A COMPARISON OF TWO OPTIMIZATION APPROACHES FOR AIRPORT TAXIWAY AND RUNWAY SCHEDULING

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Abstract

Surface congestion causes significant taxi delays at busy airports. This paper proposes two different approaches to optimizing both taxiway and runway schedules simultaneously. The first is an integrated approach based on a single mixed-integer linear programming (MILP) model, while the second is a sequential method that sequentially combines runway scheduling and taxiway scheduling algorithms. The two optimization approaches are compared and evaluated using flight schedules at Detroit airport (DTW), by analyzing several airport performance metrics. The effectiveness of the proposed optimization methods in the current operational environment is also investigated through fast-time surface traffic simulations.

Introduction

With the growth of air traffic, busy airports currently experience congestion on the surface and in the surrounding terminal-areas. Surface congestion increases the taxi times of flights, leading to increased fuel costs and environmental impacts. It can also result in increased controller workload and safety concerns. The airport congestion problem can be mitigated through the efficient planning of surface operations. This motivates the development of decision support tools based on optimized airport resource allocation for airport surface movement control.

There have been prior efforts to develop the optimization models for taxiway scheduling and for runway scheduling and sequencing. In most of these cases, optimization models were independently developed for taxiways and runways, and then combined in the integrated system for airport management as separate modules [1, 2, 3].

Similarly, there exist optimization models for aircraft ground movement problem that calculate optimal taxi schedules, subject to operational and safety constraints. These optimization models have significant potential for taxi time reduction when applied to busy airports. However, they are not suitable for real-time implementation currently due to their weak computational performance. They also assume that either a scheduled or a target takeoff time is given by another tool such as a *Runway Scheduler* [1] or a *Taxi-out Time Estimator* [3].

The runway has been identified as a main bottleneck in airport operations [4]. Runway scheduling algorithms have been proposed for maximizing runway throughput, considering wake vortex separation requirements [5, 6]. These approaches focus on runway sequencing and inter-aircraft spacings, but do not consider the interaction with taxiway conditions and impact of arrivals on the taxiway and ramp areas. An optimal runway schedule that does not account for taxiway operations could potentially have adverse effects, such as long wait times in the departure queue [3].

The main objective of this paper is to bridge these two different scheduling models, and to develop efficient algorithms for solving both runway and taxiway scheduling problems simultaneously.

Background

Runway and taxiway scheduling algorithms cannot work in isolation at an airport because they are closely interlinked. However, the optimization models embedded in these planning tools are typically developed independently. If the taxiway schedule were optimized through the integration with the runway schedules, more benefits could be expected. However, few studies to date have focused on this integration due to its complexity [7].

Departure schedules have been previously considered by taxiway scheduling optimization models [8, 9, 10]. These efforts have assumed that the target departure times are given, and the models ensure that the departures satisfy the wake vortex separation requirements. In addition, these models have focused on minimizing the overall taxi times, and not on optimizing the takeoff times as well.

As an alternative to simultaneously optimizing taxiway and runway operations, sequential coordination of the two modules has also been attempted [1, 2, 3]. In this approach, the runway schedule is optimized first, and the taxiway scheduling is then conducted using the optimal takeoff times. This sequential planning makes it possible to link the independent optimization components in the integrated system for airport management with common data. However, it may result in a suboptimal runway schedule because the takeoff times are fixed, without considering taxiway conditions.

Assumptions

Several simplifying assumptions are made in modeling airport surface operations, as explained below.

- Airports have standard taxi routes in a given runway configuration. Therefore, given the runway and the gate, the taxi route of each flight is predefined.
- Nominal taxi speed in free flow is assumed to be given. Therefore, given the length of the taxiway, the minimum travel time on each taxiway link can be derived. The taxi speed values are independent of aircraft types and weight classes.
- The scheduled pushback times and the estimated landing times are known.
- The preparation times for taxi-out are fixed and the same for all flights. Therefore, departures push back as planned by the optimization model.
- Airlines accept up to two position shifts from the First Come First Served (FCFS) takeoff sequence.
- Flights can meet the passage times determined by optimization at key points along taxi routes.

Integrated approach

The best way to integrate optimal taxiway scheduling and runway scheduling is to put both objectives into a single optimization model. The single MILP model for taxiway and runway scheduling proposed in this section is obtained by modifying the taxiway scheduling approach proposed by Rathinam et al. [11].

Decision Variables

The proposed MILP model for integrated taxiway and runway scheduling has two kinds of decision variables: 1) Continuous time variables for the passage times at nodes along the taxi routes of the flights, and 2) Binary sequencing variables for determining the relative order of two flights at intersection nodes and runway thresholds where these flights may reach at about the same time.

Objectives

For efficient taxiway scheduling, the model is designed to minimize the sum of taxi times of the flights moving on the ground within the given time window for optimization. In this objective function, the taxi times can be categorized by the taxi-out time for departures and the taxi-in time for arrivals. These two objective terms can be expressed as follows.

$$\mathrm{Q(Taxi\_outTime)} = \alpha_d \left(\sum_{i \in D, r \in R} t_{i,r} - \sum_{i \in D, g \in G} t_{i,g} \right)$$

$$\mathrm{Q(Taxi\_inTime)} = \alpha_a \left(\sum_{i \in A, g \in G} t_{i,g} - \sum_{i \in A, r \in R} t_{i,r} \right)$$

In the objective terms above, α_d and α_a are the coefficients of the taxi-out time for departures and the taxi-in time for arrivals, respectively.

An additional objective is to minimize runway delay, which is defined as the difference between the optimized takeoff time and the earliest possible takeoff time (EarliestOffT). The runway delay term is as shown below, where α_r is the coefficient for the runway delay when a flight takes off after its earliest possible takeoff time.

$$\mathrm{Q(RunwayDelay)} = \sum_{i \in D, r \in R} \alpha_r \left(t_{i,r} - \mathrm{EarliestOffT}_{i,r} \right)$$

The objective function of the single MILP model is the sum of the three terms described above.

Constraints

The MILP model includes several operational constraints that need to be taken into account in airport operations. Firstly, departing flights can only leave their gates after their scheduled pushback times, by which time passengers complete boarding, and crews are ready to depart. However, during congested periods, it may be beneficial to hold flights at the gate in order to decrease taxi-out times and fuel burn. This is known as a "gate-holding strategy." However, departures need to leave the gate before a maximum possible gate-hold time (MaxGateHold). Arrivals are assumed to land on the assigned runway at their scheduled landing times. In addition, speed limits under airport operation rules are enforced for taxiing flights. For reasons of safety, taxiing aircraft have to keep sufficient separation from each other on the taxiway and ramp areas. For the same reason, overtaking cannot take place on the same taxiway link. Also, the flights moving on the airport surface must avoid head-on conflicts at intersections and on bidirectional taxiways. Finally, departures must satisfy wake vortex separation requirements on the runway, which depend on the weight classes of consecutive flights.

