Scheduling of Runway Operations for Reduced Environmental Impact

Gustaf Sölveling

PhD Candidate

School of Industrial and Systems Engineering, Georgia Institute of Technology, 765 Ferst Drive, Atlanta, GA 30332, USA, gustaf.solveling@gatech.edu

Senay Solak

Research Advisor, Assistant Professor

Department of Finance and Operations Management, Isenberg School of Management, University of Massachusetts, solak@som.umass.edu

John-Paul B. Clarke

Research Advisor, Associate Professor

School of Aerospace Engineering, Georgia Institute of Technology, johnpaul@gatech.edu

Ellis L. Johnson

Research Advisor, Coca-Cola Chair and Professor

School of Industrial and Systems Engineering, Georgia Institute of Technology, ejohnson@isye.gatech.edu

This work has been published in

Transportation Research Part D: Vol. 16, Issue 2, March 2011, pages 110–120.

Contents

This work has been published in *Transportation Research Part D: Vol. 16, Issue 2, March 2011, pages 110–120.*

Abstract

Efficient runway operations are a necessary input for the optimal use of the air transportation system. Most efforts at improving runway efficiency have failed to capture the impact of environmental costs. Here we develop an integrated approach that models this complex relationship, and provides insights regarding the value of environmental optimization for runway scheduling. More specifically, using actual flight data we compare environmentally optimal schedules with first-come-first-serve based policies and fuel-optimal schedules. We determine that while significant savings in environmental costs can be achieved through environmentally optimal schedules, these savings are not very different than those obtained through fuel-optimal schedules. Further, we find that any increase in the operational costs of airlines due to an environmentally optimal schedule is minimal.

Keywords: runway scheduling, environmental impact, emissions.

1 Introduction

The US National Airspace System (NAS) is operating at or near its capacity (Borener, 2005); a problem also experienced in other parts of the world. In such a constrained operating environment, any reduction in system capacity results in significant delays with consequential costs for airlines. According to the US Air Transport Association (2009), the direct costs of air traffic delays in 2009 was around $10 billion, 70% of which was due to ground operations.

Given this situation, air transportation authorities in both the US and Europe are investigating various technologies that they hope will increase capacity and the efficiency of resource utilization, especially with regards to runway operations. These efforts include the development of tactical algorithms for arrival and departure scheduling, taxiway routing, and for gate assignments. Despite the growing importance of the environment as a consideration in strategic and tactical decisions, the environmental costs of runway operations have not been explicitly accounted for in any of these algorithms, possibly because they are assumed insignificant when compared with direct operational costs[*].

---

[*] There is limited work that includes environmental impacts within the runway scheduling. Kesgin (2006) develops estimation methods for aircraft landing, take-off and taxi emissions, while Celikel *et al.* (2005) study the levels of environmental impact using operational scenarios. Monroe *et al.* (2008) analyze the environmental effects of eliminating arrival aircraft stops at active runway crossings using simulation tools. Hsu & Lin (2005) discuss an airline network design model to determine optimal routes and flight schedules in response to airport noise charges, while Nero & Black (1998) address the environmental costs in hub-and-spoke network design. Finally, Brinton *et al.* (2007) develop a departure planning tool that also accounts for emission costs.

This paper looks at the characterization of the environmental impact for different runway scheduling policies, and identifies tradeoffs between environmental savings and non-environmental costs. In addition, we derive cost functions with environmental components for air traffic, which can serve as inputs to similar optimization based air traffic scheduling algorithms.

2 Problem

Several deterministic optimization models have been developed for scheduling arrivals and departures on a runway. Given that the problem is combinatorial in nature, all exact approaches are based on integer models. Our analysis of the impact of environmental costs in runway scheduling algorithms also involves an integer programming model, which contains several generalizations over the standard definition and includes an environmental component.

We assume that the scheduled operations involve two parallel runways with a crossing taxiway (Fig. 1). This configuration is based on operations at Detroit Metropolitan Wayne County Airport (DTW), runways 22L and 22R, and is similar to the configuration at most other major airports. Without loss of generality, we assume that the outer runway is dedicated to arrivals, while departures take place on the inner runway. Thus, an arriving aircraft has to cross the departure runway, interacting with departure operations while taxiing to its assigned gate. In addition, as with many other airports, we consider the option for an arriving aircraft to go around the departure runway at the expense of increased taxiing time and costs. It is assumed that the longer route is not congested, and thus consists of a fixed taxiing time. On the other hand, if an aircraft is scheduled to cross the departure runway, it may be subject to taxiing speed adjustments or idling before the crossing. No runway crossing occurs for the departing aircraft.

