Evaluation of Strategic and Tactical Runway Balancing*

Adan E. Vela, Melanie Sandberg, Tom G. Reynolds

Air Traffic Control Systems Group

MIT Lincoln Laboratory

Lexington, MA, USA

Abstract— **Under the Terminal Flight Data Manager program new functionalities are envisioned at many large airports. One function is the Airport Resource Management Tool, which seeks to strategically balance departure demand at runways. Another related functionality is tactical runway balancing, which provides greater flexibility in tactical runway assignments. Both functions aim to reduce surface delays for departing aircraft. This paper provides a study into the potential delay-reduction benefits of both runway balancing capabilities at three case-study airports (DFW, LAX, and MCO). Via simulation studies it is found that delay-reduction benefits correlate to departure demand and imbalances in demand across filed aircraft departure procedures. So while large benefits are expected at LAX -- which exhibit both large demand and departure imbalances -- the benefits observed at DFW are smaller, while at MCO there is no perceived reduction in delays.**

Keywords-runway balancing, runway assignment; benefit analysis; terminal flight data manager.

I.   INTRODUCTION

Two capabilities considered for the Terminal Flight Data Manager (TFDM) automation system are an airport resource information platform for strategic runway balancing and a tactical runway balancing tool. Both capabilities are expected to aid in balancing demand at airports with multiple departure runways to maximize throughput and minimize delay. While a similar system for strategic runway balancing is currently in use at Atlanta Hartsfield International Airport (ATL), there is a pending need to evaluate the potential delay-reductions of both capabilities over a greater diversity of airports for a system-wide benefits assessment. Towards this goal, this paper documents a benefit analysis at three case-study airports of differing characteristics, each a candidate for TFDM: Dallas-Fort Worth International Airport (DFW), Los Angeles International Airport (LAX), and Orlando International Airport (MCO).

Under TFDM, departure runway assignments for aircraft follow airport-specific rule-sets that consider factors such as airline preference, departure procedure and aircraft type. At the same time, the runway assignments must be consistent with an airport's runway configuration at departure time, standard operating procedures, noise abatement procedures and any aircraft restrictions. Should any factors change (e.g. airport configuration) TFDM will automatically adjust runway assignments where operationally feasible and practical. [1]

The Airport Resource Management Tool (ARMT) is a TFDM core capability aligned with airport-specific runway assignment rule-sets. ARMT serves as an information platform for managing resources like arrival and departure runways. In particular, air traffic control can use ARMT to observe projected demand at each runway and over each departure fix. Based on predicted demand, strategic runway assignment rules can be adjusted to better balance departure demand. One common approach to balancing demand is to re-map flights to departure runways based on departure procedures.

Separate and distinct from strategic runway assignments, the TFDM Concept of Operations permits aircraft to be tactically reassigned to alternative runways to further balance demand and advance aircraft take-off times. When delay imbalances are present, candidate aircraft are considered for new runway assignments prior to entering the active movement area. Tactical runway balancing selects alternative runway assignments when open take-off slots are available or when the alternative runway has a shorter taxi time and departure queue. As such, tactical runway balancing provides fine-tuned, real-time corrections to runway assignment through opportunistic substitutions.

To date, significant study on runway assignment algorithms have focused on arrival procedures [2, 3, 4, 5, 6]. There is however a select set of research efforts that have considered departures [7, 8, 9]. In each case, studies have suggested that balancing departure demand at runways might improve throughput and reduce surface delays. The work here seeks to build on these prior research efforts to help quantify the benefits of strategic and tactical runway balancing.

The primary contribution of the work presented here is to report potential delay-savings as a result of strategic and tactical runway balancing. In support of the benefit analysis, a generic simulation model and a structured framework for performing the analysis is presented.

The remainder of the paper is divided as follows. Section II provides a description of the overall process used to perform the benefits analysis. Section III follows with benefit-analysis results for the airports DFW, LAX, and MCO. Section IV ends with the conclusion and discusses additional opportunities for further analysis.
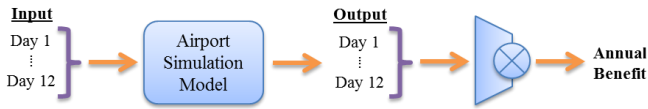
Figure 1. Benefit Analysis Process

II. BENEFITS ANALYSIS METHOD

The general method for the benefits analysis is to **(1)** simulate multiple days of traffic at an airport at current and future year demand levels, with different strategic runway assignment schemes, with and without tactical runway balancing; **(2)** evaluate and compare the resulting aircraft delays; **(3)** and scale the results to yield an annual benefit. An overview of the process is illustrated in Figure 1.

The next portions of this section detail the airport simulation model (inputs, outputs, and behaviors) and provide a procedure for calculating the annual predicted benefits.

A. Airport Simulation Model

The simulation-based analysis requires that airport-specific models for each site are constructed. While a number of airport simulation models exist (e.g., Simmod, TAAM, AirTop, etc), the generic model constructed in support of this work is designed to provide flexibility in specifying the behavior of various air traffic control elements and phenomena. Each airport-specific simulation model (i.e. the simulation model in Figure 1) is based on the generic airport queuing model depicted in Figure 2. The generic airport queuing model simulates aircraft from push-back, through taxiing and waiting at runway queues, until final departure take-off. The model components of interest to the benefits analysis are the strategic runway assignment and the tactical runway assignment modules; this is where the strategic and tactical runway balancing functionalities reside.

For the generic airport queuing model represented in Figure 2, aircraft are processed through the model via a number of processes and control actions. Example processes include taxiing between spot areas and the runway, and waiting in a runway departure queue for take-off. Control actions include runway assignments and take-off clearances. Some of the control and process models are airport-specific and require that they be regenerated for each site; these airport-specific models include taxi time models and runway assignment control.

1) Model Inputs and Outputs

The primary inputs to the simulation model are a departure schedule and an airport runway configuration description. Departure schedules are provided via the System-Wide Analysis Capability Tool (SWAC), a fast-time system-wide model that forecasts airport demand and performance over the NAS [10] into the future. Select days from the SWAC model covering 2010 until 2030 in 5-year increments are used in this analysis. The SWAC model considers evolving factors like fleet mix, aircraft equipage, and most importantly demand schedules in creating the output for each day. The airport simulation model described in this paper takes a portion of the SWAC output to formulate a schedule: destination airport for departing aircraft; aircraft type; airline; scheduled push-back time; actual push-back time; and filed departure procedure.