Mathematical Formulation

Incorporating the objective function and constraints described above, the single MILP model for runway and taxiway scheduling can be expressed as follows.

$$\text{minimize} \quad \mathrm{Q(RunwayDelay)} + \mathrm{Q(Taxi\_outTime)} + \mathrm{Q(Taxi\_inTime)}$$

$$\text{subject to} \quad z_{ij}^{u} + z_{ji}^{u} = 1,\ \ \forall i, j \in D \cup A, i \neq j, u \in I \tag{1}$$

$$t_{i,v} \geq t_{i,u} + \mathrm{MinTaxiT}_{uv},\ \ \forall i \in D \cup A, (u,v) \in E \tag{2}$$

$$z_{ij}^{u} = z_{ij}^{v},\ \ \forall i, j \in D \cup A, i \neq j, u, v \in I, (u,v) \in E \tag{3}$$

$$z_{ij}^{u} + z_{ji}^{v} = 1,\ \ \forall i, j \in D \cup A, i \neq j, u, v \in I, (u,v) \in E \tag{4}$$

$$t_{j,u} - t_{i,u} - (t_{i,v} - t_{i,u}) \frac{\mathrm{Dsep}_{ij}}{l_{uv}} \geq -(1 - z_{ij}^{u}) M,\ \ \forall i, j \in D \cup A, i \neq j, u \in I, (u,v) \in E \tag{5}$$

$$t_{j,v} - t_{i,v} - (t_{j,v} - t_{j,u}) \frac{\mathrm{Dsep}_{ij}}{l_{uv}} \geq -(1 - z_{ij}^{v}) M,\ \ \forall i, j \in D \cup A, i \neq j, v \in I, (u,v) \in E \tag{6}$$

$$t_{j,r} - t_{i,r} - \mathrm{Rsep}_{ij} \geq -(1 - z_{ij}^{r}) M,\ \ \forall i, j \in D, i \neq j, r \in R \tag{7}$$

$$t_{i,r} \leq \mathrm{EarliestOffT}_{i,r} + \mathrm{MaxRunwayDelay}_{i,r},\ \ \forall i \in D, r \in R \tag{8}$$

$$t_{i,g} \geq \mathrm{OutT}_{i,g},\ \ \forall i \in D, g \in G \tag{9}$$

$$t_{i,g} \leq \mathrm{OutT}_{i,g} + \mathrm{MaxGateHold}_{i,g},\ \ \forall i \in D, g \in G \tag{10}$$

$$t_{i,r} = \mathrm{OnT}_{i,r},\ \ \forall i \in A, r \in R \tag{11}$$

$$t_{i,u} = \mathrm{FrozenT}_{i,u},\ \ \forall i \in D' \cup A', u \in N \tag{12}$$

$$z_{ij}^{u} \in \{0,\ 1\},\ \ \forall i, j \in D \cup A, i \neq j, u \in I \tag{13}$$

where D and A denote the set of departures and arrivals, respectively. Similarly, I denotes the set of intersection nodes, E the set of taxiway links connecting two nodes u and v, R the set of runways, and G the set of gates. M is a large positive constant. $t_{i,u}$ is the primary decision variable for the passage time of flight i at node u along its taxi route.

Constraint (1) is a sequencing constraint that determines which flight goes first when two flights reach an intersection node at the same time. Constraint (2) enforces the maximum taxi speed limit in terms of the minimum travel time on a taxiway segment. Constraint (3) ensures that two flights exit a taxiway link in the same order as when they entered it. This constraint prevents overtaking on a taxiway link. Constraint (4) is a sequencing constraint for bidirectional taxiway links that prevents two flights from simultaneously entering a taxiway link in opposite directions, and that determines which flight moves into the link first.

Constraints (5) and (6) enforce the separation requirements ($Dsep_{ij}$) between two flights taxiing at different speeds on the ground. Another constraint for safety is also included in (7) for runway operations. Since the required separation distance and time are dependent on the weight classes of the successive aircraft over the runway, the separation time between takeoffs ($Rsep_{ij}$) can be different depending on the types of aircraft i and j.

Schedule constraints (8)-(11) define the latest takeoff time (EarliestOffT+MaxRunwayDelay) based on the earliest possible takeoff time and the maximum delay allowed for takeoff, the earliest gate-out time (OutT), the latest gate-out time (OutT+MaxGateHold) for departures, and the estimated landing time (OnT) for arrivals, respectively.

Constraint (12) determines (as a constant) the passage times of flights that have already pushed back and are taxiing on the surface at the time of optimization. The passage times of these flights (FrozenT) come from the results of the previous time window, and cannot be updated subsequently.

The binary decision variable z_{ij}^{u} for sequencing aircraft i and j at intersection node u is defined in constraint (13). This variable will be equal to one if aircraft i passes through the intersection before aircraft j, and 0 otherwise.

Discussion of Formulation

This single MILP model is an extension of the taxi scheduling model proposed by Rathinam et al. with several key enhancements. Firstly, the model optimizes the runway schedule as well as the taxiway schedule by introducing an additional term for runway delay in the objective function. Without this term, the optimization would focus solely on minimizing the taxi time, and as a result, the takeoff time may be further delayed. It could also result in excessive gate-hold times, causing gate conflicts. Secondly, the proposed model determines a feasible takeoff time window having a reasonable range based on the earliest possible takeoff time, whereas Rathinam et al.'s model uses the scheduled takeoff time constraint. In their model, this constraint may make the problem infeasible if the taxiway system is very congested. Thirdly, the new model accounts for the existing flights taxiing on the surface that can interact with new flights pushing back in the current optimization period. In this way, the model adopts a rolling horizon as time progresses. Finally, the model considers other safety constraints like collision avoidance on bidirectional taxiways.

The main strength of this single MILP model is that it simultaneously implements runway scheduling and taxiway scheduling. In other words, it simultaneously determines the optimal takeoff sequence and times on runways, pushback times at gates for departures, and passage times at control points along taxi routes, as well as the gate-in times for arrivals. However, the mixed integer program can need long computation times, especially at high traffic demand.

Another problem is that of fairness in the takeoff sequence. In order to achieve a more efficient runway schedule, the model can allow significant position shifts from the first-come, first-served (FCFS) sequence based on the original schedule. Apart from impacting the fairness of the takeoff order for airlines, these significant deviations from FCFS can increase controller workload.

In order to address these concerns, an alternative approach proposed. Instead of a single model, two separate optimization models are used for taxiway and runway scheduling, but they are closely integrated through the sharing of schedule data and operational conditions. In this step-by-step approach, the two optimization processes are sequentially implemented.

