Runway Assignment by Minimizing Emissions in Terminal Airspace

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NOMENCLATURE

A	the set of arrival flights
R_{Arr}	the set of runways for arrival
F_{Arr}	the set of arrival fixes
E_i^T	emission index during terminal transition for $i \in A$
E_i^H	emission index at holding area for $i \in A$
E_i^S	emission index on surface area for $i \in A$
F_i^H	fuel flow rate at holding area for $i \in A$
F_i^S	fuel flow rate on surface area for $i \in A$
C_i^T	amount of emission during terminal transition for $i \in A$
$T_i^S(k)$	estimated transition time on surface between runway k and gate for $i \in A$, $k \in R_{Arr}$
$T_i^T(l,k)$	estimated transition time in terminal area between fix l and runway k for $i \in A$, $k \in R_{Arr}$, $l \in F_{Arr}$
t_i^R	time at runway threshold for $i \in A$
t_i^F	time at arrival fix for $i \in A$
S_i^F	scheduled time at arrival fix for $i \in A$
p_{ij}	sequencing decision variable at runway for $i, j \in A$
q_{ij}	sequencing decision variable at arrival fix for $i, j \in A$
r_{ik}	assigning decision variable of runway for $i \in A$, $k \in R_{Arr}$

ABSTRACT

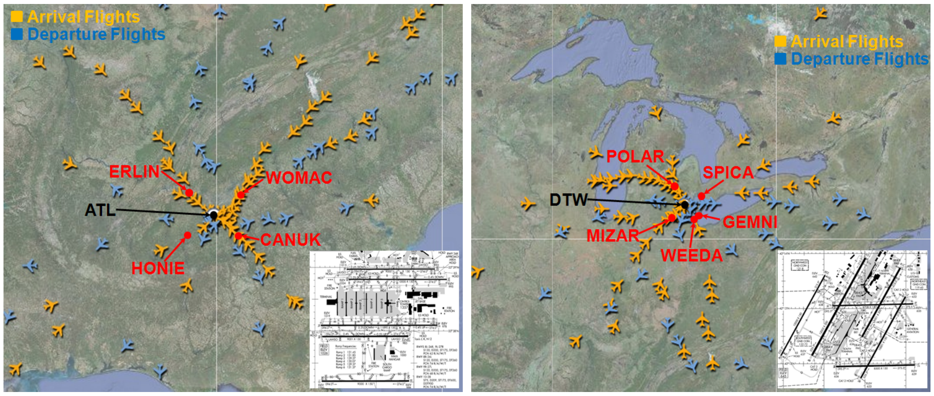
In general, air traffic volume from different directions is unbalanced. If all aircrafts use the shortest path to runways, then some runways will be overloaded, resulting unbearable delays while other runways maybe idle, resulting resources wasted. Therefore, one of the important jobs of air traffic controllers is to assign runways for landings and takeoffs so that limited runway resources can be effectively utilized. This paper presents a novel optimization model that minimizes total emissions in terminal airspace. The model assigns a runway for each landing and takeoff and sequences the landing and the takeoff on the same runways, accounting for safety separation rules, transition costs from fixes to runways, and taxi costs from runways to gates. The optimization results show that the

proposed model for planning terminal airspace operations is beneficial to improve airport efficiency and local environments.

I. Introduction and Motivation

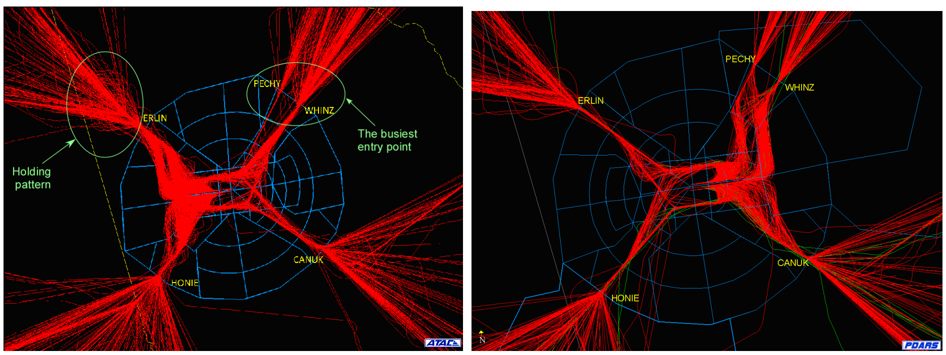
Aircraft arriving to and departing from congested airports often experience severe delays, especially during peak traffic times. At congested airports, these delays are often attributed to insufficient runway capacity. At some airports, however, the shortage of airfield resources is not the primary contributor of delays, but rather the management of airfield resources. As a result, some parts of an existing runway system may have excess traffic whereas other parts are operating at less than capacity, creating idle resources. For example, the air traffic volume from four posts/fixes at the Hartsfield-Jackson Atlanta International Airport (ATL) is unbalanced. As illustrated in figure 1(a), the volume of traffic is unbalanced, with the heaviest traffic coming from the northeast, followed by traffic from the northwest. During peak traffic periods, when in triple landing operations, this unbalance results in air traffic controllers, hereafter referred to as controllers, utilize dedicated landing runways for the Northeast and Northwest arrivals and merging the traffic streams from the Southeast and Southwest to the remaining landing runway. Even with dedicated landing runways, some re-routing is necessary to create slots to offload the heavy traffic streams to the under-served landing runways as shown in figure 2. Similar to the Atlanta airport, Detroit Metropolitan Wayne County Airport (DTW) experiences unbalanced traffic volume as presented in figure 1(b) with the majority of the traffic volume arriving from the west. Motivated by the traffic management of experienced controllers, an optimization model for runway assignment is proposed which would be beneficial for improving the throughput of runway systems and reducing flight delays as well as minimizing fuel burn producing positive environmental effects.