Given such a general runway configuration, we can consider a set of flights $I = A \cup D$, where A and D represent the sets of arriving and departing aircraft. For each arriving flight $i \in A$, we assume that the following attributes are known at the time of decision making:

T_i^S : scheduled arrival time for flight $i \in A$

l_i : latest possible arrival time for flight $i \in A$

where the arrival time corresponds to the touchdown time for the aircraft. The latest arrival times are based on the possible airspeeds for the aircraft and other operational limitations. We consider a similar characterization for the departing flights, where the parameters are T_i^S, the scheduled departure or wheels-off time for flight $i \in D$, and l_i, the latest possible departure time for flight $i \in D$. We assume that a flight cannot depart before its scheduled time, and the upper bound l_i on the delay is imposed to prevent extensive

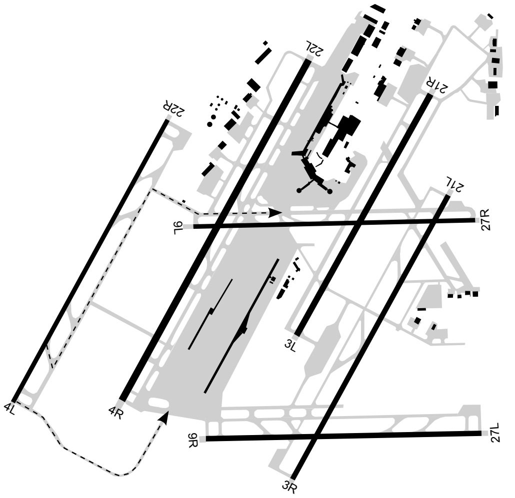


Figure 1 – A two-runway configuration similar to runways 22L and 22R at DTW.

		Trailing Operation							
		AH	A7	AL	AS	DH	D7	DL	DS
Leading Operation	AH	96	138	138	240	15	15	15	15
	A7	96	108	108	198	15	15	15	15
	AL	60	72	72	162	15	15	15	15
	AS	60	72	72	102	15	15	15	15
	DH	48	56	56	80	90	90	120	120
	D7	48	56	56	80	90	90	120	120
	DL	48	56	56	80	60	60	60	60
	DS	48	56	56	80	60	60	60	60

(a) Separation requirements (in seconds) for two parallel runways.

		Trailing Operation							
		AH	A7	AL	AS	DH	D7	DL	DS
Leading Operation	AH	-	-	-	-	10	10	10	10
	A7	-	-	-	-	10	10	10	10
	AL	-	-	-	-	10	10	10	10
	AS	-	-	-	-	10	10	10	10
	DH	35	35	35	35	-	-	-	-
	D7	40	40	40	40	-	-	-	-
	DL	40	40	40	40	-	-	-	-
	DS	100	100	100	100	-	-	-	-

(b) Separation requirements (in seconds) at runway crossing.

Table 1 – Separation requirements for close parallel runways with runway crossing.

delays at the gate. Additional parameters and bounds can be defined to model operational limitations such as maximum taxi times or queue times.

Key inputs for a runway operations planner are the separation requirements between different operations. These are based on safety measures imposed by the air traffic authority, and depend on the type of aircraft and operation. We define $S_{i,j}^{\min}$ as the minimum required time separation between flight operations i and j, and present the values of these parameters in Tables 1a and 1b.

The separation requirements in Table 1a are defined for operations in Instrument Flight Rules (IFR) conditions on a configuration with one runway for arrival operations and one runway for departure operations where the distance between the runways is less than 4300 feet. In Table 1, the first letters of the row and column headers represent the type of operation, i.e. arrival or departure, while the second letters represent the aircraft weight class. The considered aircraft classes are heavy, Boeing 757, large and small, denoted by H, 7, L and S. Wake turbulence caused by the leading aircraft is the source of the separation requirements for runway operations (Bly, 2005).

The runway-scheduling problem consists of minimizing an objective function subject to these separation requirements. To this end, we define:

$$\begin{aligned} x_{i,j} &: 1 \text{ if operation } i \in I \text{ is scheduled before operation } j \in I, \text{ 0 otherwise} \\ t_i &: \text{ time of operation for flight } i \in I \\ t_\ell &: \text{ time of the latest arrival or departure operation} \end{aligned}$$

A flight operation may refer to an arrival, a departure or a runway crossing action. If we let $g(t, x)$ represent the overall cost function with environmental impact, then the runway operations scheduling problem can be expressed as follows:

$$\begin{aligned} \min \quad & g(\mathbf{t}, \mathbf{x}) && && (1) \\ \text{s.t.} \quad & t_i \geq T_i^S && \forall i \in D && (2) \\ & t_i \leq l_i && \forall i \in I && (3) \\ & t_\ell \geq t_i && \forall i \in I && (4) \\ & t_j - t_i \geq S_{ij}^{\min} - M(1 - x_{ij}) && \forall i, j \in I \times I && (5) \\ & t_i - t_j \geq S_{ji}^{\min} - M x_{ij} && \forall i, j \in I \times I && (6) \\ & \mathbf{t} \in \mathcal{R}_+ \quad \mathbf{x} \in \mathcal{B} \end{aligned}$$

Constraint sets (2) and (3) limit the times for which each aircraft can arrive/depart and constraint set (4) identifies the time for the last activity on the runway. Operations need to meet the mandated separation requirements, which are defined in a general form through constraint sets (5) and (6). These constraints are used to model the separation requirements for the aircraft at the runway-taxiway intersection, as well as the minimum and maximum taxi idling time at the runway crossing. Treating (1)-(6) as a core model, it is possible to include additional decisions into the runway-scheduling problem by introducing new variables and constraints.