Three-step approach

Methodology

The sequential process follows the three steps described below.

Step 1 is to estimate the earliest runway arrival times for departures. This time can be computed by adding the unimpeded taxi-out time to the scheduled pushback time. The unimpeded taxi time is obtained based on the distance from gate to runway along the given taxi route and on the nominal taxi speed. The parameters used in this step are the same as those used in Step 3 for taxiway scheduling, so that consistent assumptions are maintained during the entire optimization process.

Step 2 of the approach optimizes the departure runway schedules using a runway scheduling algorithm. It determines the departure sequence and takeoff time schedule, accounting for the separation requirements over runways, available time windows, etc. The initial takeoff times used to optimize runway schedules are the same as the earliest runway arrival times obtained in Step 1. This common assumption makes the takeoff time window used in the next step reasonable.

Step 3 optimizes the taxiway schedules using an MILP model. The MILP model determines the optimal pushback times for departures, gate-in times for arrivals, and passage times at taxiway intersections, by using a gate-holding strategy to minimize the taxi-out times. While optimizing the aircraft taxi schedule, takeoff times from both Step 1 and Step 2 are used. The earliest runway arrival time for a departure from Step 1 defines the lower bound of the available takeoff time window, and the optimized takeoff time from Step 2 is used as a "target" takeoff time, while accounting for the taxiway conditions and potential conflicts.

This sequential process is illustrated in Figure 1.

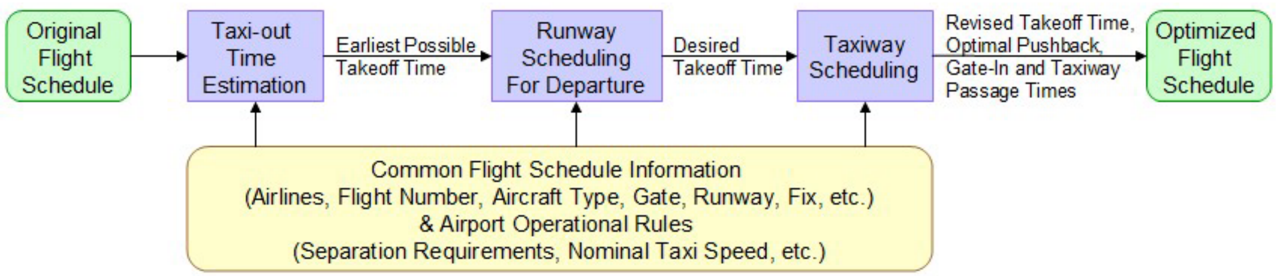

Figure 1. Sequential Process for Three-Step Approach

CPS Algorithm for Runway Scheduling (Step 2)

For runway scheduling in Step 2, the algorithm proposed by Balakrishnan et al. [5] is chosen because of its good computational performance and fairness considerations. This algorithm uses Constrained Position Shifting (CPS) as a basis for fairness, by limiting the maximum deviation from the FCFS takeoff sequence to be less than a value *k* [12, 13]. The basic objective of the CPS algorithm used in the three-step approach is to minimize the sum of takeoff delays, which is the difference between actual takeoff time and the earliest possible takeoff time. This objective can also be changed to minimize the makespan, the takeoff time of the last aircraft in the given schedule. While computing the optimal takeoff schedule, the algorithm accounts for runway separation requirements.

MILP Model for Taxiway Scheduling (Step 3)

The MILP model for taxiway scheduling used in Step 3 is similar to the single MILP model proposed in the previous section. The model has the same decision variables, which are $t_{i,u}$ and z_{ij}^{u}.

The objective of the MILP model in Step 3 is to minimize taxi-out times and taxi-in times, with an additional penalty for late takeoff, if a flight departs later than its optimized takeoff time (DesiredOffT) from Step 2. This penalty term corresponds to the runway delay term in the single MILP model. Note that this model allows a flight to take off earlier than the optimal takeoff time determined in Step 2. The penalty term in the objective function can be expressed as follows and can be rewritten in a linear form by introducing a new decision variable to indicate a late takeoff.

$$\mathrm{Q(Penalty)} = \alpha_p \left(\sum_{i \in D, r \in R} \max\left[t_{i,r} - \mathrm{DesiredOffT}_{i,r}, 0 \right] \right)$$

The constraints are basically the same as in the single MILP model. They account for the minimum travel time between nodes, minimum separation between aircraft, no overtaking on taxiways, conflict avoidance at intersection nodes and on two-way taxiways, and time schedules for pushback, takeoff, and landing. In the rolling horizon framework, existing taxiing flights optimized in the previous time window are also considered.

Expected Benefits

There are several benefits expected from this three-step approach. Firstly, we can determine efficient runway schedules for various objectives such as maximum runway throughput, minimum takeoff delay, and minimum weighted sum of takeoff times. Since Step 2 is dedicated to optimal runway scheduling, different alternative algorithms having different objectives can be used in it. The final sequence position of departures will not deviate significantly from the FCFS sequence based on the earliest possible takeoff time if the CPS method is adopted, although the departure sequence can still change in Step 3.

The taxiway schedule is also optimized while maintaining the separation requirements on runways. Using the gate-holding strategy, we can achieve less congested taxiways, lower taxi times, fewer stop-and-go situations, and less fuel burn during taxiing. We expect that these benefits will be similar to those of the single MILP model, as will be shown later using optimization results.

Another advantage of this approach is its fast solution time. An optimal solution of the MILP model in Step 3 can be obtained quickly because runway scheduling, which makes it more difficult to find a solution of the single MILP model, is already almost complete in Step 2.

Evaluation

In this section, the two alternative approaches to runway and taxiway scheduling are applied to various flight schedules at DTW for evaluating their effectiveness and performance.

Optimization Set-up

The runway configuration used in the evaluation is (22R, 27L | 21R, 22L), which is the most frequently used configuration at DTW in 2007. Figure 2 and 3 illustrate the DTW airport layout and the corresponding node-link network model used for optimization models. It is assumed that there are enough gates to accommodate all the flights without duplication. There are four aircraft types: Heavy, B757, Large, Small; Heavy aircraft can depart only from Runway 22L because of the minimum takeoff roll distance needed.

