase that happens before integration into the larger airport communications system.

The other risk a software change DCGA might pose would be due to human error. The SMS manual states that “Human error is estimated to be the causal factor in 60 to 80 percent of aviation accidents” (p 17). Because our designed system should be an algorithm fully integrated into existing system interfaces, there should be no additional risk involved in human error. That is to say, the level of human error should remain at current rates as there are no changes in the human-to-the-system interface.

Our design should require no further safety analysis, since according the SMS manual, “if the change is not expected to introduce safety risk into the NAS, there is no need to conduct further safety analysis” (p 23). Therefore, there is no need to perform steps D through H in the SMS Manual SRM process to follow through Phase 5 in the FAA Advisory Circular 150/5200-35 SRM process. Instead, if implemented, our design should simply require an SRMDM, signed when there is no additional risk introduced to the NAS.

Our proposal will actually improve safety and risk management in several ways. Dynamic collaborate gate allocation aims to decrease the amount of gate-delay at an airport. When gate-delay is reduced, the amount of idling aircraft waiting in the penalty-box is reduced, as well as the amount of time an aircraft waits in the dead-zone. When an aircraft is idling at the penalty-box, they burn fuel, engine life, crew cost, passenger cost, and opportunity cost to be in another flight. DCGA would decrease all of these costs as well as decrease multiple risks that are caused by traffic congestion, backlog, fuel burn and depleting engine life.

Traffic congestions at an airport leads to possible traffic incursions and traffic delays, requiring additional work and management. Our DCGA proposal should reduce traffic congestion by reducing the time aircraft are on the tarmac, therefore reducing the risk of traffic incursion. Reducing gate-delay also reduces the necessity for the aircraft to travel to and from the penalty box after landing. If there is no gate-delay, aircraft will be able to travel directly to the gate without stopping. This reduces the amount of time an aircraft needs to spend traveling on the tarmac and reduces the chance of crossing the paths of other travelling aircraft. Reducing necessary movement lowers the probability of traffic incursions. This added efficiency will afford airport operators more time and allow them to focus on monitoring other operations, improving safety overall.

Safety and risk management is also improved through minimizing fuel burn and prolonging engine life. By minimizing the amount of time an aircraft engine remains running, the chances of any engine related mishap is reduced. An aircraft engine’s life may be extended by reducing amount of necessary engine use. DCGA makes the ground aircraft maintenance crew and transportation more efficient, therefore reducing the amount of equipment and time needed of ground transport. By reducing the amount of fuel burned by both the idling aircraft and ground transportation, the amount of harmful gases and $CO_2$ emitted is reduced. In the short term, this means reducing the times employees are exposed to hazardous fumes. In the long run, reduced emissions mean better air quality locally. Being more efficient, contributing less greenhouse emissions makes the airport more sustainable overall.

In accordance with the FAA Advisory Circular 150/5200-35 and the FAA Management System Manual, our proposal poses no new hazards. In an assessment of our proposal, our proposal provides a safer way of gate allocation by reducing aircraft congestion and bringing more aircraft into a stable state compared to the current practices. When an aircraft is gated earlier, there is less risk and thus no additional risk analysis is needed nor is any additional risk treatment needed.

## VI. Technical Aspects

### VI. a. Purpose of Model

Implementing DCGA necessitates innovation because the concept is not currently implemented in the US. There exist gate allocation algorithms and software, but because we are proposing a very new concept, we start from the ground up in terms of analysis. In the first step, we design an algorithm which models the DCGA process and affords an objective justification for choosing a specific scenario among different gating scenarios. We tailor a proposed model towards exactly what we want to find, and optimize it for the cases we expect to run. Furthermore, by using an algorithm rather than other analytical methods, we provide truly robust results for review, while providing the ability to scale up for arbitrary input size and processor power.

The problem of gate allocation is NP-hard. This means that the optimal gate allocation scheme is impossible to find for any reasonably large input (such as the dozens of gates and hundreds of flights / day that major airports are faced with), and as such, our algorithm could always use more refining. In this section we define the inputs, outputs, and parameters of the model, describe the baseline algorithm that we start with, look into various strategies for optimizing the algorithm, and discuss the potential of the model to expand.

## VI. b. Design Philosophy

The first step in designing the model is to establish goals for what we want the model to accomplish while recognizing the constraints of our project. Our ultimate goal for the model is to minimize gate-delay as a result of the use of a given gate allocation scheme at a given airport. Here a “gate allocation scheme” is defined as an association of each airline with a set of gates that it is allowed to allocate its flights to. For example, assume there exist gates [1, 2, 3, 4, and 5] and airlines [A, B, C]. You might allow airline A access to gates [1, 2, 3], B access to gates [2, 3, 4], and C access to gates [3, 4, 5]. In this way, gate 3 is collaboratively shared by all three airlines, gates 2 and 4 are shared by two airlines each, and gates 1 and 5 are only used by one airline each. Once this scheme has been defined, our gate allocation algorithm can run on a flight schedule input, seeking to minimize the gate-delay.