With the concern regarding global warming, reducing environmental effects resulting from aircraft operations is a stated goal of NextGen. Aviation greenhouse gas (GHG) is directly related to fuel burned and approximately 3.5% of the total GHG emissions is attributed to the aviation industry. This percentage, in the worst case scenario, could grow to 15% by the year 2050 [1] if the aviation industry does not take positive action to reduce aircraft/engine emissions. Engine emissions include



(a) Atlanta airport (b) Detroit airport

Fig. 1 Unbalanced traffic stream URL: http://www.flightstats.com



(a) ATL east flow (b) ATL west flow

Fig. 2 Arrival jet flows to the ATL airport

nitrogen oxides NO_x, sulfur dioxides SO_2, and carbon oxides CO_x. NO_x which is the primary cause of smog, and contributes to the formation of condensation trails, cirrus clouds, and acid rain. The impact of NO_x is estimated to be two to four times greater than that of CO_2, and its impact at high altitudes (8-13km) is even greater than at the low altitude. [2] Moreover, engine emissions along with air traffic control (ATC) efficiency have great impacts on the local air quality. Engine emissions depend on the engine power setting, time at that power setting, and altitude. Based on the ICAO engine emission databank, the highest NO_x index is during the takeoff phase while the highest production of HC and CO is during the ground taxi operation. Aircraft altitude and associated engine power setting are directly influenced by ATC's air traffic management. To improve safety, capacity, and efficiency in response to environmental issues, the United States and Europe have initiated ambitious projects: NextGen and SESAR, respectively with long-term tasks of enlarging airfields, launching new air traffic management (ATM) systems, and developing more fuel efficient aircraft and engines. [3] The short-term tasks include optimizing ATC operations within the current infrastructure systems. This research dedicates for short-term solutions that aims to optimize traffic planning in terminal airspace. Specifically, we assign a runway for each arrival and departure and also sequence landings and takeoffs on the same runways given an airport configuration, safety spacing, and capacity constraints.

The runway-scheduling problem has been well researched. For instance, Brinton suggested a branch and bound algorithm to find the optimal arrival schedule. [4] Carr et. al optimized the arrival sequence and schedule accounting for relative priority specified by air carriers, and they compared their optimal solutions with the First-Come First-Served (FCFS) policy by fast-time simulation. [5, 6] Bianco et. al formulated an integer model for the arrival scheduling problem. [7] The above mentioned work separated runway operations from the entire terminal airspace operations. Thus, the improvement of operational efficiency is very limited. To gain more improvement, Saraf and Slater [8] investigated dynamic hierarchical scheduling with a wide view of terminal airspace, and later, Bianco et. al [9] expanded their study to a multi-resource problem including arrival fixes and runways. Gilbo suggested an optimization scheme by minimizing cumulated queuing delays for air traffic flow management. [10] A literature review resulted in very little published work explicitly formulating emissions in an optimization model for the runway scheduling problem. However, many researchers attempt to quantify and analyze spewed pollutants associated with aviation stakeholders and ground taxi operations. The Environmental Protection Agency (EPA) estimated emissions relevant to U.S. airports [11] while EUROCONTROL analyzed environmental benefits for the free route airspace project and the relationship between environmental impacts and delays for both ground and airborne operations. [12, 13]