Airport runway configurations are taken from historical data in the Aviation System Performance Metrics (ASPM) database that tracks active runways. While an airport's runway configuration may change according to traffic demands and weather conditions, simulations are performed under the assumption that airports operate in configuration to maximizes throughput. Doing so ensures the maximum number of operationally acceptable runways is active throughout the day so that runway and staffing resources do not artificially constrain departures.

The primary outputs of the airport simulation model are the surface-delay times for all aircraft on a given simulation day. The surface-delay time takes into account both taxi times between spot locations and the runways, and aircraft wait-times at runway departure queues.
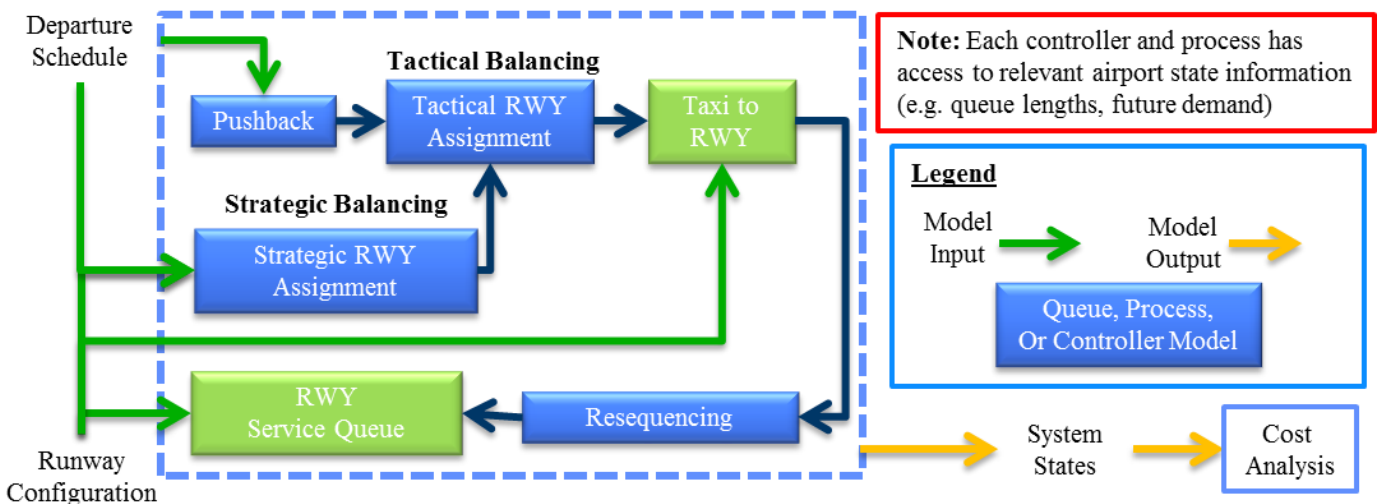

Figure 2. Generic Airport Queuing Model

2) Model Component: Strategic Runway Assignment

Airports have operating procedures that map an aircraft's filed departure procedure (and their associated departure fix) to a pre-assigned departure runway. The mapping helps separate arrival and departure flows, manage controller workload, and improve operational efficiency. An example runway assignment mapping based on departure procedures for a generic airport is illustrated on the left in Figure 3. Groupings of departure procedures are represented by numbered color-coded nodes, each mapping to a similarly color-coded runway.

Strategic runway assignment mappings are not necessarily static. Air traffic control can adjust mappings to balance workload and to manage the demands and delays at each runway. For the airport in Figure 3, air traffic control can adjust the mapping such that flights in departure group (5) take-off from the southern runway 9R. By remapping departure groups on the boundaries, the demand at each runway can be approximately balanced (from 60%-40% to 53%-47%).

The strategic runway balancing within the airport simulation model dynamically adjusts the mapping according to current and future traffic demand. Strategic runway balancing replicates the actions of air traffic control to manage runway demand, but goes beyond near-term planning. At a regular interval of 30 minutes, the strategic runway balancing function observes current runway queues and forecasts the departure demand up to 30 minutes in advance to find an optimal runway assignment mapping. A time horizon of 30 minutes is selected because the TFDM ARMT decision-support tool for strategic runway balancing also uses a 30-minute planning horizon [4].

Strategic runway balancing begins from a static departure fix-to-runway mapping as a baseline representing the default operations. From the static mapping, select departure groups near dividing boundaries are considered changeable, so that they may be re-associated with another runway over the 30-minute timespan. To ensure operationally suitable mappings, the departure fix-to-runway mappings cannot have crossing departure routes. For the example in Figure 4 one option for changeable departure groups is indicated by the dashed nodes.
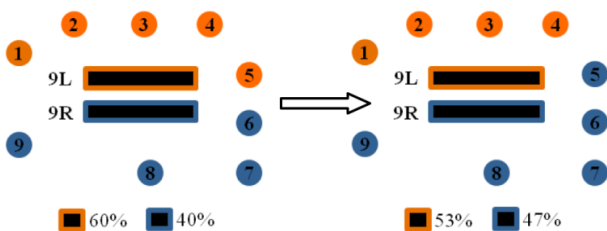

Figure 3. Departure fix-to-runway departure mapping for a generic runway
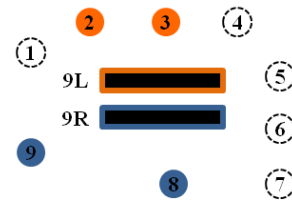

Figure 4. Departure fix-to-runway mapping with changeable departure groups

For the simulations, the static departure fix-to-runway mappings are extracted from historical data based on the airport runway configuration. Details of extracting the mapping are provided in [11]. The static mappings for DFW, LAX, and MCO are provided in Section III.