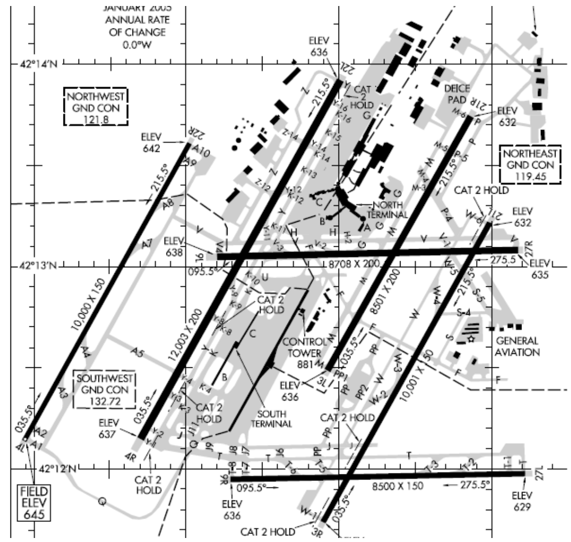

Figure 2. DTW Airport Layout

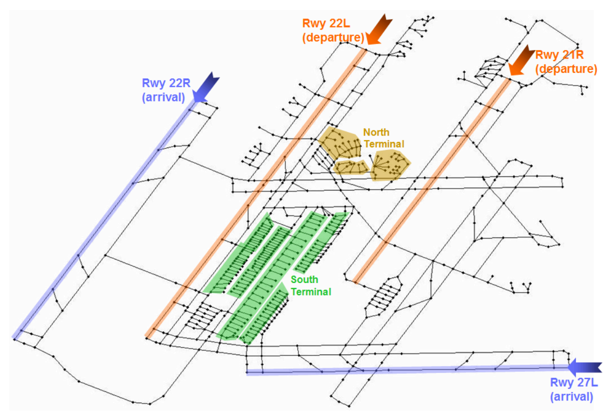

Figure 3. Node-link Network Model for DTW

For runway scheduling under CPS, five cases for takeoff sequencing are considered, depending on the maximum number of position shifts allowed and on the objective: 0CPS (equal to FCFS), 1CPSd, 2CPSd, 1CPSm and 2CPSm. The prefixed number denotes the limit on position shifts from the FCFS takeoff sequence. The suffixes, "d" and "m", represent the objective of the runway scheduling algorithm, minimizing runway delay and minimizing makespan, respectively. The time window of the runway scheduling algorithm is 45 min, which has an overlap of 15 min with the next time window.

The runway separation time requirements between successive departures are shown in Table 1, and depend on the weight classes of the leading and trailing aircraft.

Table 1. Minimum Separation Time (in Seconds) between Takeoffs

Leading Aircraft	**Trailing Aircraft**			
	Heavy	**B757**	**Large**	**Small**
Heavy	120	120	120	120
B757	90	90	90	90
Large	60	60	60	60
Small	60	60	60	60

The MILP models were implemented in AMPL [16] using the CPLEX solver [17]. The tolerance of optimization was set to 'mipgap=0.0001' and 'integrality=1e-07'. The time limit of the solver is restricted up to 30 min. The optimization time window of the model is 30 min, with a 15 min overlap with the next time window. In this way, the model accounts for frozen flights, which have already been optimized in the previous time window, and are traveling on the taxiway.

In the objective functions for the MILP models, the taxi time weights are set to $\alpha_d = 1$ for departures and $\alpha_a = 2$ for arrivals, because many aircraft employ single-engine procedures while taxiing out to reduce fuel cost. The coefficient for runway delay is $\alpha_r = 1$, and the penalty factor, α_p = 100 is used for late takeoffs.

The minimum separation between taxiing aircraft on the ground (Dsep) is assumed to 150 m, regardless of the aircraft types. The minimum separation requirements between takeoffs (Rsep) are the same as those shown in Table 1. The maximum time for which an aircraft can be held at gate (MaxGateHold) and the maximum runway delay allowed (MaxRunway Delay) are set to 10 min and 15 min, respectively.

Based on surface surveillance data from DTW, the nominal free flow taxi speed values are set to 3, 7, and 18 kn on gate area, ramp area, and taxiways, respectively. The minimum taxi time on each link (MinTaxiT) is calculated in advance using these taxi speed assumptions and the length of each link.

Table 2 summarizes the eight different cases that are evaluated. There are five cases derived from the three-step approach, depending on the runway scheduling objective and on the maximum position shifting value. For the integrated approach, two cases are implemented. The first case named 'FPSr' is the original optimization model minimizing both taxi time and runway delay simultaneously, where the case name 'FPS' represents Free Position Shifting, in contrast with the other constrained position shifting (*k*-CPS) cases from the three-step approach. The FPSt case is a control group that minimizes the taxi time only by putting $\alpha_r = 0$ in the objective function. This case was added to see the impact of the runway delay term in the MILP model. Finally, the NoGH case presents the taxiway and runway schedule when no gate-holding is applied and departures leave their gates at their scheduled times. This case is used as a baseline to evaluate the benefits of gate-holding.

Table 2. Optimization Cases

Approach	**Runway Scheduling Objective**	**Optimization Case Name**
Three-step Approach	FCFS	*0CPS*
	Min runway delay	*1CPSd, 2CPSd*
	Min makespan	*1CPSm, 2CPSm*
Integrated Approach	Min runway delay	*FPSr*
	None	*FPSt*
No Gate-holding	FCFS	*NoGH*

These optimization cases are compared using airport performance metrics such as taxi-out times, taxi-in times, takeoff delays, and the number of position changes in the takeoff sequence.

Fast-time Simulations

Optimization approaches to individual aircraft trajectory-based control assume that all flights use enhanced onboard equipment and meet the required times of arrivals (RTAs) at taxiway intersections given by optimal scheduling. Through fast-time airport traffic simulations using an air traffic simulation tool like SIMMOD [14], this 'RTA control' approach can be compared with the pushback time control approach so as to investigate the effectiveness of the proposed optimization methods in realistic operational conditions.

For this comparison, the optimized pushback times for departures and the scheduled landing times for arrivals are input to the SIMMOD simulations. Similar to the current operational environment, SIMMOD only controls the entry times of the flights into the taxiway, and maintains a given constant taxi speed on the surface.

Scenario 1

To model a high traffic demand scenario at DTW, we first assume that flights are consistently supplied to this airport for 3 hours at the rate of 160 flights per hour, with 80 departures and 80 arrivals. This rate is twice the average hourly traffic demand at DTW in 2007 and close to its declared capacity, namely, 184-189 operations/hour in optimal conditions and 168-173 operations/hour in marginal conditions [15].

The detailed flight schedule data for individual flights, including scheduled pushback or landing times, gates and runways, are randomly generated by SIMMOD. Consistent with operations at DTW, the fleet mix ratio is assumed to be 5%, 10%, and 85% of heavy aircraft, B757, and large aircraft, respectively. As two runways are usually used for departures, runways are assumed to be balanced. For this experiment, 28 sets of flight schedule scenarios are generated and optimized using the eight different optimization cases.