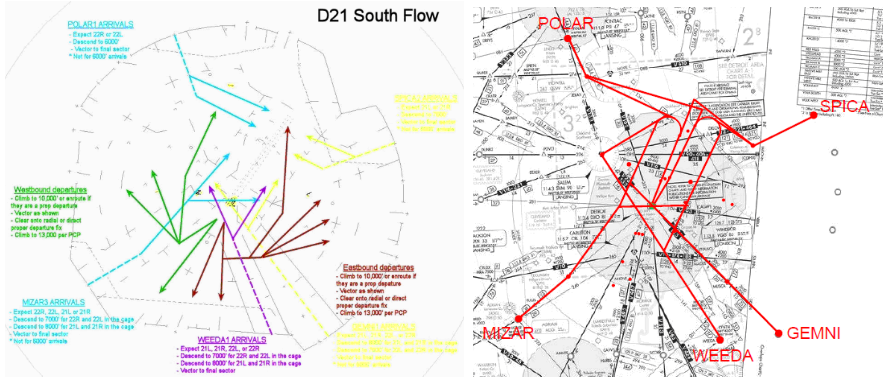
This paper presents a novel optimization model for terminal ATM that assigns runways and optimizes the sequence on the same runways. Given an airport configuration, the model minimizes the total emissions in the terminal area accounting for required safe aircraft spacing, capacity, and assignment constraints. The optimal solutions resulting from the model produce a runway assignment and schedule with fewer emissions within the terminal airspace. Because the model balances the traffic volume among runways and fixes, the optimal schedules also reduce delays and improve runway throughputs. The remaining part of this paper is organized as following. Section II discusses relationship between runway assignment and scheduling. The technique of balancing runway is also explained in section II. In section III, we formulate a mixed integer optimization model for this problem. Section IV describes the method of quantifying emissions associated with terminal operations. Finally, we provide numerical examples on DTW airport.

II. Runway Assignment and Scheduling

Two important jobs in terminal airspace operations are assigning flights to runways and scheduling the time of landings and/or departures. Runway assignment balances the traffic volume on multiple runways due to the inherent unbalance in the traffic streams. To utilize limited runway resources effectively, controllers, when assigning runways, have to account for many factors, including destinations (arrival gates or departure fixes), traffic volume on runways, and differences in aircraft performance. Scheduling landings and departures determines the sequence of takeoffs and landings accounting for flight delays and aircraft separation. The minimum separation is generally five NM for all aircraft in en-route space and three NM within terminal airspace. However, the separations at the final approach fix (FAF) to runways depend on the types of leading and trailing aircraft, ranging from 2.5 NM to 6 NM. Furthermore, approach and landing speeds also aircraft specific, therefore, the sequence of aircraft have an impact on runway throughputs. Because of these factors, both runway assignment and runway scheduling should be considered in a single optimization model as opposed to separating one from the other.

The simple and most conventional approach to runway assignment is to assign a runway to each flight based on the distance from its fix to the runway. For example, DTW has five arrival fixes: SPICA for northeast flow, MIZAR for southwest flow, GEMNI and WEEDA for southeast flow, and POLAR for northwest flow. This approach can be useful in the balanced traffic volume for the five arrival fixes. Unfortunately, this strategy cannot achieve a balanced runway utilization because due to the heavier volume from the west that is prevalent during certain periods and, as a result, leads to considerable delays.

To achieve effective runway balancing, controllers need the flexibility to choose paths from a



(a) South flow operation of Detroit TRACON (b) Suggested landing path

Fig. 3 TRACON area of Detroit Airport for South Flow

fix to act as feeders to the runways. To achieve this flexibility, several new arrival paths are added between the arrival fixes and runways. Figure 3(a) depicts the current south flow within the Detroit TRACON which is located in the Cleveland ARTCC. Based on this traffic pattern, new paths for the south flow are defined as illustrated in figure 3(b). Compared with the current track map, the new track map is more complex. Each fix connects a runway with two arrival paths, which results in an opportunity to build an optimization model for assigning runways based on traffic scenarios. Although there are several crossing points in figure 3(b), these crossing points are at different altitudes ensuring required vertical separation, therefore, each path is independent. To ensure minimum separation within the TRACON airspace, each aircraft must satisfy this requirement at the fixes along the paths to the runway. Since the landing sequence interacts with sequence at a fix, delays due to the landing sequence propagate to a fix crossing time. We will discuss the formulation in details in next section.

III. Mathematical Model

Runway assignment is formulated in a Mixed-Integer-Linear-optimization model. To simplify the model, we make the following assumptions.