3 Cost functions with environmental impacts

An accurate and comprehensive representation of function $g(\mathbf{t}, \mathbf{x})$ is needed for the validity of the model. The objectives in the runway-planning problem are twofold: maximization of throughput by re-sequencing the arrival and departure streams, and minimization of operational and environmental costs associated with deviations from scheduled operation times. By putting a monetary value on these conflicting objectives, a global cost function can be constructed that consists of several parts, each of which involves some impact on the environment.

The overall cost function consists of a number of elements. First, for each arrival flight we consider the cost of deviating from the scheduled arrival time and the cost of deviating from the fuel-optimal arrival time, if different from the scheduled arrival time. For these latter flights we also consider the cost of additional time spent on the taxiway due to interactions with the departure operations. The second component captures the delay cost for departing aircraft that can be incurred either at the gate or on the taxiway. The third component captures the cost of runway throughput. Hence, we can express the objective function as:

$$\begin{aligned} g(\mathbf{t},\mathbf{x}) = &\sum_{i\in A} (\text{Cost of Schedule Deviation} + \text{Cost of Taxiway Operations}) + \\ &\sum_{i\in D} (\text{Cost of Delay}) + \text{Runway Throughput Cost} \end{aligned} \tag{7}$$

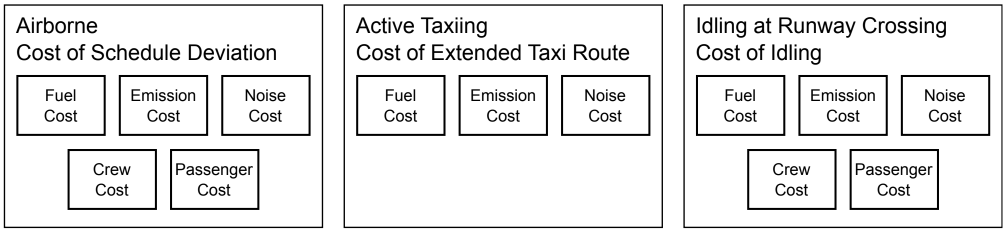
where the individual parts with an emphasis on environmental cost components are detailed below.

3.1 Components of the global cost function

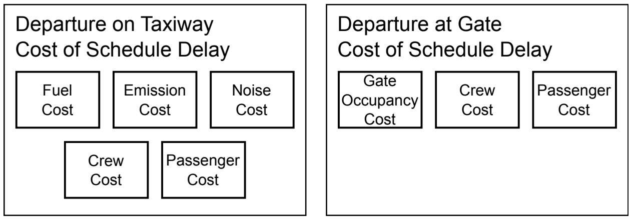
An important aspect of the global cost function is that it models the cost of deviations from a nominal schedule, i.e. the additional cost incurred by the scheduling process. Hence, all components modeling the costs for individual aircraft assume a zero cost if the aircraft arrives/depart on schedule, taxies according to the pre-assigned route and no delay is experienced due to runway crossings.

The planning model considers two decisions related to arriving aircraft that need to be captured in the global cost function. The first is the runway arrival time. The arriving aircraft is airborne when the decision is made and the deviation is easily calculated as the difference between the updated optimized arrival time and the scheduled arrival time. Two actions can be taken to achieve the desired deviation, namely speed-change and vectoring. We assume that both actions are possible in the cruise phase, but only vectoring is allowed in the descent and landing phase.

The second decision deals with taxiing operations. Each arriving aircraft has a predefined taxi route based on the shortest unimpeded taxi time to the gate. For those aircraft crossing the departure runway, it may be necessary to idle while waiting for an opportunity to cross the runway. Based on the cost of idling and the fixed additional cost of taxiing the longer route around the departure runway, the model can change the initial taxi route. It is assumed that crew and passenger costs are accounted for in the planning stage of nominal taxiway operations. The three phases of the arrival operation with corresponding cost components



(a) Cost components for arrival aircraft.



(b) Cost components for departure aircraft.

Figure 2 – Cost components for arriving (top) and departing (bottom) aircraft.

are presented in the upper part of Fig. 2.

A similar representation for departing aircraft can be seen in the lower part of the figure. By assumption, a departing aircraft cannot be scheduled earlier than the initially scheduled departure time, and thus, the cost function only needs to consider delays. Delay cost can be incurred either at the gate or on the runway, depending on whether the aircraft has pushed back from the gate or not. It is assumed that the engines are turned off when the aircraft is at the gate, therefore, no fuel, emission or noise cost is considered. Instead there is an opportunity cost for using the gate. For departures that have already pushed back we assume that the engine is idling and the delay is experienced on the taxiway.

3.1.1 Fuel costs

The additional fuel costs are proportional to the amount of additional fuel burned. For vectoring, taxiing and idling, the fuel flow is obtained for the standard four aircraft weight classes (Ren & Clarke, 2008). Depending on what stage of the process an airborne arrival flight is in, the fuel flow for an appropriate flight level is used.

For speed adjustments, the fuel flow is obtained by calculating the required speed adjustment to achieve the deviation. Assuming an instantaneous speed-change, the additional fuel flow is calculated as the difference between the fuel flow with the new speed and the fuel flow with the initial speed. If the aircraft do not fly at fuel-optimal speed, a change in speed can lead to a decrease in fuel flow.