Figure 4 shows the average gate-holding time and the taxi-out time per departure for each optimization case. The whiskers denote the standard deviation of the sum of the two times, across the 24 flight schedules. All the optimization cases from two different approaches show similar taxi-out times, except for the FPSt case that minimizes only taxi times, but at the expense of long pushback delays. The figure shows that the taxi-out time can be reduced by about 64 s per departure relative to the NoGH case through gate-holding. The takeoff times (sum of gatehold and taxi-out times) are similar, showing that the gate-holding time translates to taxi-out time savings.

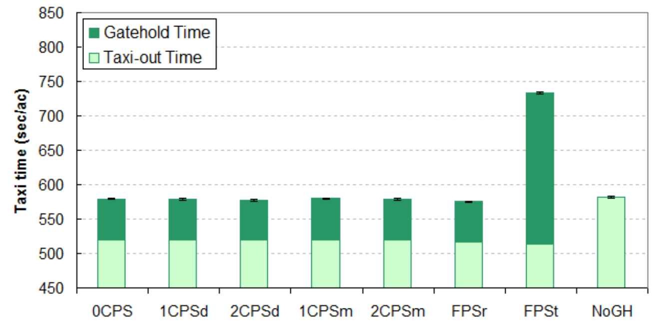

Figure 4. Average Taxi-out Times for Scenario 1

The average taxi-in times shown in Figure 5 are also similar to one another (except for the FPSt case, which has a lower average taxi-in time). It appears that holding departures at their gates has little effect on the arrivals.

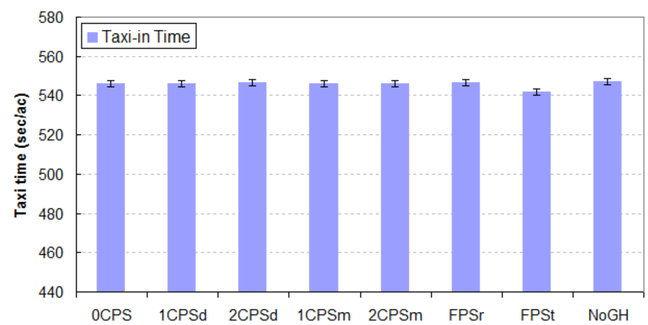

Figure 5. Average Taxi-in Times for Scenario 1

Figure 6 shows the takeoff delay per departure for each of the eight optimization cases. The takeoff delay is defined as the actual takeoff time minus the earliest possible takeoff time (obtained by adding the unimpeded taxi time to the originally scheduled pushback time). In the three-step approach (left five cases in the graph), the takeoff delay from runway scheduling in Step 2 arises from the separation requirements between takeoffs. In Step 3, small additional delay occurs due to taxiway interactions, consequently leading to a little longer delay than the FPSr case in the integrated approach. The FPSt case does not consider runway delay in the optimization, and consequently has a significantly larger delay than the other cases.

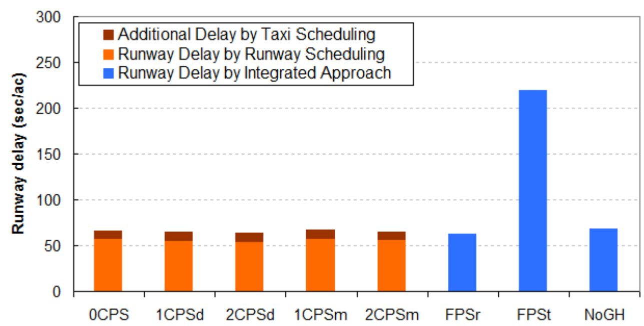

Figure 6. Average Takeoff Delays for Scenario 1

Some flights may not meet the initially assigned takeoff slots due to unexpected interactions on the taxiways. This could increase the workload of air traffic controllers. Figure 7 illustrates the number of position changes from the initial takeoff sequence relative to the earliest runway arrival times. A comparison of the 0CPS, 1CPSd, 2CPSd, and FPSr cases shows that the number of takeoff sequence changes increases as the position change limit increases. The NoGH case shows the largest impact (except for the FPSt case) of taxiway interactions on the takeoff sequence.

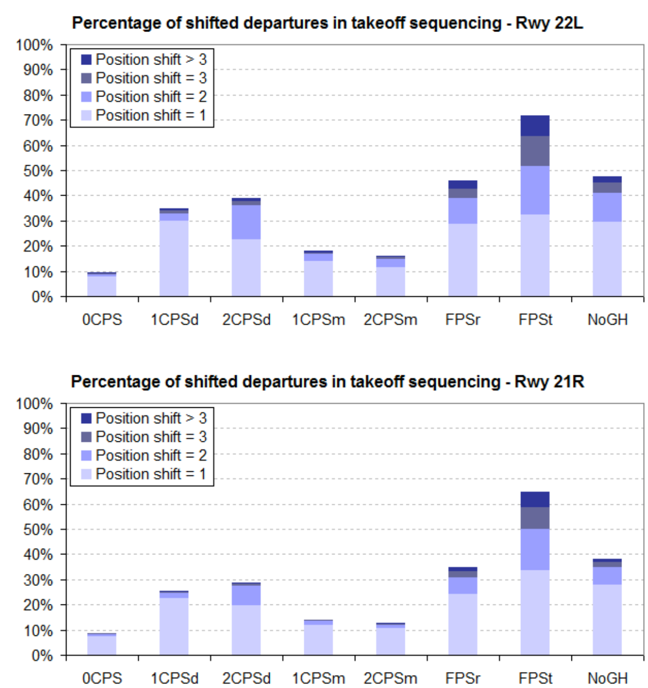

Figure 7. Takeoff Order Changes for Scenario 1

The effects of taxiway scheduling on the takeoff sequence can also be studied by observing the difference between the takeoff orders from Step 2 and Step 3 in the three-step approach, as shown in Figure 8 for each runway. In this scenario, 8-11% of flights cannot meet the optimal takeoff slots determined by a CPS algorithm. These position changes are a consequence of taxiway scheduling, and may result in additional delays to takeoffs.