While the goal of the overall project is to minimize net cost by approaching the system optimum, the goal of the model is to apply a gate allocation scheme. It is left to the user to define the gate allocation scheme itself, the target airport, and the desired precision, and to communicate with the various stakeholders (airlines, airports, the FAA, and the public) to decide on which allocation scheme is best, based on the quantitative results of the model.

It can be seen by inspection that full collaboration in an ideal world would be the optimal gate allocation scheme - that is to say, all airlines are allowed use of all gates, which is effectively equivalent to one big airline. However, this is only true if competition between airlines is ignored (and a passenger walking distance for transfer passengers is optimized). In the real world, competition is important, and as such the aforementioned stakeholders must look at the results and decide amongst themselves which gate allocation scheme would be best. Each competing airline can apply its own metric to determine the cost of the gate allocation scheme from their perspective. Our algorithm is sufficiently generalized such that we could apply various cost functions for different airlines and compare them.

An important design criterion is the ability to vary the optimality of our gate allocation algorithm. The problem of optimal gate assignment is NP-hard, and as such we can only approximate a solution. We can seek a more optimal solution by increasing the sophistication of the algorithm and running it for a longer period of time. If we were pursuing a static CGA strategy then we could set some constant time, i.e. 1 hour, that we would like our program to run before producing a gate assignment. However, since we run this algorithm in real-time with evolving delays and flight schedule inputs, there might be some scenarios where we would want to run the algorithm very fast and get a suboptimal solution. As such, we want to be able to vary the desired optimality of the algorithm's output at will. The related techniques are expanded in section *VI.e.*

## VI. c. Scenarios and Parameters

Before running our DCGA algorithm, we need to configure a desired scenario, which includes a certain number of **parameters** and a **collaborative gate allocation scheme**. A **CGA scheme** is a generalized version of the aforementioned gate allocation scheme, which is the special case of a CGA scheme with minor collaboration. Essentially, the CGA scheme is a way of designating which gates each airline is allowed to use, according to the level of collaboration we are aiming for. The **parameters**, on the other hand, are constants dictated by the scenario we want to model.

We define a **scheme** as follows:

set of n airlines = A $\{a_1, a_2 ... a_n\}$

set of m gates = G $\{g_1, g_2 ... g_m\}$

**scheme** = S $\{s_1, s_2 ... s_n\}$, $s_i \in G$ where $s_i$ is the set of gates that $a_i$ is allowed to use

The degree of collaboration, then, would be related to the magnitude of each $s_i$ in S as compared to the magnitude of G. In other words, the more total gates that all of the airlines are allowed to use in sum, the more total collaboration there is for that scheme.

The **parameters** include buffer times, boarding times, distance between gates, and any other constants that apply to an airport and scenario that one need or want to be defined for use in the gate allocation algorithm. These parameters can be added or removed at will based on the needs of the desired algorithm; their defining characteristic is that they are constant for a given scenario and independent of flight schedule input. We configure the parameters and the scheme such that we can run the algorithm on various data sets and see which parameters and schemes work best for us.

## VI. d. Inputs and Outputs

Aside from the aforementioned parameters and scheme (which are part of the initial configuration of the program and are thus considered separately) the main input to the algorithm is a flight schedule. This schedule is defined as a set of flights:

set of q Flights $= F\ \{f_1, f_2 \ldots f_q\}$

flight i arrival time $= a_i$

flight i departure time $= d_i$

gates flight i can use $= G_i \in G$

The subset of gates $G_i$ is a function of the type of the aircraft and is based on the physical limitations of the gating equipment (such as size). Note that this set is independent of the ones defined in the scheme above, which are based on rules of collaboration and not equipment capability. The output produces:

revised flight schedule $= F_{revised}$

gate mapping M $= M(f)$

resultant cost sum $= C_{out}$

M is a mapping of flights to gates; it is an association of keys (flights) to their values (gates). $C_{out}$ represents the total cost incurred by the delays in the flight schedule. $C_{out}$ will be compared with $C_{in}$, the cost incurred by the original delays $D_{in}$. If the algorithm is successful, $C_{out}$ should be $\leq C_{in}$, since an optimal gate assignment with shared gates should be at least as good as one without.