	Low	Base	High
CO	0.07	0.09	0.13
CO_2	0.007	0.024	0.042
HC	1.7	3.6	5.5
NO_x	2.9	4.1	6.9
SO_2	1.4	3.9	7.2

Table 2 – External costs of aircraft emissions. ($/lb)

	Phase 1			Phase 2			Phase 3			Taxiing			Idling		
	L	7	H	L	7	H	L	7	H	L	7	H	L	7	H
CO	8.1	5.1	14.6	60.1	503.6	366.4	54.6	455.4	307.9	43.4	98.9	178.1	52	340.9	225.9
HC	1.7	4.0	1.9	12.4	6.1	111.9	11.3	6.1	86.9	9.0	5.3	40.9	10.8	5.9	56.7
NO_x	53.8	32.2	94.4	4.6	3.2	8.3	5.1	3.8	6.2	7.5	9.5	11.5	5.8	4.8	9.0
SO_2	3.7	4.4	7.4	1.0	1.2	1.7	1.1	1.4	1.8	1.4	2.4	2.6	1.2	1.6	2.3

Table 3 – Emission rates (lb/hr) based on the Boeing Fuel Flow Method 2.

3.1.2 Emission costs

For the emission costs, we consider the emission of CO_2 caused by the burning of jet fuel, as well as the emission of other pollutants, such as SO_2, NO_x, CO, and HC. The emissions of CO_2 are proportional to the fuel flow with a factor of 3.14, i.e. 1 lb of jet fuel emits 3.14 lb of SO_2 (EIA, 2009). The cost of CO_2 emissions is obtained by multiplying the additional fuel burn with $3.14c^{CO_2}$, where c^{CO_2} can be based on the cost of CO_2 emission based on the current market price on the CO_2 emission trading market. In addition, Celikel *et al.* (2005) report three levels of estimates for aircraft emission costs by pollutant type, which are shown in Table 2. We use all three levels of estimates when conduction the sensitivity analysis of the environmental impact of schedules on variation in these costs.

For other pollutants, the emission rates are based on the Boeing Fuel Flow Method 2 (Dubois, 2006). Representative equipment in each weight class is used to approximate the emissions for all phases of the flight, including taxiing and idling (Table 3). Due to the wide variety of aircraft types in the small weight class, and the relatively small impact they have on the overall emissions from aircraft, we omit this class when estimating environmental cost. Instead, a fraction of the emission cost for the large weight class is used as an approximation. The unit cost for each pollutant is again based on the estimates in Table 2.

Similar to the calculation of fuel flow for arriving flights, we divide emission costs into two components, depending on whether the maneuvers correspond to speed adjustment or vectoring. While the emission rates in Table 3 are used for vectoring based maneuvers, emission rates centered on the optimal cruise speed are used to calculate emission costs for speed adjustments.

In defining the cost of additional noise due to deviation in flight time, we use the estimates of Levinson *et al.* (1999) who suggests an average noise cost of $0.043 per kilometer traveled. While this is a crude estimation, it enables us to calculate a noise impact measure based on the time deviation and the average

	Weight class (passengers)			
Level:	S (70)	L (160)	7 (230)	H (270)
Low	1.9	4.4	6.4	7.5
Base	2.8	6.3	9.1	10.7
High	3.6	8.2	11.8	13.8

Table 4 – Noise cost, \$/minute, for three different cost levels. *Source:* Cook *et al.* (2004)

	Crew Cost		Passenger Cost	
	Short	Long	Short	Long
S	0	575	0	1165
L	0	800	0	3344
7	0	893	0	5533
H	0	1926	0	8226

Table 5 – Crew and passenger delay costs.

speed of a given aircraft[†]. Using the value as a base cost level, we also consider low and high noise cost parameters to account for any inaccuracy in the approximation. The resulting costs can be seen in Table 4.

3.1.3 Crew and Passenger costs

To estimate the cost of delays for crew and passengers, we use the information found in Cook *et al.* (2004). The report includes delay costs for 12 specific aircraft types under three cost scenarios. For the purpose of estimating crew and passenger costs we consider the base scenario that includes costs for two types of delays; a short delay of 15 min and a long delay of 65 min (Table 5). It is assumed that any delay of 15-min or less does not incur crew and passenger costs, resulting in the short delay costs being zero[‡]. Moreover, the minimum connection time for passengers and minimum turn around time for aircraft are typically around 30 min. It is concluded that any crew and passenger costs for short delays will be incurred only in rare cases and even then their impact will be minimal.

The crew cost portion of costs includes salaries and expenses for flight and cabin crew. The passenger cost portion includes hard cost (re-bookings, accommodations, etc.) together with soft cost (e.g. lost market share) for the airline.

Given these cost parameters, we can calculate the marginal cost for a long delay assuming that marginal delays grow linearly. The marginal cost for any delay is then calculated through interpolation. The cost of

---

[†] The approximation does not directly model the complex relations that use community characteristics and property values in calculating noise costs of runway operations, which are discussed in Nelson (2004) without any specifics on the dollar amounts for the costs. However, the use of a linear relationship between flight time and noise costs in our optimization model can be justified. First our analysis considers the additional cost of operations due to inclusion of environmental factors, which are incurred by delaying or speeding the aircraft mostly through vectoring. The number of operations and aircraft velocities, therefore, remain constant and only the flight times change due to the vectoring maneuvers. Moreover, these changes are mostly small. Even if an exact relationship between flight time and noise costs were to be established, these need to be defined individually for each specific airport. Thus, we utilize the approximation of Levinson *et al.* (1999) as a general relationship, and perform sensitivity analysis around that approximation to serve as a valid input to the runway scheduling algorithm.