At each 30-minute decision point, strategic runway balancing recalculates the departure fix-to-runway mappings by selecting the mapping that proportions the departure demand closest to the departure capacity at each runway. Additionally, a penalty is incurred for changes to the departure fix-to-runway mapping. Penalizing changes helps maintain continuity and consistency of operations over time unless the potential benefits of re-mapping are large enough to warrant a change. A departure group change is penalized at a 5-aircraft reduction in runway imbalance. That is to say, a remapping that adjusts the 30-minute runway demand from a 10-to-14 aircraft split to a 12-to-12 split is not optimal as the runway imbalance is only reduced by four aircraft, not overcoming the 5-aircraft penalty.

Proportioning traffic by runway departure capacity is only one possible method for performing strategic runway balancing. Other methods could consider average surface-delay, and delay sensitivity and uncertainty in the departure capacity. While departure fix-to-runway mappings provide guidelines for runway assignments, there can be exceptions to the assignments. Reasons for the exceptions include runway length and noise abatement. The next section will address the tactical variant of runway assignment.

3) Model Component: Tactical Runway Assignment

In practice, aircraft typically follow the strategic runway mappings. However, when operations permit strategic runway assignment rules may be overridden to advance expected take-off times or to balance overall operations.

As part of the tactical runway balancing benefits analysis, the tactical runway assignment procedure will be adjusted and analyzed. Three different options are considered: baseline runway assignment strictly following the strategic rules with no exceptions, and strategic runway balancing coupled with one of two tactical runway assignment approaches, *OpenSlot* and *GreedySlot*. OpenSlot and GreedySlot represent two possible options for implementing tactical runway balancing on top of the strategic runway balancing. Both tactical assignment procedures seek to reduce surface delays.

The OpenSlot procedure replicates the tactical runway balancing scheme described in the TFDM System Specification Document [12]. For an aircraft to be

considered a potential candidate for tactical runway balancing, the aircraft must belong to a departure group that would not engender airborne crossings between departures from adjacent runways. To be assigned an alternative runway assignment a candidate aircraft must then satisfy two other conditions: **(1)** the alternative runway assignments advances the aircraft's expected departure time; **(2)** the aircraft will not delay other aircraft already assigned to the alternative runway.

The GreedySlot procedure seeks to improve the overall system performance by taking a greedy approach to runway balancing. This effectively becomes a relaxed version of OpenSlot where condition (2) is removed, and only condition (1) is applied. An additional constraint is included that only permits aircraft from impacted runways to be reassigned to less impacted runways (based on 30-minute forecasts). Similarly, each candidate aircraft for runway balancing seeks to reduce its expected take-off time.

A measure of the *expected departure time* is required for both OpenSlot and GreedySlot. For the purposes of simulation, the expected departure time is calculated by summing the expected taxi time from the spot to the runway queue, and the expected wait-time spent within the departure queue. The wait-time within the departure queue is calculated by considering aircraft already in the queue, taxiing aircraft, and any aircraft that will be pushing back within the next ten minutes. Taxi times and estimated arrival times at the runway queue for the previous aircraft are estimated using the taxi time model described later in this section. In calculating wait-times, aircraft are assumed to depart at a constant rate according to the 30-minute departure capacity of the runway.

4) Model Component: Taxi Times

The taxi time component generates times for an aircraft to taxi from a spot location to the runway queue. The process for generating taxi times requires two steps: generating spot locations for each aircraft, and calculating the taxi time from the spot location to the runway.

In practice, spot locations are determined by the aircraft's departure gate, assigned runway, surface traffic, as well as spot availability. Because historical gate information is not available for all airports, a simpler model is used. The model generates random spot locations using only airline information and flight type (international or domestic). Next, accounting for the spot location and the assigned departure runway, a regression model assigns the aircraft a taxi time. The spot location model is built using historical spot location distributions for each airline, while the taxi-time regression model uses a random forest approach. Both models are constructed from 100 days of historical Airport Surface Detection Equipment, Model X (ASDE-X) data (see [11]). By constructing a regression model that only considers spot location and runway, the effects of surface congestion are omitted, which is preferred in order to isolate the direct benefits of runway balancing. Otherwise, inclusion of surface congestion requires consideration of departure metering, which is expected to reduce surface congestion and taxi times.

5) Model Component: Sequencing

The sequencing component in the model checks for opportunities to reduce runway delays via two-aircraft swaps. If two consecutive aircraft can be reordered such that the take-off time of subsequent aircraft are advanced, then the swap occurs. To limit aircraft from being swapped multiple times, aircraft are restricted to only one swap.

While advanced sequencing could constitute an operational improvement [13, 14], the sequencing presented here is intended to be simple and limited to single aircraft swaps. Similar swapping procedures are used at major airports when provided with sufficient taxi space. Accordingly, inclusion of the simple sequencing algorithm does not represent an operational improvement; thus simulations are independent of future sequencing operational improvements.

6) Model Component: Runway Service Queue

One critical feature of the airport model is the runway service queue, which simulates how aircraft are serviced at the runway for take-off. For dedicated departure runways, the time between successive aircraft take-off times is determined by the spacing needed to prevent wake turbulence hazards and to maintain separation along the same departure route. Using historical PASSUR data and Enhanced Traffic Management System (ETMS) flight plan data, average times between all aircraft operations are calculated. These times are used to simulate service times in the departure process.

For aircraft departing in different departure groups, runway service times reference the values in Table 1. An additional spacing table is generated for aircraft departing along the same departure route and/or over the same fix; see Table 2 (values in red indicate uncertainty due to limited data). Note that the values are not expressed as the minimum distance standards commonly found in aviation literature, but rather the table represents separation times observed in operational data. See [11] for additional details, also [14] lists similar values.