1. All aircraft must follow pre-determined transition paths in TRACON.

2. An aircraft is not allowed to change its path during the takeoff or departure procedure once it is assigned a path.

3. Within TRACON airspace, the trailing aircraft cannot overtake the leading aircraft.

4. The altitude of every crossing point in the transition path satisfies the vertical separation rule.

A. Objective functions

Given an airport configuration, and flight schedule, the mixed-integer-optimization model minimizes total emissions in the terminal airspace, formulated in the following for arrival. The formulation for departure is accomplished by replacing emission indices and fuel flow rate in additional emission term approapriately with taxiing operation while the time at entry fixes is replaced by take-off time.

$$\min \underbrace{\sum_{i\in A} C_i^T}_{\text{transition}} + \underbrace{\sum_{i\in A} E_i^H F_i^H \left(t_i^F - S_i^F\right)}_{\text{delay}} + \underbrace{\sum_{i\in A}\sum_{k\in R_{Arr}} E_i^S F^S T_i^S(k)\, r_{ik}}_{\text{surface}} \tag{1}$$

Total emissions consists of three parts: emissions from fixes to runways, emissions from runways to gates, and emissions of queuing delays. The method of calculating the emission costs is explained in detail later.

B. Constraints

Aircraft i can arrive in front of aircraft j or behind aircraft j at runways and fixes. If Aircraft i arrives before aircraft j, $p_{ij} = 1$, aircraft j arrives after aircraft i automatically, $p_{ji} = 1$, and vice versa. In addition to this, each aircraft must be assigned only one runway.

$$\begin{cases} p_{ij} + p_{ji} = 1,\ \forall i,j \in A,\ i \neq j,\ p_{ij} \in \{0,1\} \\ q_{ij} + q_{ji} = 1,\ \forall i,j \in A,\ i \neq j,\ q_{ij} \in \{0,1\} \\ \displaystyle\sum_{k\in R_{Arr}} r_{ik} = 1,\ \forall i \in A,\ r_{ik} \in \{0,1\} \end{cases} \tag{2}$$

An immediate trailing aircraft must be separated from the leading aircraft by at least the minimum required spacing. The minimum spacing requirements are the most important constraints for fix and runway assignment.

$$\begin{cases} t_i^R - t_j^R \ \geq \ S_{ji}^R - M\left(2 + p_{ij} - r_{ik} - r_{jk}\right), & \forall i,j \in A,\ \forall k \in R_{Arr},\ i \neq j \\ -t_i^R + t_j^R \ \geq \ S_{ij}^R - M\left(3 - p_{ij} - r_{ik} - r_{jk}\right), & \forall i,j \in A,\ \forall k \in R_{Arr},\ i \neq j \end{cases} \tag{3}$$

If both flights i and j are assigned to same runway k and flight i arrives before flight j, r_{ik}, r_{jk}, and p_{ij} are set equal to 1, thereby activating the second inequality. Otherwise, the first inequality is activated. M is a big dummy number that imposes the separation rule regardless of the sequence of flights and runway assignment. S_{ij}^R and S_{ji}^R are the minimum time spacings for aircraft pairs $i-j$ and $j-i$ on the same runway, respectively. Similar to runway spacing, minimum spacing for arrival fixes is written as

$$\begin{cases} f_{il}f_{jl}\left(t_i^F - t_j^F\right) \ \geq \ f_{il}f_{jl}\left(S_{ji}^F - Mq_{ij}\right), & \forall i,j \in A,\ \forall l \in F_{Arr},\ i \neq j \\ f_{il}f_{jl}\left(-t_i^F + t_j^F\right) \ \geq \ f_{il}f_{jl}\left(S_{ij}^F - M\left(1 - q_{ij}\right)\right), & \forall i,j \in A,\ \forall l \in F_{Arr},\ i \neq j \end{cases} \tag{4}$$

The f_{il} is a known variable of an assigned fix. S_{ij}^F and S_{ji}^F are the minimum time spacings for aircraft pairs $i-j$ and $j-i$ at the same arrival fix. Because the separation constraints are expressed in time, the required separation distance needs to be converted to a required time. The time constraints for arrival fixes are straightforward and determined by the minimum separation distance at the fix entry points divided by the aircraft speed. Calculating the required time separation at the runway is the more complicated. Table 1 lists runway threshold separation requirements in distance between each arrival pair. Table 2 summarizes the approach/landing speed for each weight class of aircraft. Given the speed of the leading aircraft v_i, the speed of trailing aircraft v_j, the distance from the FAF to the runway l, and the minimum separation distance d_{ij}, the time separation is calculated by the following equations.

$$S_{ij}^R = \begin{cases} \frac{d_{ij}+l}{v_j} - \frac{l}{v_i} & \text{if } v_i \geq v_j \\ \frac{dij}{v_j} & v_i < v_j \end{cases} \tag{5}$$

For arriving flights, runway time is calculated by adding a pre-calculated transition time between

Table 1 Minimum separation requirements in distance

(nmi)	Heavy	B757	Large	Small
Heavy	4	5	5	6
B757	4	4	4	5
Large	2.5	2.5	2.5	4
Small	2.5	2.5	2.5	2.5

Table 2 Approach speed by class of aircraft

(knot)	Heavy	B757	Large	Small
Approach Speed	150	130	130	90

the assigned fix and the assigned runway threshold.