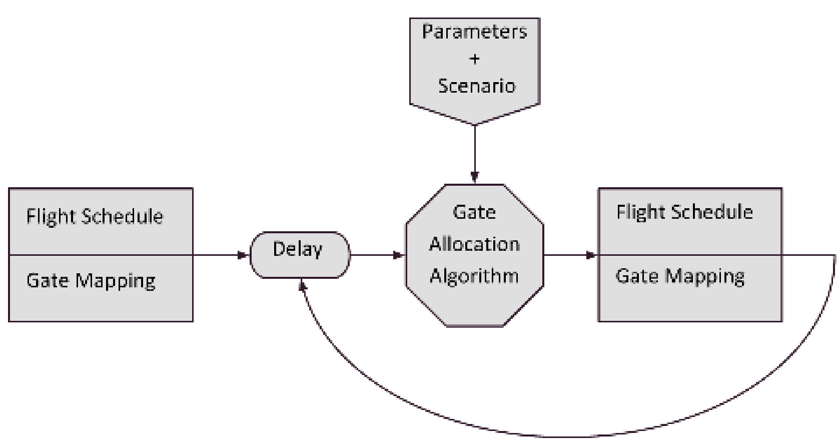


*Figure 6-1: A Visual Representation of the Flow of Proposed Analysis*

## VI. e. Algorithm

After establishing the design philosophy, we must choose an efficient algorithm. Our ultimate goal with this research study is to be able to adapt to observed flight delay by reallocating gates dynamically. This carries a couple of important implications for the functioning of the algorithm:

**1.** We want to change the running time of the algorithm at will. Since we are faced with the decision of allocating gates in real time, we would benefit from being able to run the algorithm sub optimally but much faster. This could be implemented in different ways. We could increase the tolerance level so that the algorithm would stop running earlier with a suboptimal result. We could modify the heuristic in order to make more decision branches infeasible and thus decrease the load on the algorithm. Lastly we could run an entirely different algorithm that has a faster running time. The decision of what choice to make would be based on how much time in advance we could predict gate delay - if we would like to reallocate a gate with only a few hours advance notice, we would like to run the algorithm very quickly, whereas if we have a day in advance then we might run a slower and more optimal version of the algorithm. In either case, the algorithm finalizes the schedule 40-120 minutes (depending on airport configuration and logistics) prior to the assigning time in order to allow both passengers and ground crews to reach and prepare for egress/boarding.

**2.** The difference between allocating gates to flights from a raw flight schedule and reallocating gates to flights that already have a gate assignment could represent a large difference in running time. More research in this area is necessary before making any decisions, and our project for the time being completely repeats the gate allocation process at each iteration.

However, we are able to use the previous gate assignment to compute the marginal cost of switching flights to different gates, which is helpful in optimizing the output but not helpful for improving its running time.

**3.** Since the algorithm is a method of approximation, the more processing power/time we devote to the running of the algorithm, the more optimal of a gate allocation we achieve (we cannot ever expect to achieve the optimum in suitably complex scenarios). This consequently means lower cost to the stakeholders. However, the processing power itself also incurs a cost. Assuming that the cost of the processing power increases linearly with the amount of power provided, and assuming that the benefit of improving the approximation to the optimal gate assignment decreases either exponentially or polynomially with the amount of processing power put into it, there should be an acceptable point at which spending more on processing power overcomes the benefit of increased optimality. The location of this acceptable point changes with time as processing power gets cheaper. Thus, implementing DCGA is an investment for the future when very good gate assignment can occur quickly.

The algorithm we chose is a priority-based scheduling assignment algorithm based on the Fixed Priority Preemptive Scheduling (FPPS) system, traditionally used for scheduling processes in a computer, which we use to solve the assignment problem (Burns, 2005). This algorithm uses a priority function to assign scheduling priority to flights. All of the flights are placed in a priority queue, where the flights with the highest priority are scheduled first. The highest priority flights and the costs associated with changing the gate assignment of those flights is used to formulate an assignment problem, which can be solved in polynomial time. For $q$ total flights and $n$ gates, $q/n$ assignment problems must be run. Since the assignment problem, the priority function, and the cost function are all polynomial in time, our algorithm runs in polynomial time. Since the actual problem is NP-hard, this is an approximation of the optimal solution. Descriptions of our algorithm and the assignment problem are provided below (Figure 3-6). The results of running the algorithm on flight schedule data at DEN are covered in Section VIII. Data for the peak day of the year, August 16, 2012 is obtained from the Official Airline Guide (OAG) and used in the baseline demand scenario; additional analyses of delays (and delay predictions) are based on ASPM data.