Table 1. Spacing times for aircraft on different departure routes [seconds] (L/F = Leader/Follower)

L/F	Small	Large	757	Heavy
Small	60	60	60	60
Large	60	60	60	60
757	105	105	90	90
Heavy	120	115	115	95

Table 2. Spacing times for aircraft on the same departure route [seconds] (L/F = Leader/Follower)

L/F	Small	Large	757	Heavy
Small	*60*	*60*	*60*	*60*
Large	**90**	**90**	**90**	***90***
757	*105*	105	90	90
Heavy	*120*	115	115	95

B. Baseline and Best-case Modeling

To place potential benefits in context, simulation results for strategic and tactical runway balancing are compared a baseline scenarios and to a best-case scenario. The baseline scenario represents current-day operations projected into the future without any runway balancing (aircraft are assigned to runways based solely on airline and filed departure procedure), this baseline is referred to as *traditional runway assignment*. The best-case scenario allows aircraft to depart from any runway to advance its expected take-off time, regardless of departure procedure. Accordingly, this scenario is referred to as *fully flexible*. While not operationally feasible due to crossing departure flows, fully flexible establish a potential benefits pool.

C. Simulation Settings and Assumptions

In addition to assumptions embedded in the SWAC model, the airport simulation model makes key additional assumptions. They include: **(1)** the push-back schedule follows the SWAC schedule without adjustment; **(2)** airport operations occur under ideal (VMC) conditions; **(3)** demand is known within the 30-minute horizon, and gate-out times are known 10 minutes prior; **(4)** exact taxi times are known, however, uncertainty windows are used in all calculations for identifying open departure slots; **(5)** spot location distributions remain the same for all airlines in the future.

D. Annual Airport Assessment

There are 12 available SWAC simulation days for the years 2010, 2015, 2020, 2025, and 2030 representing different typical demand days in each quarter (60 days total). The annual benefit of strategic and tactical runway balancing over each year is calculated by averaging metrics over the 12 simulation days each year, then scaling the aggregate benefits across these 12 days to annualize results. The annual benefit is scaled by the fraction of days the airport operated under visual meteorological conditions (VMC) in 2013; instrument meteorological conditions (IMC) are mostly excluded. The VMC scaling factor is required because airport operations are often adjusted during inclement weather. These adjustments were not explicitly considered in the simulation model. Because IMC days are not considered, the estimated annual benefits are potentially conservative.

III. ANALYSIS RESULTS

SWAC traffic forecasts project a significant increase in departure demand at DFW, LAX, and MCO. As shown in **Error! Reference source not found.**, from 2010 to 2030 the number of departures at MCO is expected to double to just over 800 operations per day, while at DFW, and LAX the average number of daily departure operations will exceed 1200 flights by 2030.

In this section a review of simulation results are presented for the case-study airports, with a detailed review of DFW. For LAX and MCO, the summary results are explained within the context of key characteristics of airport operations.
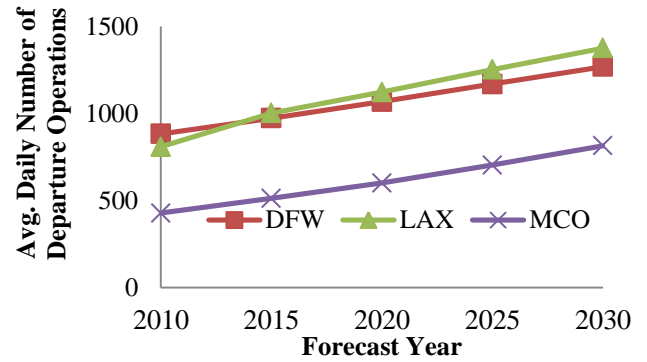
Figure 5. SWAC Departure Demand Forecast

A. DFW Airport

Operations at DFW are the most structured and predictable of the three airports analyzed. In the most common south-flow departure configuration 17R-18L at DFW (by annual departure count) historical aircraft runway assignments can be predicted with just over 92% certainty using only knowledge of the aircraft's filed departure procedure (93% when also considering airline). This suggests that runway assignments are primarily dictated by departure fix-to-runway mappings.

In the departure runway configuration 17R-18L, departure operations are performed independently, with aircraft utilizing the inner runways; an airport diagram is provided in **Error! Reference source not found.** for visualization. For departing aircraft, the difference in taxi distance between the two departure runways (18L and 17R) is approximately three-quarters of a mile. As such, even if an aircraft's departure procedure maps to a further runway, the additional taxi time incurred does not significantly delay departure, especially when persistent departure queues exists.
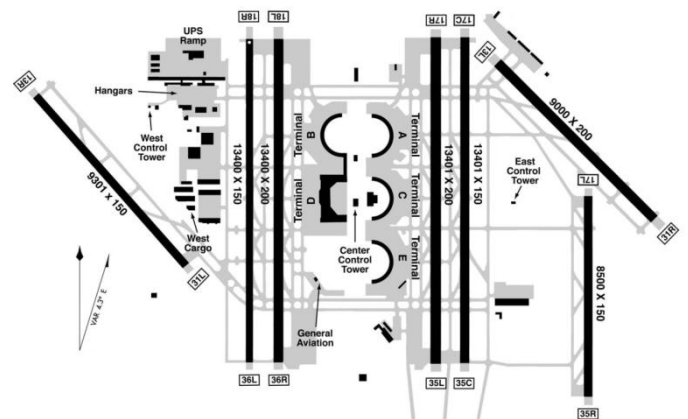
Figure 6. DFW Airport Diagram

The static baseline departure fix-to-runway mapping for DFW in the 17R-18L departure configuration is depicted in **Error! Reference source not found.**; eastern departure fixes map to 17R while western departure fixes map to 18L. The diagram for the departure fix-to-runway mapping represents 16 departure groups, which correspond to more than 70 departure procedures with transition points; departure groups include both RNAV procedures and non-RNAV using the same departure fix. When applying the static departure fix-to-runway mapping to the SWAC schedule, the aggregate runway demand over the 30 years is a 56%-44% split between 17R and 18L.

For the DFW simulations run in a 17R-18L departure configuration, three different candidate options for strategic runway assignments are considered. The first option is traditional runway assignments based on aircraft and departure procedure. The second strategic runway assignment candidate makes use of strategic runway balancing to allocate departure demand on the runways. Strategic runway balancing uses the static baseline mapping as a foundation, but allows for four northern ((1)-(4)) and four southern ((9)-(12)) departure groups to be re-associated with the runways. Finally, the fully flexible case is considered.