[‡] Justifications for the no cost assumption for delays less than 15 min are detailed such that delays below this threshold are typically included as buffers in schedules.

occupying a gate depends on the subsequent use of the gate, as the delay at the gate can potentially cause a delay for an incoming flight. The gate occupancy cost is based on the idling cost, including crew and passenger cost, for the incoming flight. Since the model only considers the arrival time to the runway, the time by which the arriving aircraft reaches the gate is approximated using the unimpeded taxi in time and the expected taxi delay.

3.2 Cost of deviation from latest scheduled operation time

With a global cost function defined for each flight in the data set, a cost function for runway throughput can be developed. For simplification, let F denote the flights included in the optimization model and F' be the flights succeeding the flights in F. For both sets F and F', the flights are ordered by scheduled departure or arrival time. For the purpose of constructing the cost function, the last flight in F is assumed optimized so that the updated time is the same as the scheduled time, i.e. $\Delta_0 = 0$.

With this assumption, the flights in F' are scheduled according to a first-come-first-serve (FCFS) policy until the FCFS policy gives a zero delay for a flight or all the flights in F' are scheduled. The cost of the delay for each flight in F' is calculated, and adding these costs together the cost for violating the last scheduled runway time in F by Δ_0 minutes is obtained. Repeating this with an assumption that the last flight in F is delayed by $\Delta_0, \Delta_1, \ldots, \Delta_q$ minutes, a cost function for violating T^L can be constructed. The interval length Δ and parameter q can be chosen to achieve a desired level of detail in the piecewise linear function that is created.

All the components in the global cost function $g(\mathbf{t}, \mathbf{x})$ are convex functions. In the mathematical model we approximate $g(\mathbf{t}, \mathbf{x})$ with piecewise linear functions which allows for modeling using standard techniques.

4 Simulations for environmental cost analysis

The input to the simulations was based on actual flight schedules at major airports, and was representative of conditions during peak periods. More specifically, we initial consider the arriving and departing traffic at DTW for a 2-h peak on September 26th, 2006. Using this schedule as a baseline, we create additional representative schedules for heavier volumes of traffic by “compressing” the baseline schedule to obtain higher operation rates. We compressed the initial 120 min schedule to schedules of 105 min, 90 min, 75 min and 60 min. The arrival and departure rates for the different schedules are presented in Table 6.

For each schedule, we simulated 40 randomly generated instances by creating a realization of the actual departure/arrival time for each flight. The realizations were based on pushback delay distributions, taxi time distributions, and for arrival flights, delay distributions while in transit. The pushback delay distributions

Length of schedule	Arrival rate (flights/hr)	Departure rate (flights/hr)	Cumulative rate (flights/hr)
120 min	21.2	25.8	47.0
105 min	24.3	29.6	53.9
90 min	28.5	34.6	63.1
75 min	34.2	41.6	75.8
60 min	43.0	52.2	95.2

Table 6 – Arrival and departure rates for the different schedules.

Length of schedule	Arrival rate (flights/hr)	Departure rate (flights/hr)	Cumulative rate (flights/hr)
120 min	17.2	23.2	40.4
105 min	18.8	26.4	45.2
90 min	20.7	29.9	50.6
75 min	23.2	34.4	57.6
60 min	27.2	41.4	68.6

Table 7 – Average arrival and departure rates after realization.

and the transit time delay distributions were obtained by analyzing the aviation system performance metrics (ASPM) and enhanced traffic management system (ETMS) data provided by the US Federal Aviation Administration (FAA), while taxi time distributions were based on the analysis of Simaiakis & Balakrishan (2009).

The initial schedule for the 2-h peak was extended with an additional hour of flights to capture the impact of violating the latest scheduled time. After a schedule had been realized, the flights in the first 2 h were included in the optimization whereas the remaining flights were used to calculate the delay cost for subsequent operations. Similarly for the compressed schedules we included all flights in the first x, $x \in \{105, 90, 75, 60\}$ minutes of the schedule in the optimization. The simulated arrival and departure rates are presented in Table 7.

As representative aircraft types in each weight class for the schedule, we use Boeing 767-300 for the heavy weight class, Boeing 757-200 for the B757 weight class, and Boeing 737-800 for the large weight class. Due to the wide spectrum of aircraft, e.g. jet and turbo-prop, in the small weight class we assume that the costs used for this weight class are 70% of what we use for aircraft in the large weight class.