$$t_i^R - t_i^F = \sum_{k \in R_{Arr}} \sum_{l \in F_{Arr}} T_i^T(l,k) f_{il} r_{ik}, \ \forall i \in A \tag{6}$$

$T_i^T(l,k)$ is a pre-calculated table of transition time between the fix l and runway k. Because flight information is updated at the given cycle, an initial delay constraint must be imposed so that the optimization module will not assign more flights to the congested runway. The following constraint requires that no flight is scheduled to runway k before the initial delay d_k.

$$t_i^R \geq \sum_{k \in R_{Arr}} d_k r_{ik}, \ \forall i \in A \tag{7}$$

IV. Emission Costs

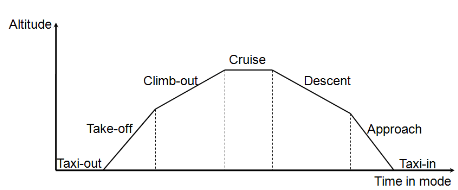


Fig. 4 Mission profile (not scaled)

Emissions are dependent on engine power settings and fuel burn. Figure 4 shows a generic aircraft mission profile. In this profile, only three parts; descent, approach, and taxi-in are relevant to terminal operations for arrivals while taxi-out, take-off and initial climb-out are included in an analysis of departure emissions. Since each flight mode has different engine power settings and vertical profile such as altitude and speed, the associated emissions are calculated separately. This computation is accomplished by the following equations.

$$E_{jk} = t_j \times FF_j \times EI_{jk} \tag{8}$$

E_{jk} :emission of pollutant k in mode j, (g)

t_j :time in mode j ,(sec)

FF_j :mode-specific fuel flow rate in mode j,(kg/sec)

EI_{jk} :emission index for pollutant k in mode j, (g/kg)

Accurate fuel flow rates and emission indices are crucial to obtain accurate results. These indices, however, are typically considered proprietary by the aircraft and engine manufacturers. Thus, the fuel flow rates and emission indices used are found in the ICAO databank. Table 3 shows typical fuel flow rates and emission indices from the ICAO databank. Even though ICAO's databank has sufficient data to compute emissions, it does not cover the entire engine power spectrum that is present during a terminal airspace transition. Fuel flow rates and an emission indices are dependent

Table 3 Sample of ICAO's databank

Engine Identification: AE3007A1/1	Take-Off	Climb-Out	Approach	Idle/Taxi
Emission Index for HC(g/kg)	0.03	0.03	0.03	3.88
Emission Index for CO(g/kg)	0.74	0.55	6.8	40.07
Emission Index for NO_x(g/kg)	16.10	14.01	7.12	4.17
Fuel Flow Rate(kg/sec)	0.3805	0.3163	0.1125	0.0459

on flight conditions (e.g., altitude and speed). To compute the fuel flow rate for descent, the Base of Aircraft Data (BADA) is used with the emission indices obtained for each flight condition by using the Boeing Method II(BM II).[14] BADA has been developed as an aircraft performance model by EUROCONTROL. According to EUROCONTROL, data for over one hundred aircraft types are included and relative information from both flight and operating manuals is used in the database. Thus with BADA, the fuel flow rate for the descent mode can be extracted for a specific flight condition by computing the relationship between mode and engine thrust. On the other hand, BM I was developed using aerodynamic test data and correcting for the altitude effect on the emission index. BM I, however, did not account for the temperature effects and to resolve this issue, BM II was introduced as an expanded version to allow for both temperature and altitude effects. Since holding area and surface operations can be assumed a stationary condition, E_i^H, F_i^H, E_i^S and F_i^S in the objective function are obtained by using both BADA and BM II. However, operating conditions are varied in time for descent, approach, take-off and climb-out cases thus the emissions can be computed by

$$C_i^T = \sum_{k \in R_{Arr}} \sum_{l \in F_{Arr}} f_{il} r_{ik} \sum_{t_{lk}=0}^{T_i^T(l,k)} E_i^T(t_{lk}) F_i^T(t_{lk}) time_{step}, \ \forall i \in A \tag{9}$$

With assumptions defined in previous section, $E_i^T(t_{lk})$ and $F_i^T(t_{lk})$ can be estimated along the transition path.

V. Numerical Example and Result

We implemented the proposed mathematical model on the DTW airport for arrival and departure flights. We use an eight-hour flight schedule on January 10th, 2007 from Aviation System Performance Metrics (ASPM) as representative input data, presented in table 4. For simplicity, we assume that runway 21L and 22R are dedicated to arrival while 21R and 22L are used for departure as representative runway configuration. Because ASPM does not provide the time at runway and crossing fixes, metering fixes, and runways, we estimate metering fixes based on origin and destination airports. For arrival flights, we calculate the heading between origin and destination using great circle, then map the heading to the metering fix. We also assume that scheduled gate-in time is the sum of scheduled touchdown time and unimpeded taxi-in time. Then schedule time at fix is obtained by subtracting the transition time between arrival fix and closer runway pair from scheduled landing time. Information of departure flights is generated using same approach.