Simulation results for DFW under the three strategic runway assignment mappings are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. With exception to the fully flexible case, at present-day demands, there is little distinction between strategic runway balancing and traditional runway assignments. For the 2010 simulation year, extracted taxi times indicate that aircraft spend 6.15 minutes in the movement-area from spot to take-off (see **Error! Reference source not found.**), of which 40 seconds are spent waiting in a runway departure queue. The 2010 per-aircraft surface-delay time translates to an average daily total surface-delay time of about 90 hours. By 2030, simulation results indicate an increase of the per-aircraft surface-delay time to about 9 minutes for the traditional runway assignment, signifying an average runway queue-time of approximately 3.75 minutes. Strategic runway balancing is able to reduce per-aircraft surface-delay times to 8 minutes in 2030. The difference in the average total daily surface-delay time between strategic runway balancing and traditional runway assignments is more than 22 hours. Under fully flexible operations there would be a reduction in surface-delay time of 50 hours; so by 2030 strategic runway balancing captures about 30% of the total benefit pool.
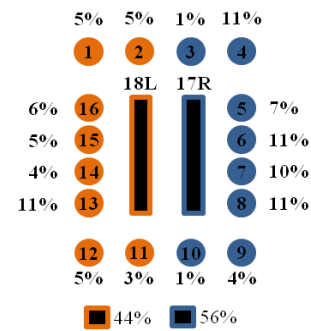

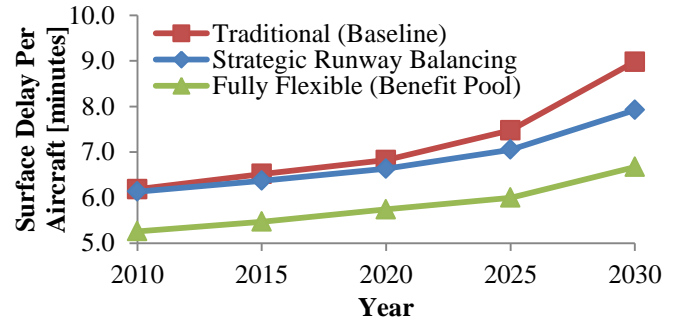**Figure 7. DFW static baseline departure fix-to-runway mapping**

Figure 8. Average surface delay per aircraft under different strategic runway assignment rules at DFW
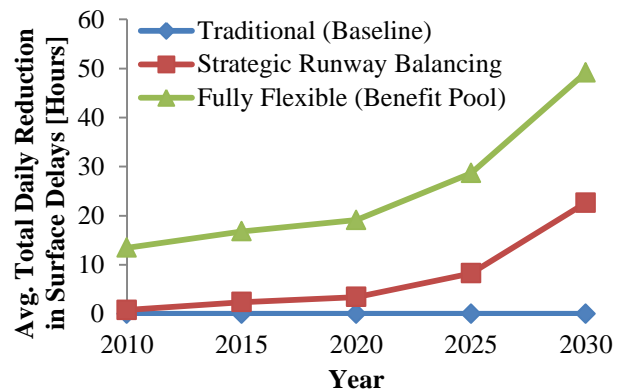

Figure 9. Average daily reduction in surface delays relative to traditional runway assignments at DFW

In the context of ARMT, simulation results indicate that strategic runway balancing has limited benefits in 2010 and 2015. However by 2030 the benefit of strategic runway balancing will be substantial, accounting for a 1-minute reduction in surface delays per aircraft. With all northern and southern departure fixes changeable, up to 25% of the flights can be re-assigned through runway assignment rules to overcome the 44%-56% demand spilt between 18L and 17R.

To introduce tactical runway balancing into operations, all departure groups that are changeable with strategic runway balancing are deemed to be potentially flexible. However, to be consistent with the TFDM ConOps and allow for safe operations, not all potential flexible departure groups can in fact be flexible. Otherwise, if adjacent

departure groups were permitted to be flexible (e.g. departure groups (2) and (3) are flexible), then it becomes possible for flight paths to cross, which would constitute a safety hazard. Only one departure group is selected as flexible between boundary splits. Flexible groups are updated with strategic runway balancing changes.

Error! Reference source not found. provides the additional benefit of tactical runway balancing when applied on top of strategic runway balancing. As such, the total benefit of tactical and strategic runway balancing is the sum of the benefits in **Error! Reference source not found.** for strategic runway balancing with the added benefit of tactical runway balancing in **Error! Reference source not found.**. When introducing tactical runway balancing the total aircraft surface-delay time is reduced by less than 2 hours for the average day even in 2030 (5.4 seconds per aircraft for GreedySlot in 2030). Compared to the total daily surface-movement time for strategic runway balancing, the reduction accounts for a surface-delay time savings of less than 1.13%. The relatively low benefit of tactical runway balancing with strategic runway balancing is a result of strategic runway balancing evenly distributing demand to both runways, thereby limiting any additional benefit from tactical balancing. In 2030, the savings for OpenSlot and GreedySlot are achieved with less than 10 and 40 aircraft being switched each day, respectively (out of about 120 candidate aircraft, from an average of 1268 total departure aircraft).

While strategic and tactical runway balancing are unable to capture the complete benefit pool represented by the fully flexible case, they decreases surface delays 12.9% by 2030.

B. MCO Airport

Like DFW, MCO has four parallel runways, two of which are often used for independent departure operations. The airport's configuration, with a difference in taxi distances of 1.5 miles between runways, causes airline preferences to play a significant role in runway assignments. Because of the limited departure demand relative to capacity, air traffic control can accommodate airline preferences without significant impact to operations. The static baseline departure fix-to-runway mapping for MCO in the 17R-18L southflow configuration is depicted in **Error! Reference source not found.**; departure groups (1)-(6) map to 17R, while all others map to 18L. The dominant departure group is (3), which accounts for 40% of all demand. The skewed distribution complicates balancing, as sequential departures on 17R departing to (3) can significantly decrease the overall departure rate due to extended aircraft spacing along the same routes.