5 Analysis and Policy Implications

5.1 Environmental value of optimization

The major policy related question involves the value of an optimized schedule from an environmental perspective. In other words, how much reduction in environmental costs can be achieved through an optimization based approach over the currently implemented FCFS system, and how does this value change with increasing schedule density? The response is given in Fig. 3 where the environmental value of optimization is

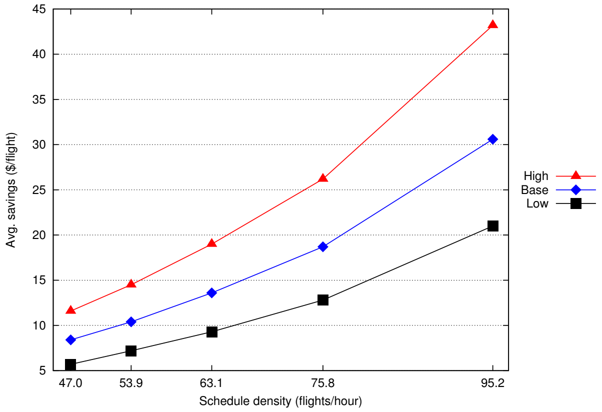


Figure 3 – Average reduction in environmental costs when an optimization based schedule is used. The savings are over a FCFS policy.

displayed for different levels of emission cost estimates. The overall savings vary between \$8/flight at low operation rates to more than \$25/flight at higher operation rates for the baseline cost estimates.

These numbers can be used to estimate a lower bound on the annual environmental savings value for any major airport and for the entire air transportation system in the US during peak operation periods. To this end, we first estimate the annual number of commercial operations during a 2-h peak period at 30 major airports based on the 2006 ASPM data shown in Table 8. Assuming an average savings value based on a peak operation rate of 40 flights per hour for two runways at each of these airports, we estimate the annual environmental savings based on the three different emission cost levels. These calculations suggest that annual savings in environmental costs can be between \$9.4 and \$19.1 million depending on the cost estimate level, if an optimization based scheduling policy is used during peak operation periods at major US airports.

Most environmental savings are realized due to the optimal scheduling of arriving aircraft. This is due to them having more flexibility in rescheduling, along with the higher rates of fuel consumption and emissions during the descent phase of a flight. Indeed, despite the approximately equal rate of arrival and departure operations, the realized costs due to arrivals are 1520 times higher than that of departures. On the other hand this does not imply that the optimization results in significant increases in departure delays to enable decreases in arrival delays. Rather, the difference in costs implies that there is more potential for savings in environmental costs by optimally scheduling arrivals than departures.

Another issue involves the comparison of optimization procedures with and without the environmental components. In other words, what is the value of considering environmental costs explicitly in an optimization model? Is minimizing fuel consumption and crew/passenger costs alone enough to minimize the environmental impact? To this end, we compare the environmental costs of optimal schedules in the two

		Savings in env. costs due to optimization		
Airport	Peak period ops.	Low	Base	High
ATL	121,195	$690,088	$1,012,381	$1,405,256
ORD	120,113	$683,925	$1,003,339	$1,392,706
DFW	96,455	$549,216	$805,717	$1,118,392
DEN	78,942	$449,497	$659,427	$915,331
IAH	74,743	$425,589	$624,353	$866,646
LAX	67,784	$385,966	$566,224	$785,959
DTW	62,728	$357,172	$523,983	$727,325
CLT	59,219	$337,193	$494,673	$686,641
PHX	58,933	$335,567	$492,287	$683,329
PHL	58,015	$330,340	$484,619	$672,685
MSP	54,682	$311,358	$456,772	$634,032
EWR	53,134	$302,544	$443,841	$616,083
CVG	50,377	$286,849	$420,816	$584,123
JFK	48,985	$278,923	$409,189	$567,982
LGA	48,923	$278,567	$408,667	$567,259
BOS	48,787	$277,795	$407,535	$565,687
SLC	48,642	$276,969	$406,322	$564,003
LAS	46,320	$263,747	$386,925	$537,080
IAD	45,947	$261,622	$383,808	$532,752
MCO	43,808	$249,446	$365,945	$507,958
SEA	43,177	$245,852	$360,672	$500,639
MIA	39,679	$225,934	$331,453	$460,080
SFO	38,670	$220,188	$323,022	$448,378
DCA	36,457	$207,588	$304,538	$422,721
BWI	36,109	$205,607	$301,631	$418,685
CLE	34,998	$199,279	$292,349	$405,801
STL	34,937	$198,931	$291,838	$405,092
MDW	33,331	$189,789	$278,426	$386,475
MEM	30,608	$174,285	$255,681	$354,904
PDX	28,403	$161,726	$237,257	$329,330
	TOTAL	$9,361,551	$13,733,692	$19,063,331

Table 8 – Annual estimate of the environmental value of optimization for 30 major airports in the U.S.

cases, and analyze the difference over the range of schedule densities considered. Explicit inclusion of environmental costs in the optimization reduces the environmental cost of the optimal schedule only minimally for each aircraft, i.e. around $0.3/flight. This result holds for all schedule densities as shown in Fig. 4.

This relatively high environmental value in fuel-optimal schedules is due to the direct relationship between fuel burn rates and emissions of aircraft. Hence, using optimal policies based on only the operational costs of airlines, which include fuel costs, will result in schedules that are very close to optimal schedules that account for environmental components. On the other hand, based on the number of peak period operations in Table 8, an environmental cost savings of $0.3 per flight translates to about $470,000 in annual savings on the environmental impact of airport operations. This amount can be viewed as a lower bound on the value of explicit consideration of environmental components in optimization based runway operations planning.