As noted in section III, minimum separation requirement is the most important regulation and every aircraft's pair should be satisfied this requirement for safety. From table 1 the separation in table 5 is converted in time unit with table 2. In conversion PULKE and GEETR are used as

Table 4 Representative schedule at Detroit airport

Day	January 10th, 2007
Runway configuration	21L,22R‖21R,22L
The number of arrival flights	331
The number of departure flights	310
Schedule hour	13:00∼21:00

Table 5 Minimum separation requirements

	21L				22R			
(sec)	Heavy	B757	Large	Small	Heavy	B757	Large	Small
Heavy	96	141.8	141.8	238.4	96	138.5	138.5	224
B757	96	110.8	110.8	211.1	96	110.8	110.8	200
Large	60	69.3	69.3	183.4	60	69.3	69.3	172.3
Small	60	69.3	69.3	100	60	69.3	69.3	100

Final Approach Fix (FAF) for 21L and 22R respectively. Since those FAFs are located in different distance from Detroit airport, separation requirement is also different slightly. Aircraft data and N-number of ASPM is used for searching specified engine from FAA N-number database. Then emission index and fuel flow rate is obtained by ICAO Aircraft Engine Emissions Databank and BADA information applying BM II as noted in section IV.

To evaluate the performance of the proposed model, we investigate the following three cases.

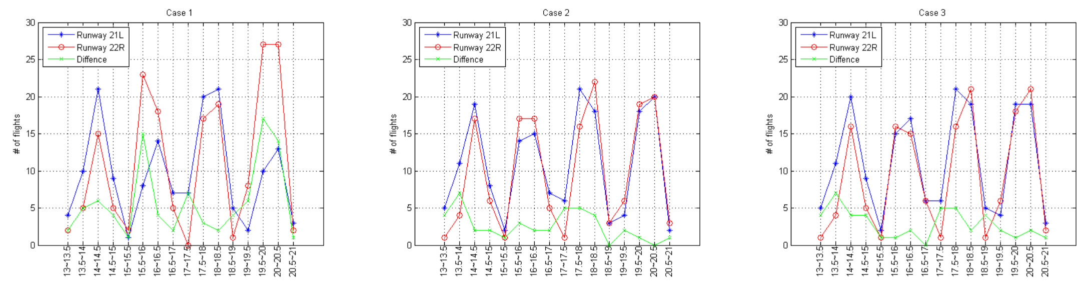
1. Baseline simulation (the shortest path from arrival fixes except WEEDA to runways with FCFS police)

2. Runway assignment with FCFS

3. Runway assignment with sequencing

In the baseline, with the given runway configuration, WEEDA arrival fix has two paths from fix to runway by Standard Terminal Automation Replacement System (STARS) of FAA, thus it does not follow this closer runway assignment rule in baseline simulation. For other fixes, each flight is assigned to closer runway and sequence of flights is determined based on FCFS at wheel-on time. Next approach is runway assignment maintaining FCFS as sequencing algorithm. The only different with first case is how to assign runway and in this case optimization model automatically keeps trying to find minimum emission cost solution in spite of detour on transition path. Last one is fully functional version of this research which is considering runway assignment with sequencing in optimization in order to give more dimensions to optimize.

Due to practical implementation, the runway assignment module takes into account a 30 minutes rolling planning window and passes the delay of each runway and meter fix to next iteration. The delay of previous iteration is included in simulation as constraints using eq. 7.



(a) Baseline

(b) Runway assignment with FCFS

(c) Runway assignment with sequencing

Fig. 5 Assigned arrival runway for minimizing emission

A. Minimizing emission for arrival

As one of the key part of this research, the spewed emission during entire operation near airport is considered in formulation. In suggested model we consider three operation modes; TRACON transit, delay mode and taxi operation. While NO_x and CO_2 are proportional to fuel consumption, in general, HC and CO are in a sort of inverse proportion to fuel consumption as listed on table 3. Thus major operation of emitting HC and CO in terminal airspace is taxi mode, even though fuel consumption rate is low in taxi mode.