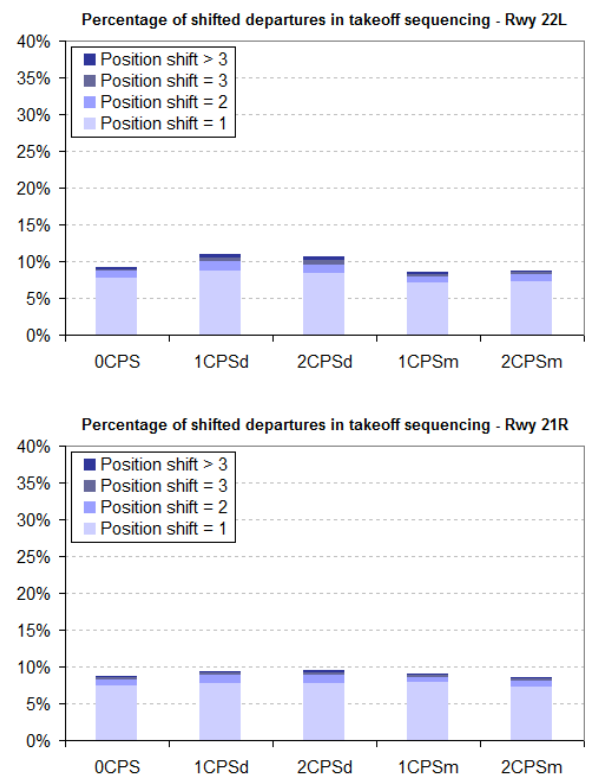

Figure 8. Takeoff Order Changes between Step 2 and Step 3 in Three-Step Approach

Figure 9 compares the total runtimes of the different optimization cases for a 3-hour flight schedule period. The CPS algorithm used in the three-step approach is typically fast, except in the 2CPSd case which takes 20 min to optimize the 3-hour long flight schedule. The MILP model used in Step 3 also shows good computational performance. As expected, the FPSr case for the integrated approach takes a long time to optimize the RTAs of the taxiing aircraft, because it simultaneously implements both runway and taxiway scheduling.

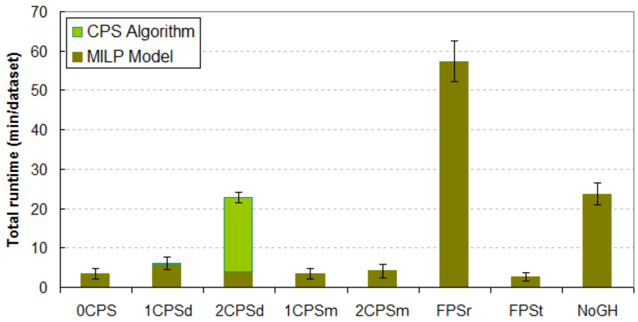

Figure 9. Total runtimes for Scenario 1

Using fast-time simulations in SIMMOD, we can investigate whether the optimized strategies are valid in the current operational environment. Figure 10 illustrates the average taxi-out time per departure from both optimization and simulation for the 0CPS, FPSr, and NoGH cases representing three-step approach, integrated approach, and no optimization cases, respectively. Compared to the NoGH case, we can see that the significant taxi-out time savings can be obtained by controlling pushback times only.

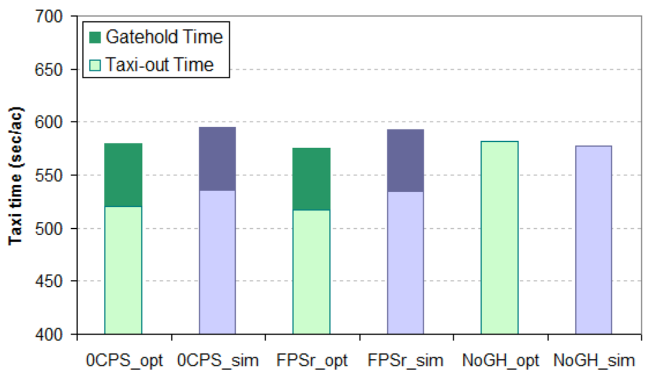

Figure 10. RTA Control vs. Pushback Time Control Only

Comparison of optimization and simulation results for the 0CPS (or the FPSr) case also shows that the RTA control can further decrease taxi-out time by up to 16 s/aircraft. When controlling pushback times, departures interact with other departures or arrivals on the taxiway. These interactions increase waiting time in the departure queue since the takeoff sequence may change, as can be verified by observing the takeoff position changes between the optimized solution and the SIMMOD simulation. Figure 11 shows that some flights are affected by the RTA control at significant points on the taxiway. In addition, the high percentage of shifted departures in the NoGH case implicates that more holds at taxiway intersections are required when gate-holding is not applied.

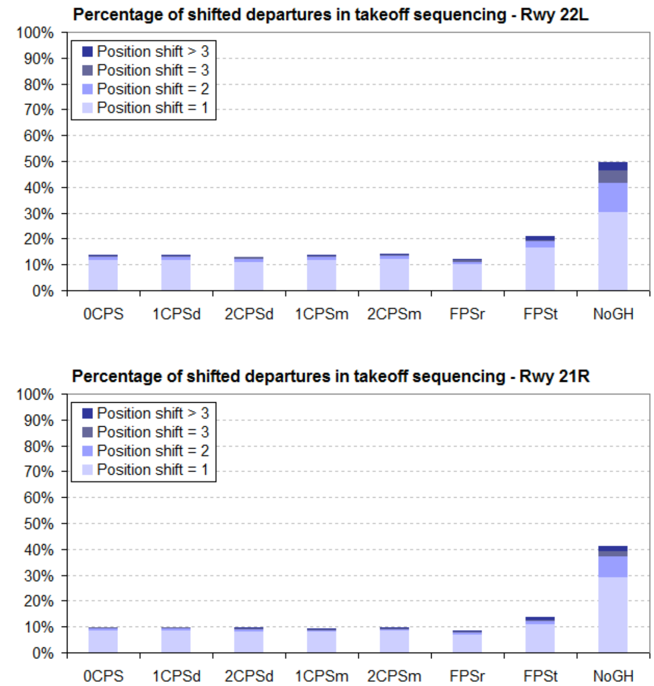

Figure 11. Takeoff Order Changes between Optimization and Simulation

Scenario 2

Scenario 2 was designed for investigating the effects of fleet mix. The flight schedules in Scenario 2 were created in the same way as in Scenario 1, except for the fleet mix ratios, which was set to 10%, 20%, and 70% for heavy aircraft, B757, and large aircraft, respectively. The detailed flight schedule data for each flight were generated by SIMMOD, as before. The same traffic demand and runway balancing were used. For this experiment, 28 different sets of flight schedules were generated and optimized in eight optimization cases.

Figures 12 and 13 show the average taxi-out times and the average taxi-in times in the eight different optimization cases. A comparison with Figure 4 and 5 shows that the average taxi-out and taxi-in times are almost the same as for Scenario 1. The metrics affected by the fleet mix change are the gate-holding time, takeoff delay, and the takeoff sequence. By comparing Figure 14 with Figure 6, we can see that the more heterogeneous fleet mix ratio leads to increased runway delay due to the separation requirements. The number of takeoff order changes also increases by about 10% for all the cases. The computational performances are similar.