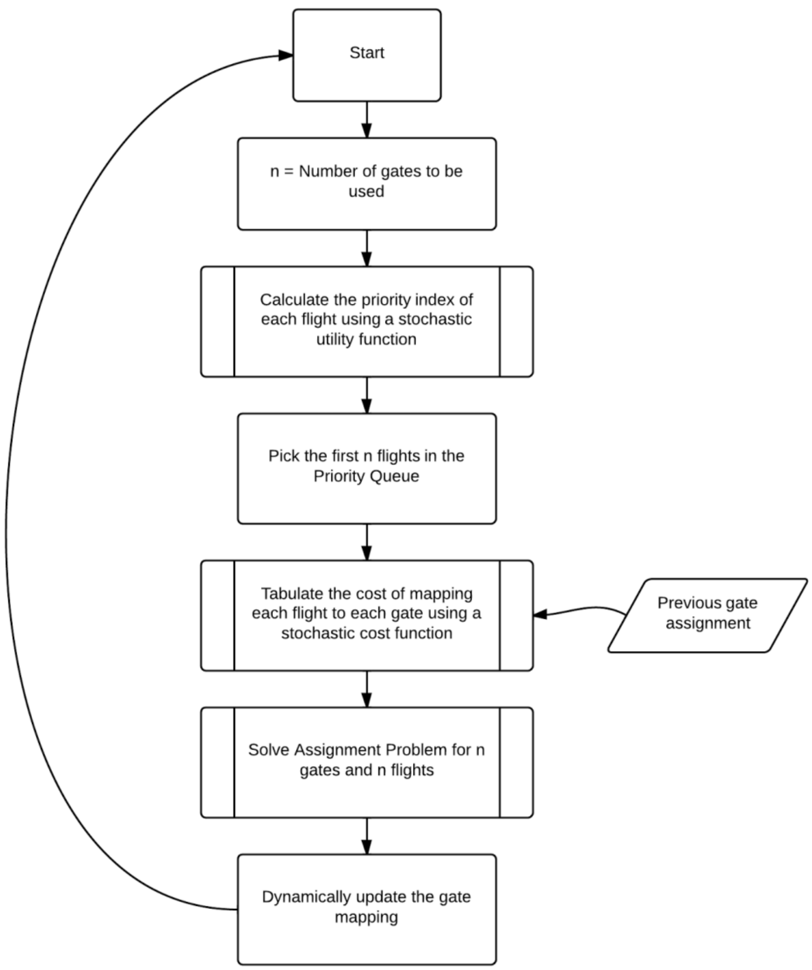


*Figure 6-2: A Visual Representation of the Algorithm's Process*

Formulation of Assignment Problem with respect to gate allocation:

$$min \sum_{i \in F} \sum_{i \in G} C(i,j)\, x_{ij}$$

$$\sum_{i=1}^{n} x_{ij} = 1$$

$$\sum_{j=1}^{n} x_{ij} = 1$$

i: Flights

j: Gates

$x_{ij}$: flight *i* is assigned to gate *j*

## VII. Interactions with Industry Professionals and Airport Operators

Throughout the development of our dynamic collaborative gate allocation model, our team was in contact with numerous aviation professionals from airports, airlines, consulting firms, and the FAA. In order to understand airlines' perspectives on collaborative gate allocation, we spoke to experienced network planners at United Airlines and Southwest Airlines. Dave Bochenek, former Director of Long Range Planning at United, encouraged us to consider the economic impacts on both large and small airlines at target airports for DCGA implementation. Consequently, we included a detailed economic analysis of DCGA implementation.

Frank Ketchum, a pilot at Delta Airlines, advised us that DCGA is a sensitive topic within the airline community and that airlines may be more interested in optimizing their own operations and not as interested in optimizing the entire aviation system as a whole. Similarly, as Mr. Bochenek suggested, DCGA may help airlines whose operations are below average but hurt those whose operations are above average. Thus, as our economic analysis suggests, the incentives for airlines to adopt and implement DCGA are not even across various airlines. There will be some “winners” and some “losers” as a result of implementing DCGA but the overall system will certainly benefit from increased global optimization. Gate control is a major goal for most carriers, as it enables larger market share and prevents other airlines from expanding. Thus, airlines that may not individually benefit from DCGA would be expectedly reluctant to implement it.

Matthew Streem, Virgin America’s ramp operations manager at SFO, advised us that branding is a very important component of the experience that airlines try to create for passengers. This is especially true in Virgin’s case, where its lighting and music sets the airline apart from the other carriers. If Virgin were required to use another gate to deplane passengers or allow another airline to use its gates, the resulting customer experience would be inconsistent and potentially confusing for passengers. Control over the experience that airlines provide for passengers is another factor our analysis includes in order to adequately evaluate airlines’ potential motivations and reluctance about DCGA.

Michael Nakornkhet, an airport economic planner at San Francisco International Airport (SFO), recommended that we begin simulating DCGA results by first applying the model to one isolated case and then applying it to larger, more complicated cases. We desired an airport with a large amount of delay due to high gate occupancy. Using ASPM and BTS databases, we found that Denver International Airport (DEN) Terminal A had a high correlation between gate occupancy and carrier delay, in addition to its variety of airline carriers (Table 7-1). In our methodology, we first test the model’s application within DEN and later generalize the application so that the model can simulate dynamic collaborative gate allocation at any airport.

| Airline | Flights | % of Time Gates are Occupied | Average Delay Caused by Carrier | % of Flights Late |
|---|---|---|---|---|
| American | 21 | 34.29 | 4.8 | 26.67 |
| Alaska | 5 | 31.05 | 0 | 0 |
| Frontier | 133.5 | 31.69 | 8.32 | 47.79 |
| JetBlue | 3 | 18.49 | 0 | 33.33 |
| Southwest | 19.5 | 46.65 | 14.06 | 52.98 |
| Correlation with Occupancy | | | 0.87 | 0.69 |