Figure 5 presents result of this model for arrival. Clearly there exists unbalanced runway assignment in case 1 and our model alleviates this unbalance. More specifically, most flights assigned to 22R runway based on closer runway assignment rule in baseline simulation because main stream during 15:30∼16:00 and 19:30∼20:30 comes from west. However this unbalanced runway assignment due to unbalance arrival stream is resolved in case (2) and (3). As representative of unbalanced arrival traffic flow, the results of 15:30∼16:30 and 19:30∼20:30 show the necessity of this research. Due to unbalanced traffic stream, the traditional way of runway assignment does not capture the optimal runway utilization and these four schedules account for 65.5% of total delays. Since our simulation consider delay of previous iteration, delay of 15:30∼16:00 and 19:30∼20:00 propagates to next iteration. This tendency also happens in 20:30∼21:00 iteration, thus emission deteriorates severely even though there are only 5 flights in the iteration.

Contrary to intuition, average delay increases for some iteration due to two reasons. Our model finds optimal solution minimizing total emission even though aircraft has to detour, thus wheel-on delay could increase for some flights. However total emission reduces as result of less taxi time and delay of arrival fix point. Secondly initial condition of iteration is different because of delay of each runway passed from previous iteration.

As presented in figure 6, the fully functional version of our model spews the least pollutants except only two iteration, 16:30∼17:00 and 19:00∼19:30. During these iterations the emission cost of case (3) is bigger than case (2) because of delay from previous iteration. Despite the fact that model fails to capture optimal solution between iterations in a row, the overall emission is reduced to 82.5% and 81.3% for case (2) and case (3), respectively.

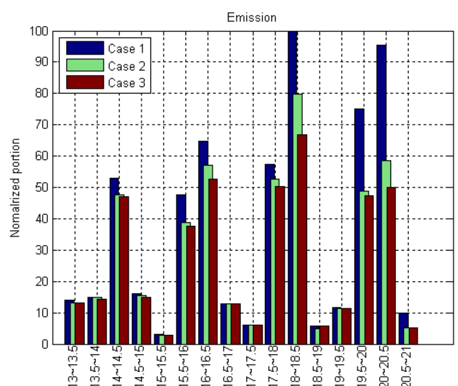
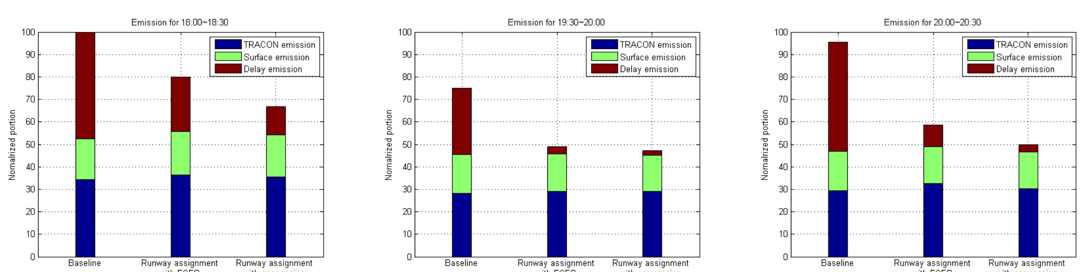


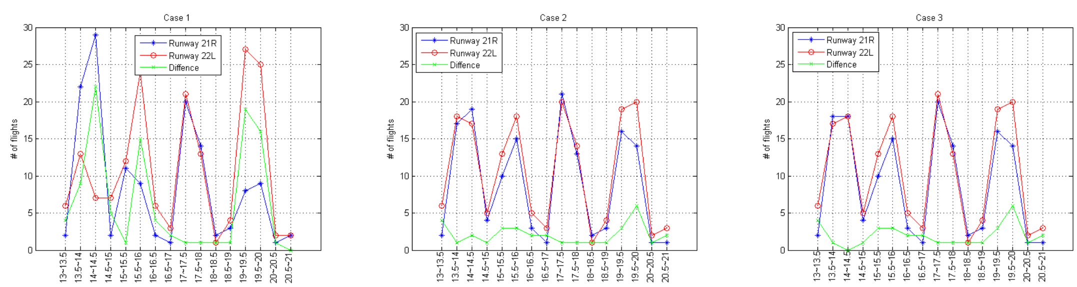
Fig. 6 Normalized total emission for arrival



(a) 18:00∼18:30 (b) 19:30∼20:00 (c) 20:00∼20:30

Fig. 7 Portion of emission for each mode of arrival procedure

The important thing is that the spewed emission decreases about 18% by only runway assignment. Since balanced air traffic flow is not guaranteed in reality, it is natural. To investigate effect of runway assignment and sequecing, we campare the results of representative balanced and unbalanced time windows in figure 7. Like previous statement, it is important to note that most saving in emission is achieved as a result of runway assignment for the unbalanced traffic stream case, 19:30∼20:00 and 20:00∼20:30, while sequencing is more valuable for the balanced traffic case. Between three modes there is a significant change in delay emission cost whereas surface and TRACON emission cost vary slightly. Indeed surface cost decreases and TRACON cost increases. This is due to runway assignment which allows balanced runway utilization. The flight which assigned to farther runway has to fly little longer than closer runway. Consequently TRACON cost always increases in our model. However this small penalty is rewarded by surface and delay emission cost, thus overall cost reduces. The surface emissions reduce because although some flights are assigned to the farther runways, the runway exits of these flights are closer to the gates. The most significant reduction of emissions is from the delay part. The reduction of surface and delay parts compromises the increase of TRACON. In figure 7 the delay cost means arrival fix delay, no need to be same with wheel-on delay, thus it is possible to increase wheel-on delay in spite of reduction in delay cost.