We also consider the relationship between environmental and non-environmental costs in optimized versus FCFS schedules, as seen in Fig. 5. The increase in non-environmental costs in a FCFS schedule is evident at higher schedule densities. This may be relevant from an airline's perspective, as optimization not only reduces its overall relevant costs but the savings increase almost exponentially at higher operation rates. On the other hand, the increase in both environmental and non-environmental costs of optimization based

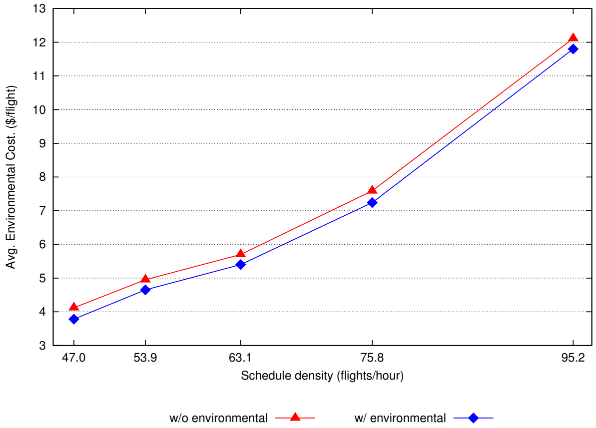


Figure 4 – Environmental costs per flight based on schedules optimized with and without explicit consideration of the environmental factors. The values are according to the base emission cost estimate.

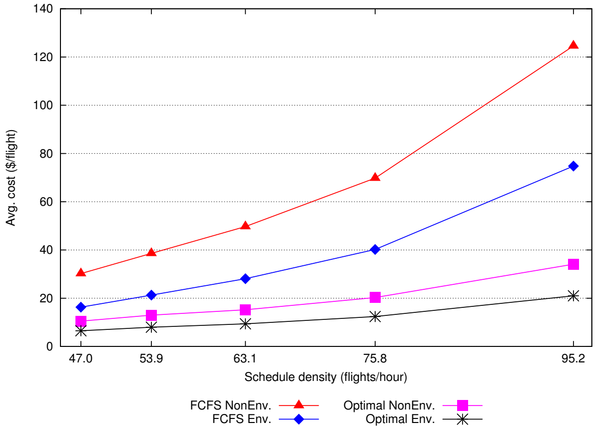


Figure 5 – Analysis of environmental and non-environmental costs per flight for optimal and FCFS schedules.

schedules is mostly linear as operation rates rise.

5.2 Cost of environmental runway scheduling to airlines

Under current regulations environmental costs are mostly relevant as a cost to the society, rather than the airlines. If runway operations are scheduled based on optimization models that explicitly include environmental costs, it is likely that schedules will not be optimal from an operational cost perspective. Thus, an important question is the additional operational costs incurred by airlines under such scheduling policies.

We compare the environmental and non-environmental costs of optimal schedules under different cost structures. In Fig. 6, we show that the additional costs are minimal, and decrease significantly for heavier traffic volumes. More specifically, for baseline emission cost rates these additional costs vary between $0.05 and $0.25 per flight. Thus, based on the peak period operations considered in Table 8 the cumulative costs for airlines add up to be between $78,000 and $391,000 annually, if environmental factors are considered in

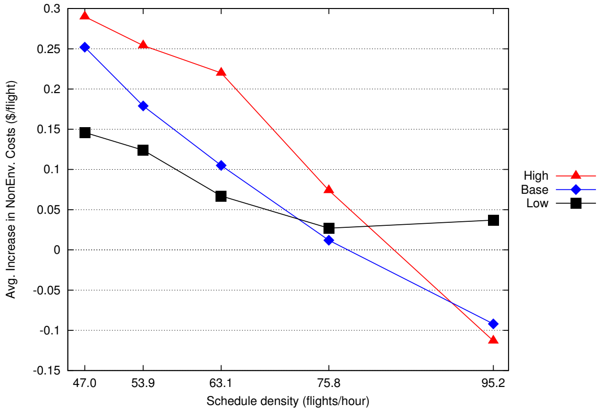


Figure 6 – Cost of including the environmental impact in optimization.

the optimization of runway schedules.

5.3 Structure of Optimal Schedules

One measure in runway scheduling relates to the structure of the schedules. Given the optimal schedules generated with and without inclusion of the environmental, the issue is whether these schedules are actually implementable. We consider the number of position shifts in the optimal schedules when compared with the FCFS schedule and analyze the magnitude of these deviations to ensure that the schedules are implementable.

The first observation is that the general structure of the optimal schedule based on maximum position shifts is similar over different levels of environmental cost estimates. Hence, the environmental components do not lead to significantly different emphasis areas in the optimization. The average maximum position shifts over all optimization instances are shown in Fig. 7. As expected due to the differences in cost functions, the re-sequencing of the arriving aircraft is done in a more conservative way than the departures, as the maximum deviation in the arrival sequences is mostly less than six, even at the highest traffic volumes. On the other hand, the maximum position shifts in the departures are typically higher at an average level of 10 over all schedule densities simulated. These high maximum position shift values do not imply long delays, however, as the maximum delay is limited due to the bounds used in the optimization.