Three strategic runway assignments are considered: traditional runway assignment (using the departure procedure and airline); strategic runway balancing with changeable groups (1), (2), (3), (7), (8) and (9); and fully flexible mapping.
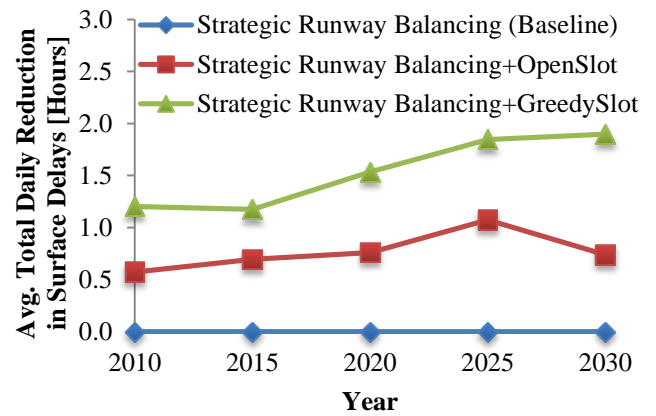

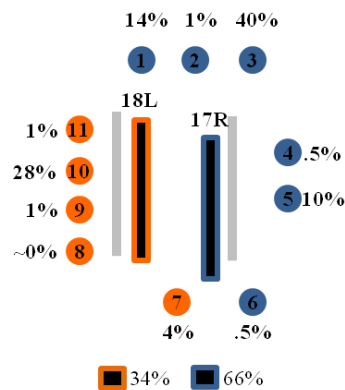**Figure 10. Relative benefit of tactical runway balancing at DFW**

Figure 11. Static baseline mapping for MCO

Comparing the simulation results for the strategic runway assignment options in **Error! Reference source not found.**, traditional runway assignments actually outperform strategic runway balancing. While strategic runway balancing aids in over-coming the persistent imbalance in the departure fix-to-runway mapping (34%- 66%), it results in increased taxi times for many aircraft.

Error! Reference source not found. plots the average daily reduction in surface-delay time with the inclusion of OpenSlot and GreedySlot relative to strategic runway balancing. Also included in **Error! Reference source not found.** is the relative benefit of traditional runway assignments. Even when applying both tactical and strategic runway balancing, surface-delay times are unable to match surface delays observed with traditional runway assignments. Thus the simulations indicate that operations at MCO are likely already well-balanced through the preferences and actions of airlines and air traffic control; the inclusion of greater structure through strategic runway balancing might inhibit efficient operations.
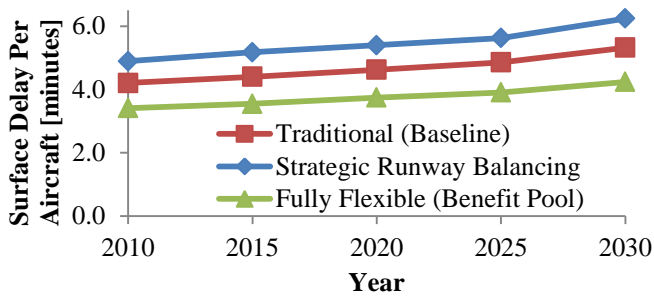
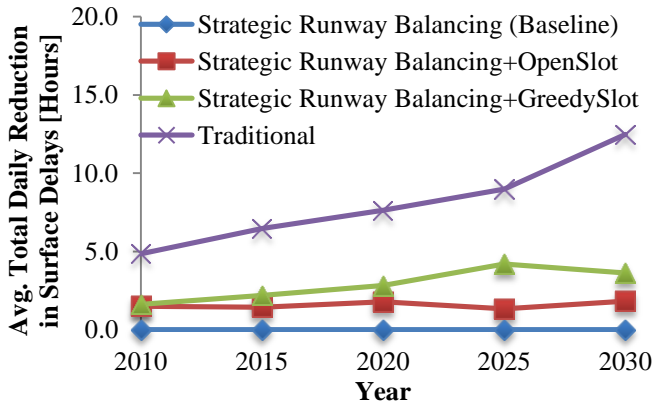**Figure 12. Average surface delay per aircraft under different strategic runway assignment rules at MCO**

Figure 13. Relative benefit of tactical runway balancing at MCO

C. LAX Airport

LAX has four parallel runways divided by a central terminal. Because of the relatively long taxi times between the north and south sides the airport (up to 3 miles), and the addition of a new international terminal slowing traffic near the crossing taxiway, there is a strong preference for flights to depart on the same side of the airport as their terminal gate.

When using the inner runways 24L-25R for departures, the standard departure fix-to-runway mapping for LAX is illustrated in **Error! Reference source not found.**; however, airline preferences override the mapping in 30% of all departures. Geographically, departure groups (1) and (2) are associated with flight paths heading north along the California coast or west for a short time period; group (3) departs out to the ocean; and the remaining departure groups curl around south to the east.

The candidates for strategic runway assignments are: traditional runway assignment (using the departure procedure and airline); strategic runway balancing with changeable groups (3), (4), and (5); and the fully flexible option. When tactical runway balancing is introduced to strategic runway balancing, the same changeable departure groups are also allowed to be flexible.
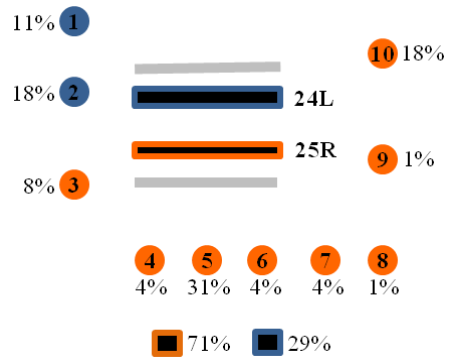

Figure 14. Static baseline mapping for LAX

The surface delay per aircraft at LAX under the different strategic runway assignment schemes are shown in **Error! Reference source not found.**. The surface-delay time measurements indicate that at present-day demands, excluding the fully flexible case, traditional runway assignment and strategic runway balancing result in average surface-delays per aircraft, between 7 and 8 minutes, which corresponds to 86 and 96 total hours of delay each day. If today's traditional approach to assigning runways continues to 2030, as traffic demand increases, delays are expected to increase up to 300%. Delays will be up to 31 minutes per aircraft, translating to 810 total hours each day. When strategic runway balancing is applied the per-aircraft delay is limited to just above 10 minutes in 2030.