*Table 7-1: Correlation between Gate Occupancy and Delay at DEN Terminal A on Aug 16, 2012 (Ref: ASPM; BTS, 2013)*

Richard Marchi, from ACI - NA, explained that negotiating long term leases with airlines for their exclusive or preferential use gates could prove to be difficult. This resulted in a major risk in our analysis - we currently assume that renegotiating gating leases will not be an issue. Since many airlines resist the implementation of CGA, they can simply refuse to renegotiate the lease and prevent CGA from affecting them. We propose increasing incentives for airlines (lower rent, better choice of gate location, etc.) so that airlines are more motivated to renegotiate their long term gate leasing contracts. Marchi mentioned that Las Vegas International (LAS) implemented a gate sharing system similar to CGA and airport operators reported an approximate 10% increase in airport capacity, which strengthens our claim that implementing CGA will be cost effective and globally optimized at various impacted U.S. airports.

## VIII. Results

On August 16, 2012, an average day in the peak travel month, there were 495 arriving flights at Denver International Airport. 130 of them were left ungated for some amount of time. Based on the inputs to our model, this corresponds to 3380 minutes of total gate delay, or an average of about 37 minutes for each of the 92 gates we're considering. Table 8-1 shows how gate-delay decreases in accordance with various DCGA scenarios. Under “Uniform Sharing” a certain percentage of gates from each airline at the airport are pooled for DCGA, while the airlines retain control of the remainder of their gates. In the “Small Players” scenario, all carriers owning less than five gates allow other small carriers to use their gates when they are faced with an ungated flight under the DCGA algorithm. Small Players are grouped together because they are more likely to experience gate delays due to scarcity of options, and because they would be more likely to want to collaborate than the big airlines. Lastly, the entirety of Terminal A was tested under DCGA, as this terminal is the most fragmented between carriers of the three terminals at Denver International Airport.

| Scenarios | Gate Delay (minutes) | Percentage Decrease from Status Quo |
|---|---|---|
| Status Quo | 3380 | - |
| Uniform (5%) | 1838 | 45.6% |
| Uniform (10%) | 891 | 73.6% |
| Uniform (20%) | 0 | 100.0% |
| Small Players | 2653 | 21.5% |
| Terminal A | 156 | 95.4% |

*Table 8-1: Summary of Gate Delay Changes under Various Scenarios*

Gate delay decreases in all scenarios, and any uniform sharing beyond 18% is associated with 0 gate delay under standard conditions. The number of ungated flights decreases semi-linearly, with evidence of diminished returns for the last few, which most likely face exceptionally large gate delays.

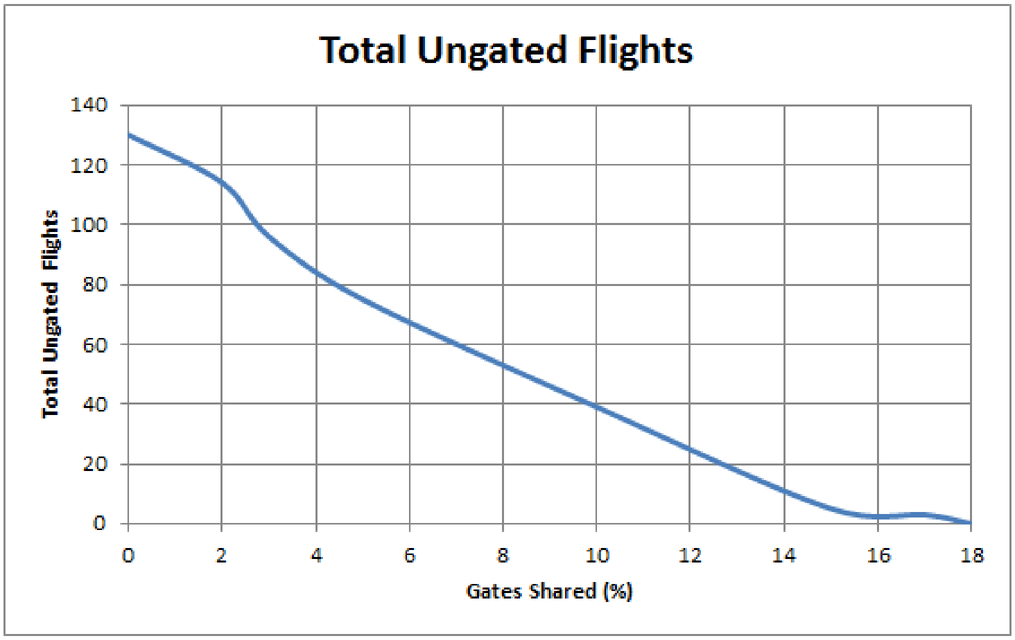


*Figure 8-1: Number of Ungated Flights relative to Percentage of Gates Shared Among Carriers*

By participating in DCGA airlines can also expect a decrease in the variance of gate delays and operations. With this added confidence, they will be able to decrease turn-around time, further packing their schedules and increasing the amount of time they are able to effectively use an aircraft. DCGA helps minimize delays, but it also helps prevent these delays from propagating and having an even greater impact on aircraft operations.