The separation requirements used in the optimization models are defined according to the weight classes of aircraft. Hence, different fleet mixes may result in different patterns in the optimal schedules. While this is the case, a study of the fleet mixes during peak periods shows that the ratios of different weight classes are mostly similar at the major airports. According to the ASPM data, the distribution at these airports is typically around 5% heavy, 7% Boeing 757, 80% large and 8% small class. These values are consistent with the distribution used in the simulations.

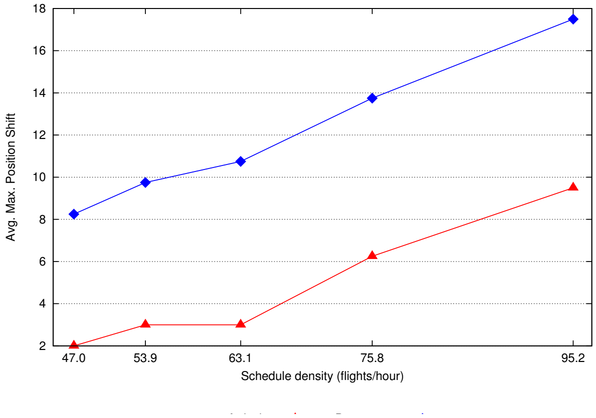


Figure 7 – Maximum position shifts in the optimized schedule with respect to the FCFS schedule.

6 Conclusions

We investigated the environmental value of optimization in runway scheduling, based on a global scheduling model that captures several complexities inherent in runway operations planning. The first complexity involves multiple interacting runways, and the second, the integrated cost structure associated with the resequencing of aircraft. To this end, we explicitly considered emission costs including CO_2 and several other pollutants, as well as noise costs.

We find that optimization based scheduling with explicit consideration of the environmental costs produce significant savings for both airlines and society. We also find that even if the environmental components are not directly included in the optimization, but instead a fuel-consumption based objective is used, the environmental savings over a FCFS policy are still significant. This implies that the additional operational costs incurred by airlines due to optimal schedules with reduced environmental impact are very minimal, especially at higher traffic volumes.

7 Acknowledgments

The author would like to thank Dr. John-Paul Clarke and Dr. Ellis Johnson at Georgia Institute of Technology for their contribution to this paper and in their roles as research advisors. The author would also like to thank Dr. Senay Solak at University of Massachusetts Amherst for many fruitful discussions and valuable input in the development of this article.

References

Bly, E. 2005. *Effects of Reduced IFR Arrival-Arrival Wake Vortex Separation Minima and Improved Runway Operations Sequencing on Flight Delay.* M.S. thesis, Massachusetts Institute of Technology.

Borener, S. 2005. Future Forecast Methods and Meaning of Preliminary Results. *In: Proceedings of the 30th Annual FAA Aviation Forecast Conference.*

Brinton, C., Cook, L., & Atkins, S. 2007. Collaborative Airport Surface Metering for Efficiency and Environmental Benefits. *In: Proceedings of Integrated Communications, Navigation and Surveillance Conference.*

Celikel, A., Hustache, J-C., Lepinay, I., Martin, K., & Melrose, A. 2005. Environmental Tradeoffs Assessment Around Airports. *In: Proceedings of the 6th USA/Europe ATM Seminar.*

Cook, A., *et al.* . 2004. *Evaluating the True Cost to Airlines of One Minute of Airborne or Ground Delay.* Tech. rept. Eurocontrol Performance Review Unit.

Dubois, D. 2006. Fuel Flow Method 2 for Estimating Aircraft Emissions. *In: Society of Automotive Engineers.*

EIA. 2009 (September). *Energy Information Administration: Voluntary Reporting of Greenhouse Gases Program.* `http://www.eia.doe.gov/oiaf/1605/coefficients.html`.

Hsu, C., & Lin, P. 2005. Performance Assessment for Airport Noise Charge Policies and Airline Network Adjustment Response. *Transportation Research Part D*, **10**(4), 281–304.

Kesgin, U. 2006. Aircraft Emissions at Turkish Airports. *Energy*, **31**, 372–384.

Levinson, D., Kanafani, A., & Gillen, D. 1999. Air, High Speed Rail or Highway: A Cost Comparison in the California Corridor. *Transportation Quarterly*, **53**(1), 123–132.

Monroe, G., Jung, Y., & Tobias, L. 2008. Analysis of Environmental Impact of Eliminating Arrival Hold Short Operations for Runway Crossings at Dallas/Ft. Worth Airport. *In: Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit.*

Nelson, J. 2004. Meta-Analysis of Airport Noise and Hedonic Property Values. *Journal of Transport Economics and Policy*, **38**(January), 1–27.

Nero, G., & Black, J. 1998. Hub-and-spoke Networks and The Inclusion of Environmental Costs on Airport Pricing. *Transportation Research Part D*, **3**(5), 275–296.

Ren, L., & Clarke, J-P. 2008. Flight-Test Evaluation of the Tool for Analysis of Separation and Throughput. *Journal of Aircraft*, **45**, 323–332.

Simaiakis, I., & Balakrishan, H. 2009 (August). Queuing Models of Airport Departure Processes for Emissions Reduction. *In: Proceedings of the AIAA Guidance, Navigation, and Control Conference.*