(a) Baseline (b) Runway assignment with FCFS (c) Runway assignment with sequencing

Fig. 8 Assigned departure runway for minimizing emission

B. Minimizing emission for departure

For validation of our model to departure flights, we implement suggested model to departure schedule and generate inputs using same technic with arrval case. Figure 8 describes result of this model for departure. Similarly there also exists unbalanced traffic stream leading inefficient runway assignment in baseline scenario and our model reduces this unbalance. In similar fashion to arrival operation, fully functional model influences to the emission more positively.

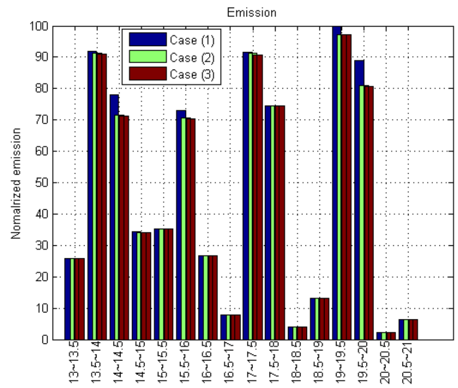
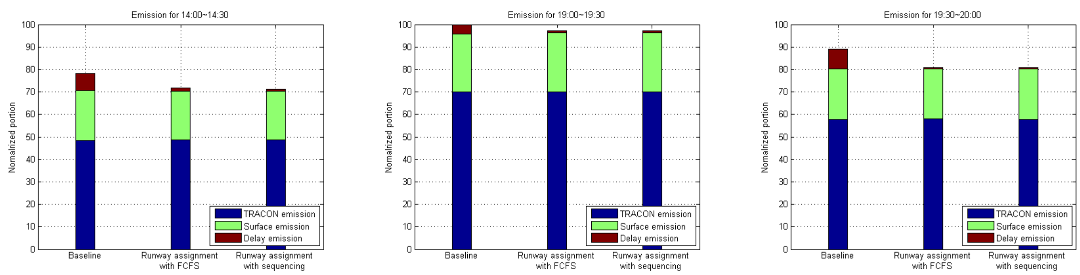


Fig. 9 Normalized total emission for departure



(a) 14:00∼14:30

(b) 19:00∼19:30

(c) 19:30∼20:00

Fig. 10 Portion of emission for each mode of departure procedure

Table 6 Total emissions reduction for different portions

Compared to baseline	Arrival				Departure			
	TRACON	Surface	Delay	Total	TRACON	Surfaec	Delay	Total
Assignment with FCFS	101.0%	99.7%	41.2%	82.5%	100.3%	99.7%	25.0%	97.2%
Assignment with sequencing	101.1%	99.0%	37.5%	81.3%	100.2%	99.7%	20.6%	96.9%

As summarised in table 6, the benefits of the three parts gained from arrival flights are much more than those from departure flights. The reason is that the fuel flow rate is much higher for take-off and climb-out modes. Therefore total emission reduction is smaller than arrival in spite of significant delay decrease.

Although baseline simulation is very easy to implement and to operate in ATC controller's perspective, significant delay and emission are induced as a trade-off. This is reason why emission cost is important not only for satisfying upcoming regulation of environmental impact but also for improving runway capacity.

Average computation time of arrival case (2) is 28.1 seconds while arrival case (3) is 138.1 seconds. For departure case, the average runtimes of case (2) and (3) are 4.7 and 207.1 seconds, respectively. Clearly considering sequence of flights needs more time to solve the problem because the number of decision variables increase quadratically. However our simulation result shows the value of sequencing for balanced traffic volume case.

VI. Conclusion

In this paper, we proposed a mix-integer-linear model to optimize terminal operations from an environment perspective. The proposed model minimizes the total emissions in terminal airspace by optimizing runway assignment and the sequence of takeoffs and landings simultaneously. The demonstrated cases with eight-hour flight schedule on the DTW airport show that arrival emission decreases 18.7% compared with the baseline case. For departure, benefits from emission is reletively smaller than arrival while delay benefit are much more. The major part of delay and emission reduction comes from the improved unbalanced traffic volume on runways. Therefore, the proposed optimization for planning terminal operations is beneficial to improve airport efficiency and local environments.

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