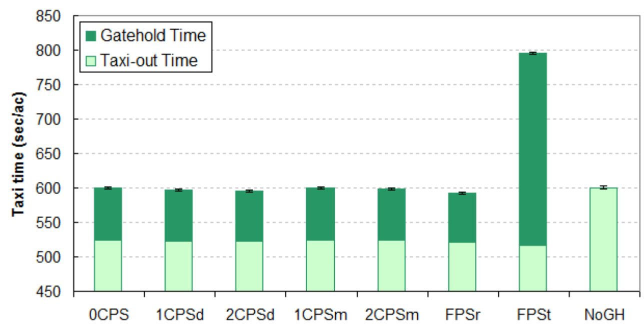

Figure 12. Average Taxi-out Times for Scenario 2

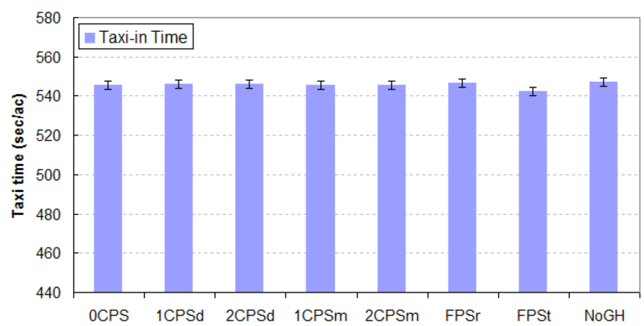

Figure 13. Average Taxi-in Times for Scenario 2

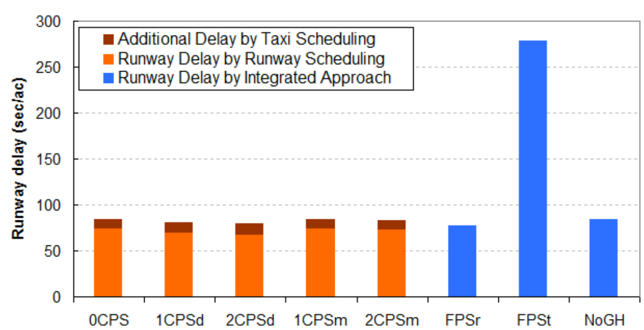

Figure 14. Average Takeoff Delay for Scenario 2

SIMMOD simulations were also run with the optimized pushback times. The simulation results in Figure 15 show that the taxi-out time can be reduced up to 53 s/aircraft with just pushback time control, compared to the NoGH case. Furthermore, the additional taxi-out time reduction from RTA control increases from 16 s/aircraft (Figure 10) to 30 s/aircraft, because the average runway separation time between takeoffs and the resultant waiting time in the departure queue increase with more heavy aircraft.

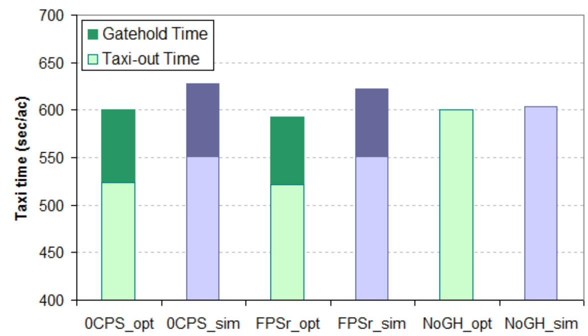

Figure 15. RTA Control vs. Pushback Time Control Only

Scenario 3

In Scenario 3, we consider more realistic flight schedules with demand fluctuations. It is assumed that the air traffic demand has two peaks which are 4 h in length, and varies with time (either 4, 8, 12 or 16 aircraft per 15 min for each runway), while the total hourly demand rate is 160 aircraft/h as before. Arrivals are out of phase with departures. Fleet mix ratio and other assumptions are the same as in Scenario 2. For this experiment, 27 different sets of flight schedules were generated and optimized in eight optimization cases.

The average gate-holding times, taxi-out times, and taxi-in times for the eight optimization cases are summarized in Figure 16 and 17. Although the time held at the gate significantly increases with the new traffic pattern in Scenario 3, the optimized taxi times are similar to those in previous scenarios. However, the FPSr case shows the lower takeoff delay in this scenario, as shown in Figure 18. This is because the FPSr case allows unlimited position changes in the takeoff sequence. It is justified by the graphs in Figure 19 showing that the excessive position changes more than 3 position shifts are observed more frequently in the FPSr case.

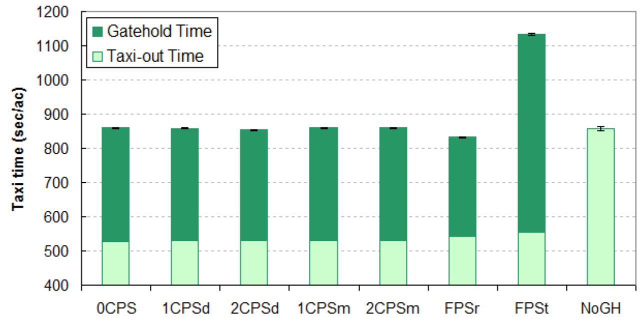

Figure 16. Average Taxi-out Times for Scenario 3

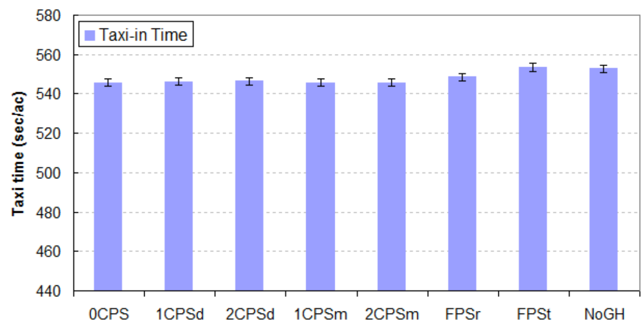

Figure 17. Average Taxi-in Times for Scenario 3

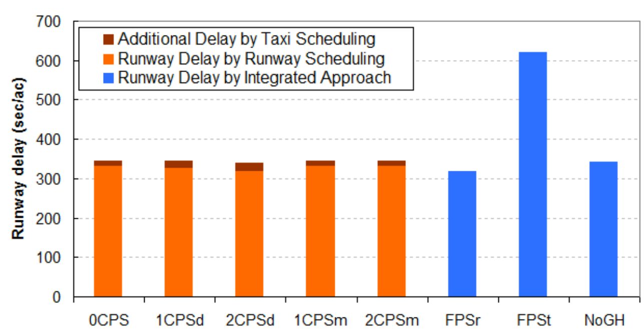

Figure 18. Average Takeoff Delays for Scenario 3

Although the FPSr case provides a better optimization result than the other cases in the three-step approach, its computational performance is weak. Figure 20 shows the total runtimes of the eight different cases for Scenario 3. Each bar is subdivided into the average runtime of the CPS algorithm and the average runtimes of the MILP model by optimization time window. Given a time limit of 10 min for the MILP, the FPSr case often reaches the time limit with a suboptimal solution.