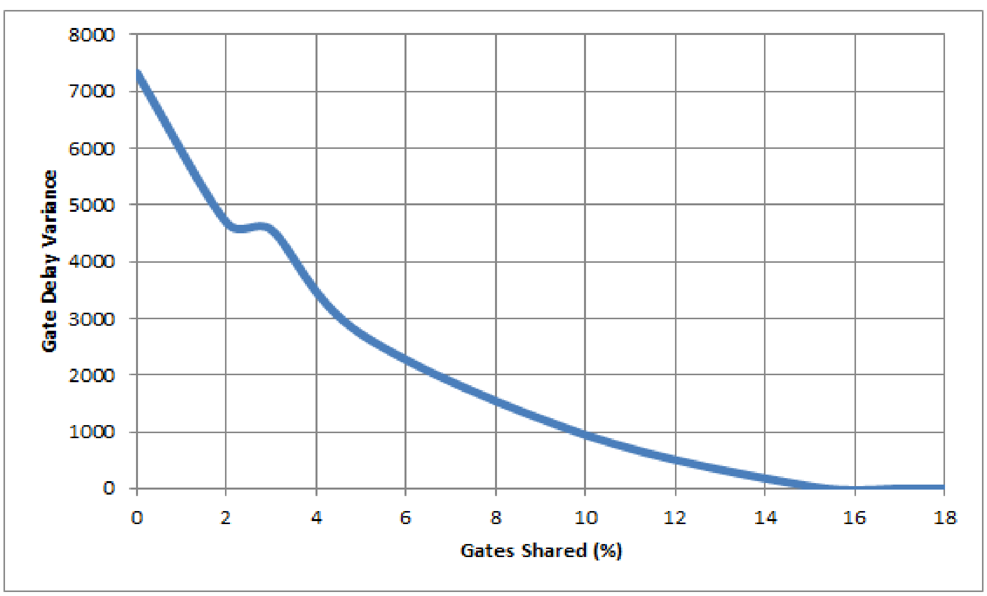


*Figure 8-2: Gate Delay Variance as a function of Percentage of Gates Shared*

The above analysis was performed with full hindsight knowledge of the delays that occurred on that day, by assigning flights based on their actual arrival and departure times (as opposed to scheduled times). Because in hindsight we have perfect information of the delays that occurred, this is the ideal scenario for DCGA. However, we have performed a sensitivity analysis in which we apply random delay (between 0 and 5 minutes) to flights as they are gated, and reassign the gates using DCGA to observe its effects. This simulates information that might be available a couple of hours before flights are scheduled. This was implemented in two different cases: 1) In the case where no collaboration is used, and we simply reassign the gates after the random delays are applied; 2) 5% Uniform Sharing is implemented throughout, and we still reassign the gates. We generated the random delays and ran the DCGA 10 times and averaged them out. The results are tabulated in Table 8-2. The total gate-delay increases, but much less than it would if the delays propagated throughout the schedule with no reassignment.

| All Values in minutes | Total gate-delay of scheduled flight | Avg total gate-delay after random delays and DCGA | Difference |
|---|---|---|---|
| No collaboration | 2994 | 3219 | 225 |
| 5% Uniform Sharing | 1323 | 1848 | 525 |

*Table 8-2: Comparison of dynamic gate assignment in collaborative and non-collaborative cases*

Here we see that assigning gates dynamically with no initial collaboration is more helpful than with, by doing a better job of mitigating the additional random delays; however, including collaboration is much better for reducing total gate-delay even after the random delays are applied.

## IX. Summary, Conclusion, and Recommendation

To date, ATFM concepts such as CDM and SARDA have produced significant operational improvements at airports. However, when observing the management of airport operations more holistically, we notice that aircraft gate assignments are not integrated with the existing ATFM concepts for tactical planning purposes. When further observing tactical management of gates, we notice (1) lack of information exchange between airlines and ATC, (2) routing of arriving aircraft to predetermined gates "owned" and assigned by the airlines months in advance, and (3) weak inter-airline collaboration. Although inter-airline collaboration for slot trading is encouraged in the CDM program with the objective to reduce arriving delays on runways, such collaboration among airlines in the gate-management domain is neglected at U.S. airports.