As shown in **Error! Reference source not found.**, the introduction of OpenSlot or GreedySlot is able to reduce the surface delays for the average day. In the case of GreedySlot for the year 2030, tactical runway balancing reduces surface delays by an additional 1.5 minutes per aircraft, which accounts for a 30 hour decrease in surface delays per day. When compared to traditional runway assignments at LAX, the combined benefit of strategic runway balancing (~20 minutes per aircraft) and the tactical runway balancing approach GreedySlot (1.5 minutes per aircraft) approaches 70% by 2030. That said, traditional runway assignments are unsustainable and will likely be forced to change; runway balancing can support that change.
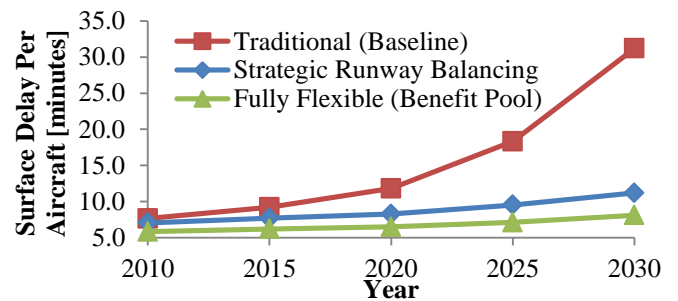

Figure 15. Average surface delay per aircraft under different strategic runway assignment rules at LAX
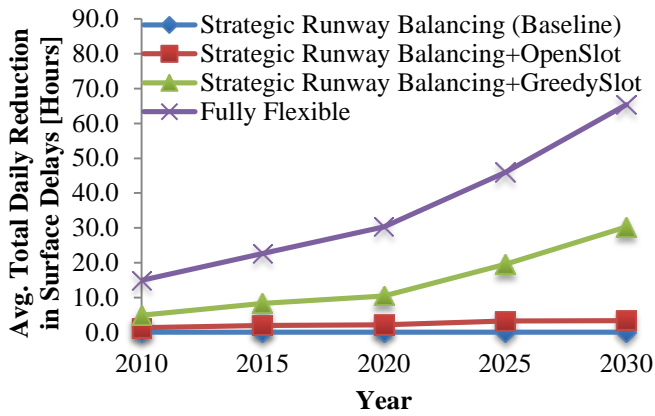
Figure 16. Relative benefit of tactical runway balancing at LAX

Figure 17. Summary of cumulative benefits for strategic and tactical runway balancing

D. Cumulative Benefits of Strategic and Tactical Runway Balancing

The simulation results for DFW, MCO, and LAX presented earlier provided average daily reductions. The expected cumulative benefit of runway balancing at each airport can be calculated by scaling the daily results by the number of VMC days in a year (225 for DFW, 183 for LAX, and 233 for MCO), interpolating over every year, then integrating over the TFDM analysis period of interest from 2017 to 2030; 2017 is the proposed start-date for many TFDM core capabilities.

Error! Reference source not found. summarizes the cumulative benefits from 2017 to 2030 for strategic and tactical runway balancing at DFW, LAX, and MCO. In total, the magnitude of influence of strategic runway balancing surpasses that of tactical runway balancing (for both GreedySlot and OpenSplot). At DFW and LAX the positive effect of implementing strategic runway balancing (30,000 hours and 515,000 hours) is significantly larger than the greatest observed benefit of GreedySlot at DFW and LAX (5,600 hours and 52,000 hours). Even in the case at MCO where strategic runway balancing yields a negative benefit of 35,000 hours, the effect of runway balancing is more than a factor of two smaller (13,600 hours).

Furthermore, for the three simulated airports the tactical runway balancing algorithm GreedySlot consistently out-performs OpenSlot yielding greater reductions in surface-delay time at each airport. As shown in **Error! Reference source not found.**, the difference between GreedySlot and OpenSlot can be quite significant. At DFW and MCO, the benefit of GreedySlot is approximately double that of OpenSlot. And at LAX the delay savings from GreedySlot is five-times greater than OpenSlot. GreedySlot is not necessarily the only or best option for runway assignment for all airports. While GreedySlot provides a positive impact, in the case of MCO, when compared to current-day operations traditional runway assignment provides substantially greater benefits than the combination of strategic and tactical runway balancing. Thus, for MCO the advantage of GreedySlot over OpenSlot may be irrelevant.
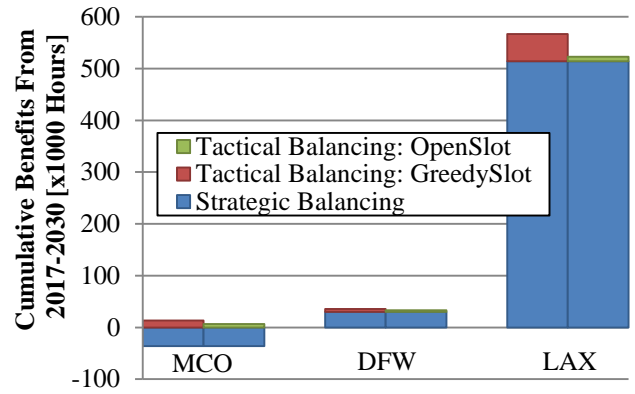
Comparatively, at LAX the benefits derived from strategic runway balancing and the tactical runway balancing algorithm GreedySlot far exceed those observed at DFW and MCO. There are two key differences that may account for such a distinction. First, demand across the different departure groups at LAX are imbalanced and skewed when compared to DFW. One departure group accounts for 31% of all traffic at LAX, while at DFW demand is evenly spread out and already nearly balanced. In other words, at DFW the benefit derived from balancing a minor demand imbalance to a 50%-50% demand split is limited. Meanwhile at LAX, there is a large and persistent demand imbalance that strategic runway balancing is able to mitigate, thereby yielding significant reductions in total surface delays. Additionally, at LAX GreedySlot and OpenSlot are able to tactically correct for any imbalance that persists even after strategic runway balancing is applied. On the other hand, while MCO has a skew demand across its departure groups, overall departure demand at the runways is relatively low. So while there are opportunities for tactical runway balancing, the aggregate benefits. As such, the second key distinction LAX has is significant departure demand relative to capacity.