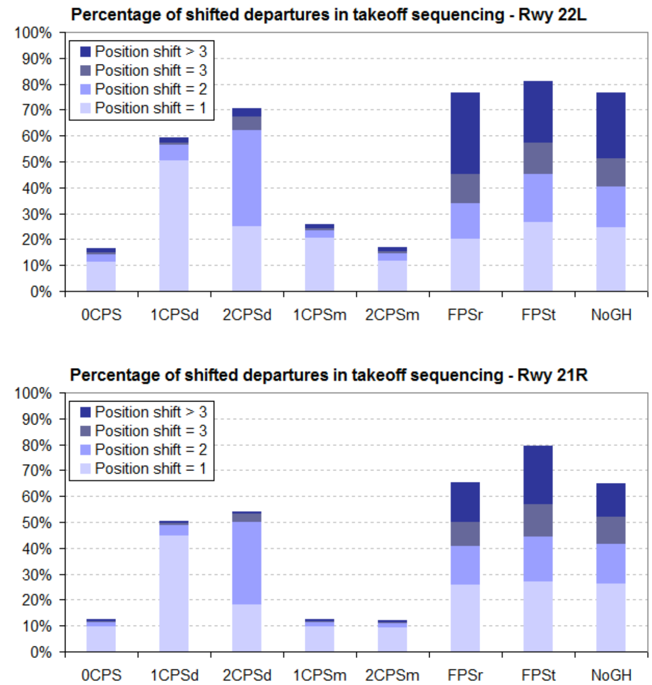

Figure 19. Takeoff Order Changes for Scenario 3

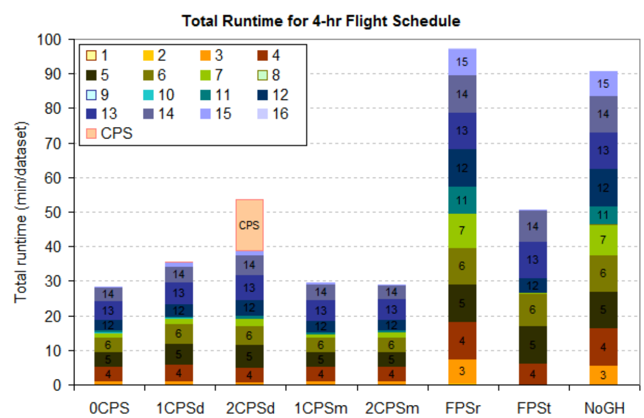

Figure 20. Total runtimes for Scenario 3

The optimization and simulation results shown in Figure 21 compare the average taxi-out times per departure for the 0CPS, FPSr, and NoGH cases. In Scenario 3, the taxi time savings from optimization are bigger than for the other scenarios. When we use the optimized pushback time schedule from the 0CPS case, we can reduce the taxi-out time by 4.4 min/aircraft and 5.5 min/aircraft by using pushback time control and RTA control, respectively.

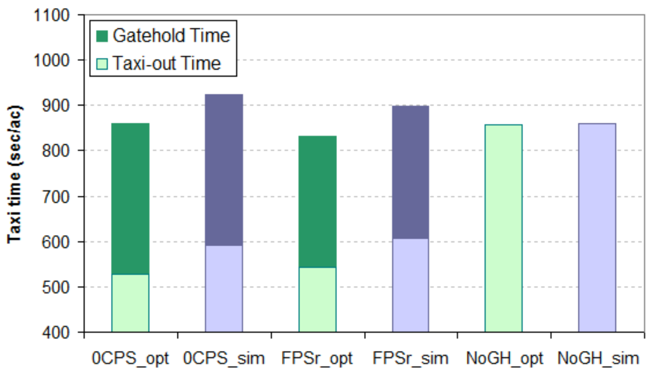

Figure 21. RTA Control vs. Pushback Time Control Only

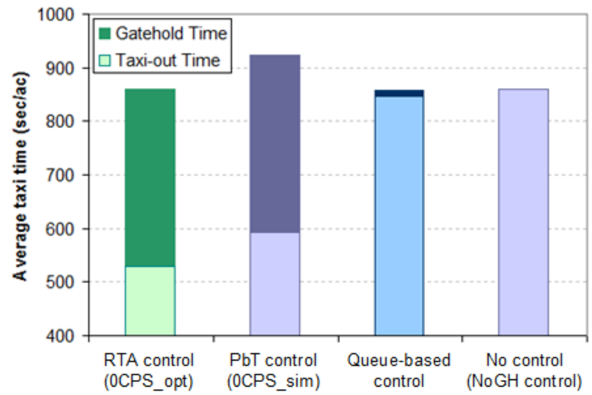

Figure 22. Comparison of Departure Control Approaches

Comparison of Aggregate Queue-based Control and Aircraft Trajectory-based Control

Aggregate queue-based control of departures is a simple strategy that can easily be implemented under current operational procedures [18]. In this section, the aggregate queue-based control is applied to the flight schedules in Scenario 3 and compared with the individual aircraft trajectory-based optimization approach. The detailed application of the queue-based control to DTW is described in [19].

Departure queue control parameters for two departure runways were chosen to be N^*_{22L} = 15 and N^*_{21R} = 14. In this condition, 14 flights would be held at their gates on average. The total gate-holding time for a 4-hour flight schedule was 57.9 min, consisting of 51.5 min and 6.4 min for flights taxiing toward runways 22L and 21R, respectively. The average gate-holding time was 0.2 min, while the average gate-holding time of flights held was 4.1 min.

Figure 22 illustrates the average taxi-out times from four different control approaches, namely, RTA control, pushback time control, aggregate queue-based control, and no control. For a reasonable comparison, the pushback times adjusted by the queue-based control were implemented in the same SIMMOD simulation environment. According to the simulation results, queue-based control provides relatively small taxi time savings with only a few departures held at gates, compared to the other control approaches. However, there is no additional takeoff delay, whereas the pushback time control from the trajectory-based optimization experiences the takeoff delay of 1.1 min/ac.

Conclusions

This paper proposed and compared two different optimization approaches to simultaneously scheduling runway and taxiway operations. The evaluation of these optimization methods using various flight schedules showed that both approaches could save taxi-out time significantly and mitigate taxiway congestion. It was shown that the optimized taxi time was not affected by the fleet mix ratio of the flights, whereas the takeoff delay was impacted due to the runway separation requirements depending on the aircraft types. During peak times, the integrated approach provided the better optimal schedule at the cost of computational performance.

Fast-time simulations using SIMMOD showed that significant taxi-out time savings could be obtained by only controlling the pushback times determined by optimization. Additional taxi time reduction could be achieved by controlling the passage times at the taxiway intersections. Simulations at DTW showed that aggregate queue-based control could get a smaller level of taxi-out time savings than individual aircraft trajectory-based control. However, by contrast, more aggressive queue control could save enough taxi time without additional takeoff delay.

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