Gate delays have traditionally been resolved by investing in additional infrastructure, effectively increasing the capacity of the node and eliminating the bottleneck. Table 9-1 reveals the impact that the construction of new infrastructure, namely gates, could have on gate delay according to the model using DEN as a case study. This value is converted to the percentage of existing gates that would need to be designated as shared for an equivalent decrease in gate delay, based on the results of Section VIII.

| Constructing *x* Additional Gates | Which is Similar to Uniform Sharing of *y* of Existing Gates | Reduces Gate Delay by |
|---|---|---|
| 1 | 2% | 17% |
| 5 | 9% | 68% |
| 10 | 16% | 98% |

*Table 9-1: Summary of Gate Delay Changes under Infrastructure Scenarios*

A more efficient utilization of existing gates is highly favorable to the construction of additional gates for a variety of reasons. The cost of constructing a new gate varies greatly, but most estimates place it around $2000 per square meter of passenger space (Neufville, 2003). This puts the Denver International construction cost per gate, including infrastructure, at around $2.7 million. Addition of gates would likely mean addition of terminals, which would incur more comprehensive costs including cost of planning, demolition, not to mention potential inconvenience costs to passengers and airlines alike. This estimate, however, includes only the capital costs invested by the airport and its investors. The actual costs of construction are much higher, as large projects bring with them a certain responsibility to the environment and society, including preventing unnecessary noise, waste production, and environmental impacts associated with construction which can have huge impacts on the life cycle costs of a project, both by energy and by emissions standards (USGBC, 2013). Therefore, unnecessary construction should be avoided whenever possible. Striving for sustainability means striving for more efficient strategies of utilizing scarce resources, which ideally means avoiding having to use these resources in the first place.

In light of these economic, societal, and environmental concerns as well as the land constraints many airports must also consider, it is most advantageous for airports to restructure their existing infrastructure to solve the problems of infrastructure related delays. Of the scenarios considered, we believe that Uniform Sharing of 5% of the total gates would have the highest benefits for the lowest relative cost. This small degree of dynamic collaboration could already provide a 45.6% decrease in gate delay, increasing gate utilization and helping optimize the air traffic system as a whole.

The improvement experienced at each airport will vary proportionally to the severity of the gate delay they suffer, but DCGA will at the very least optimize gate capacity and improve how these airports handle situations of unexpected delay. Though it requires converting a small percentage of gates to common use, this is a relatively small capital investment that could be easily implemented at many US airports in which exclusive and preferential lease agreements are typical. By utilizing collaborative decision making and pooling already existing resources, both large and small airlines across the US could collectively save millions of dollars daily in reduced delay expenditures. DCGA presents a low-cost alternative to expensive infrastructure expansion that improves airport capability while significantly reducing ground-based delays that incur costs of time, money, and fuel.

## Appendix A: List of Complete Contact Information

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## Appendix B: University Description

The University of California, Berkeley is consistently ranked the world's number one public university by the Academic Ranking of World Universities. It serves as a home for higher education for around 36,000 students, including 25,800 undergraduates and 10,200 graduate students. UC Berkeley holds 1,582 full-time faculty serving fourteen colleges and schools with over 130 academic departments and more than 80 research units. The school houses a library system that contains more than ten million volumes and is among the top five research libraries in North America. More than 52% of all UC Berkeley seniors have assisted faculty with research or creative projects during their undergraduate career, leading more UC Berkeley undergraduates to go on to earn Ph.D.'s than any other U.S. university.

The Civil and Environmental Engineering department consistently ranks at the top of the best civil engineering programs in the country by the U.S. News and World Report. The Department of Civil and Environmental Engineering has fifty full-time faculty members and twenty-two staff dedicated to the education of more than 400 undergraduate students and 360 graduate students. UC Berkeley civil engineering laboratories for teaching and research are among the best in the nation, providing opportunities for hands-on experience for all students.

UC Berkeley was chartered in 1868 as the first University of California in the multicampus UC system. More than 7,000 UC Berkeley students every year do volunteer work in 240 service-oriented programs and there are more Peace Corps volunteers from UC Berkeley than from any other university. Clearly, UC Berkeley is focused on more than just academia as countless research and outreach initiatives are focused on public benefits to the community, nation and world.

## Appendix C: Non-University Partners Involved in the Project

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Leigh|Fisher is an international consultancy that has over 60 years of expertise within the aviation industry. According to its website, Leigh|Fisher specializes in business advisory, facility and operational planning, environmental and sustainability planning, management and strategy, and government advisory services. Leigh|Fisher's Bay Area office, located in Burlingame, serves west coast airports, including San Francisco International (SFO).

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San Francisco International Airport (SFO) is the busiest airport in the San Francisco Bay Area and the second busiest airport in California, following Los Angeles International (LAX). SFO serves as a hub for both United Airlines and Virgin America. Hosting a variety of legacy airlines, low cost carriers, and international flag carriers, SFO offers nonstop service to most states and many countries around the world. SFO is owned by the City and County of San Francisco.

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San Francisco International Airport (SFO) is the busiest airport in the San Francisco Bay Area and the second busiest airport in California, following Los Angeles International (LAX). SFO serves as a hub for both United Airlines and Virgin America. Hosting a variety of legacy airlines, low cost carriers, and international flag carriers, SFO offers nonstop service to most states and many countries around the world. SFO is owned by the City and County of San Francisco.