IV.   CONCLUSIONS & FUTURE ANALYSIS

Of the three airports considered in this case-study, LAX showed the greatest potential for improvement using strategic and tactical runway balancing. The delay reductions observed at LAX derive from a combination of heavy departure demand and a skewed departure demand distribution. Unlike LAX, at DFW the large departure demand is easily balanced over the runways, resulting in fewer opportunities to apply tactical runway balancing. And while MCO has a skewed demand over the departure groups, the departure demand is limited and does not stress airport operations. Accordingly, runway balancing provides does not provide significant benefit over current-day operations.

Based on the case-study airports, three features have been identified as associated with runway-balancing benefits: departure demand at the runways, an unbalanced departure group distribution, and asymmetrical taxi times. One measure of departure demand is the number of daily

departures per runway (where shared runways are counted as half a runway). In **Error! Reference source not found.** the average number of daily departures per runway for the year 2030 is plotted for each TDFM airport. The second axis represents a measure of balance in the departure group distribution (specifically *information entropy*).
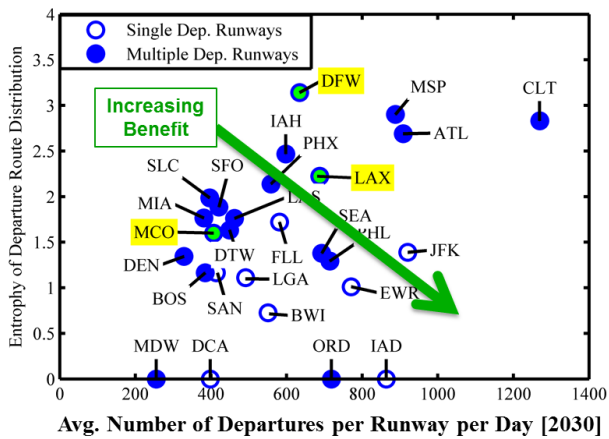

Figure 18. Demand departure and departure procedure imbalance for TFDM airports

Based on the metrics, other airports like MCO (e.g. DTW, MIA) will not likely benefit from strategic and tactical runway balancing because they lack the departure demand. In contrast, the airports likely to benefit from strategic and tactical runway balancing are those on the lower-right of the figure relative to MCO (e.g. SEA, PHL) where demand is high and unbalanced. For MSP, ATL, and CLT, it is likely that the demand can best be balanced through strategic runway balancing, much like at DFW. Therefore the potential benefits of runway balancing at these airports are more likely aligned to the delay reductions observed at DFW, but scaled by the total demand. Accordingly, future evaluation should focus on high-benefit airports and those near the benefits-boundary so that it may become possible to develop a model to predict system-wide benefits without running complex simulations for each airport.

REFERENCES

[1] Federal Aviation Administration. "Terminal Flight Data Manager Core for Air Traffic Control Towers Concept of Operations." Revision 2.1, November 4, 2013.

[2] Brinton, Christopher R. "An implicit enumeration algorithm for arrival aircraft." IEEE Digital Avionics Systems Conference, 1992.

[3] Isaacson, Douglas R., Thomas J. Davis, and John E. Robinson III. "Knowledge-based runway assignment for arrival aircraft in the terminal area." AIAA Guidance, Navigation, and Control Conference, 1997.

[4] Berge, Matthew E., Aslaug Haraldsdottir, and Julien Scharl. "The Multiple Runway Planner (MRP): Modeling and analysis for arrival planning." IEEE Digital Avionics Systems Conference, 2006.

[5] Cheng, V. H. L., L. S. Crawford, and P. K. Menon. "Air traffic control using genetic search techniques." IEEE International Conference on Control Applications, 1999.

[6] Bolender, Michael A., and G. L. Slater. "Evaluation of scheduling methods for multiple runways." Journal of Aircraft, vol. 37, no. 3 (2000), pp. 410-416.

[7] Anagnostakis, Ioannnis, et al. "A conceptual design of a departure planner decision aid." USA/Europe ATM Research & Development Seminar, 2000.

[8] Atkins, Stephen, and Deborah Walton. "Prediction and control of departure runway balancing at Dallas/Fort Worth airport." IEEE American Control Conference, 2002.

[9] Chandrasekar, Sureshkumar, and Inseok Hwang. "Algorithm for Optimal Arrival and Departure Sequencing and Runway Assignment." Journal of Guidance, Control, and Dynamics, vol. 38, no. 4 (2015), pp. 1-13.

[10] Noonan, K., "FAA's System-Wide Analysis Capability." IEEE Integrated Communications, Navigation and Surveillance Conference, 2011.

[11] Vela, A.,Sandberg, M, Reynolds, T. "Terminal Flight Data Manager (TFDM) Runway Balancing Assessment." MIT Lincoln Laboratory, Lexington MA, ATC-421, 2014.

[12] Federal Aviation Administration, "Terminal Flight Data Manager: Draft - System Specification Document", March 3, 2014.

[13] Anagnostakis, Ioannis, et al. "Runway operations planning and control: Sequencing and scheduling." Journal of Aircraft, vol. 38 no. 6 (2001), pp. 988-996.

[14] Gupta, Gautam, Waqar Malik, and Yoon C. Jung. "A mixed integer linear program for airport departure scheduling." AIAA Aviation Technology, Integration, and Operations Conference, 2009.

AUTHOR BIOGRAPHIES

Adan E. Vela is technical staff in the Air Traffic Control Systems group at MIT Lincoln Laboratory. He obtained his Ph.D. in Mechanical Engineering from the Georgia Institute of Technology. His research interests include the application of control theory and optimization towards air transportation systems, particularly related to human-factors and decision-support systems.

Melanie Sandberg is associate staff in the Air Traffic Control Systems group at MIT Lincoln Laboratory. She obtained her Master of Science in Transportation from the Massachusetts Institute of Technology. Her research interests include operational strategies for improvements in air traffic management.

Tom G. Reynolds is Assistant Leader of the Air Traffic Control Systems Group at MIT Lincoln Laboratory. He obtained his Ph.D. from the Massachusetts Institute of Technology. His research interests span air transportation systems engineering, with particular focus on air traffic control system evolution and strategies for reducing environmental impacts of aviation.