## Appendix E: Evaluation of Education Experience Provided by the Project

*Students*

**1. Did the FAA Design Competition provide a meaningful learning experience for you? Why or why not?**

We thoroughly enjoyed this project because we believe that, if implemented, dynamic collaborative gate allocation could have a tremendously positive impact on the global aviation industry. As students, we felt empowered to employ our research skills and available resources to try to make this potential impact more likely. We enjoyed reaching out to industry experts and learning about their diverse experiences and expertise. Speaking to them has increased our awareness of and interest in aviation challenges that the industry currently faces.

**2. What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?**

Since collaborative gate allocation is a relatively new topic within the airline industry in US, there are much fewer resources available than for other better-researched topics. We overcame this challenge by reaching out to industry experts and conducting extensive academic research in order to find out the necessary information. Additionally, as undergraduates, we were not familiar with advanced statistical and modeling methods so we had to learn many of these methods as our project progressed. We studied these new methods primarily through internet research.

**3. Describe the process you or your team used for developing your hypothesis.**

Based on our knowledge of collaborative decision making, we believed that by implementing dynamic collaborative gate allocation, airport operations would be more efficient. This greater level of efficiency would lead to increased capacity and higher airport utilization. We brainstormed the ways that various stakeholders (including airports, airlines, the FAA, and passengers) would benefit and built a dynamic model to predict and simulate these benefits.

**4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?**

We felt that industry participation was highly appropriate since, as undergraduates, we needed experts to advise, guide, and enrich our research. Their advice, combined with our own academic research helped ensure that our report was both comprehensive and credible. Interviewing experts was meaningful to us because, by talking to them, we gained an appreciation for the immense challenges that the aviation industry currently faces. The experts' data and advice proved to be tremendously useful and helped give rise to much of the analyses and considerations that we currently have in this report.

**5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?**

During interviews with industry experts, we learned about the current challenges that the aviation industry faces. Specifically, we learned about current gate allocation methods and the many challenges associated with capacity constraints. We also had experience researching our topic through academic resources and interviewing experts by phone and in person. These skills will prove valuable as we all graduate this year and enter the workforce. Some of us, who will pursue further study, will certainly use these research skills in the future.

*Faculty*

**l. Describe the value of the educational experience for your student(s) participating in this Competition submission.**

My students gained tremendous educational value from this Competition. They went through the entire creative process of designing a policy for dynamic collaborative aircraft gate assignments from the initial stages to the end by creating a methodology and a model for testing their gate assignment policy. As some of the students are planning to apply to various graduate programs, this educational experience was a perfect way for them to learn about how to start creating new concepts and new knowledge. Once they start their graduate programs, the experience gained while participating in this Competition submission process will help them make a smoother transition towards conducting more advanced research that is expected in any graduate program.

**2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?**

The learning experience was quite appropriate for the context in which the competition was undertaken. It tested the intellectual capability of the students at the right level, and offered challenging insight into practical, "real-world" problems. This Competition also allowed students collaborate in a small team of six students, which required them to co-operate, organize and designate tasks within a complex goal-oriented endeavor.

**3. What challenges did the students face and overcome?**

There were many challenges the students faced and successfully overcame. First, these are undergraduate students with no prior experience in conducting research. Furthermore, they came from a civil engineering, operations research, and business/management background, and had little previous knowledge or understanding of aviation or airport systems. The Airport Design class that they took the previous semester was their only formal education in aviation. Hence, the beginning of the research process included a long learning process about how to conduct research and how to understand more advanced aviation concepts, such as the Dynamic Collaborative Decision Making (DCDM) method. Another challenge the students faced was the initial misunderstanding of their proposed gate sharing policy by airport operators and industry experts, and the industry's initial "suspicion" about the proposed policy design. Whenever the experts commented on their design from a more tactical, operational perspective, the students very professionally and patiently would explain their paradigms and strategic goals. Consequently, their communication with the airport operators and industry experts was a very positive and productive enterprise.

**4. Would you use this Competition as an educational vehicle in the future? Why or why not?**

I would definitely use this Competition as an educational vehicle in the future. In previous years I conducted a significant amount of undergraduate research through the UC Berkeley Undergraduate Research Opportunities (URO) program. This program was designed to assist undergraduate students in developing research skills early in their college education. On average, half of my students from the Airport Design Class would participate in aviation research projects in the following semester, and would formally be funded and sponsored by URO. However, due to recent budget cuts, this program had to be closed. By using this Competition as an educational vehicle, I am not only continuing research with undergraduate students, but also teaching them how to structure, organize and present their work to a large number of experts in the field.

**5. Are there changes to the Competition that you would suggest for future years?**

I would expand Challenge Areas by adding more emphasis on the Next Generation Air Transportation System (NextGen) requirements and expectations, as well as on aviation sustainability.

## Appendix F: Reference List

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