A Comparison of Two Optimization Approaches for Airport Taxiway and Runway Scheduling

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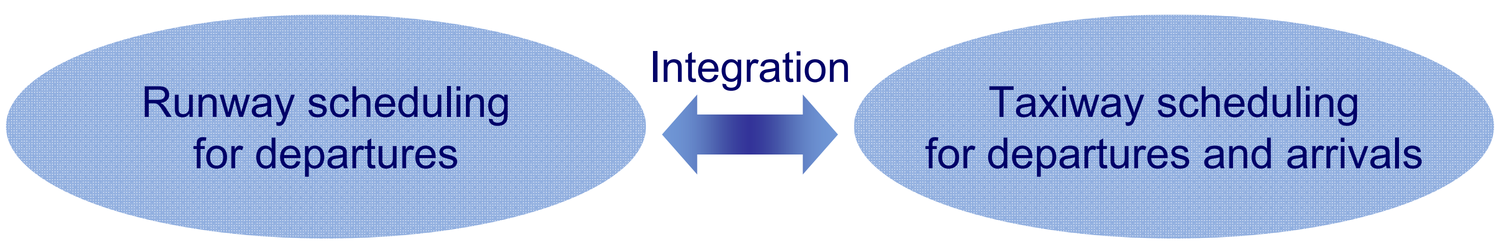
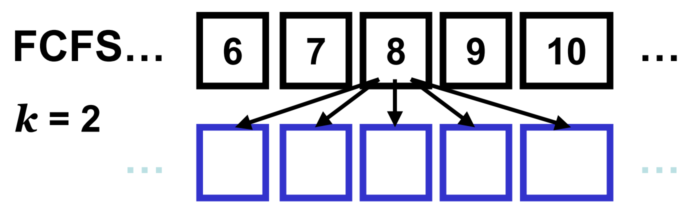
Introduction

- Airport congestion problem
  - Long departure queues for takeoffs
  - Fuel costs and environmental impacts
- Optimization models for efficient airport operations
  - Independent scheduling algorithms for taxiway and runway operations
  - Integration of the separate optimization models
- Need to develop fast, efficient algorithms for solving both runway scheduling problem and taxiway scheduling problem
  - Optimize both runway and taxiway schedules simultaneously
  - Fast run time required to be used in practice as a decision-support tool



Runway Scheduling Problem

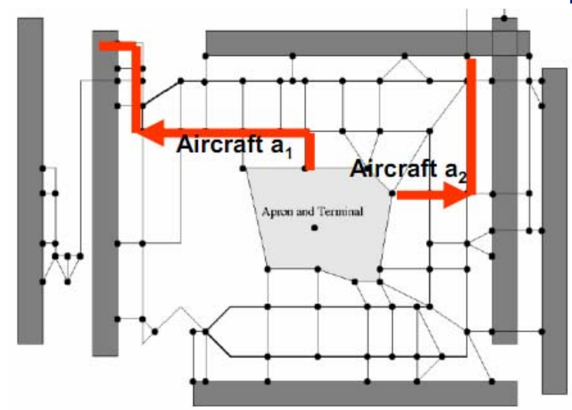
- Runway sequencing and scheduling
  - Maximize runway throughput or minimize runway delay
    - Subject to separation requirements depending on the weight classes, airlines priority/fairness, and available time window
- Constrained position shifting (CPS)
  - Limits the range of position changes from FCFS sequence (Dear 1976)
    - Maximum number of position shifts, *k* value

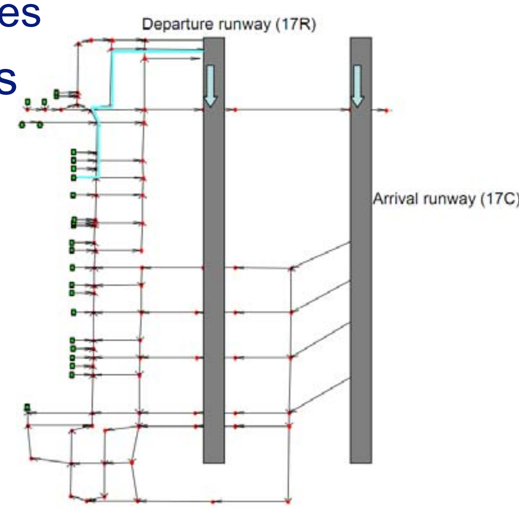


  - Maintains a sense of fairness to airlines
  - Easy to implement by controllers
    - Small, local shifts in position ($k \leq 3$)

Taxiway Scheduling Problem

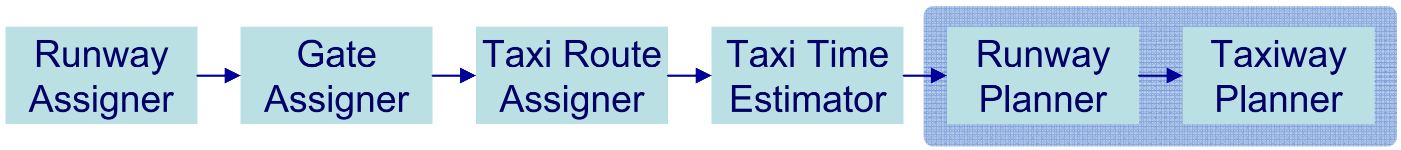
- Surface traffic management
  - Aggregate queue-based control approach (Simaiakis 2009)
    - Control pushback times depending on the taxiway & runway congestion level
  - Individual aircraft trajectory-based control approach (Lee 2010)
    - Control 4D trajectories (4DTs) on the surface
- Aircraft Taxi-scheduling Problem (ATP)
  - Assigning optimal passage times at significant points on taxiways
    - Subject to airport operational rules and safety concerns
    - Gate-holding strategy or alternative taxi routes
  - Node-link network models for airport layouts





Integration of Runway and Taxiway Scheduling

- Sequential approach
  - Connect separate optimization modules with common data
  - Flexible implementation, but sub-optimality possible (Clarke 2010)



- Integrated approach
  - MILP model for taxiway scheduling with runway separation constraints
    - Minimizing taxi-out times only at DFW airport (Rathinam 2008)
  - MILP model for optimization of taxiway routing and runway scheduling
    - Long run time and departures only at LHR airport (Clare 2009)
  - Difficult to optimize two objectives simultaneously
    - Weighting the cost coefficients
    - Weak computational performance

Model 1: Integrated Approach

- A single MILP model for runway and taxiway scheduling
  - Modified from Rathinam's MILP model for taxiway scheduling
- Decision variables
  - Passage time of flight *i* at node *u*, $t_{i,u}$
  - Sequencing variable between flight *i* and *j* at intersection *u*, $z^u_{i,j}$
- Objective
  - Minimize total taxi-out/in times and runway delays for departures
- Constraints
  - Minimum travel time between nodes (with nominal taxi speed)
  - Keep minimum separation on the surface and runways
  - No overtaking allowed along taxiways
  - Conflict avoidance at intersection nodes and on 2-way taxiways
  - Time schedules for pushback, takeoff, and landing
  - Existing flights on the taxiway optimized at the previous iteration

Single MILP Model

- Mathematical formulation

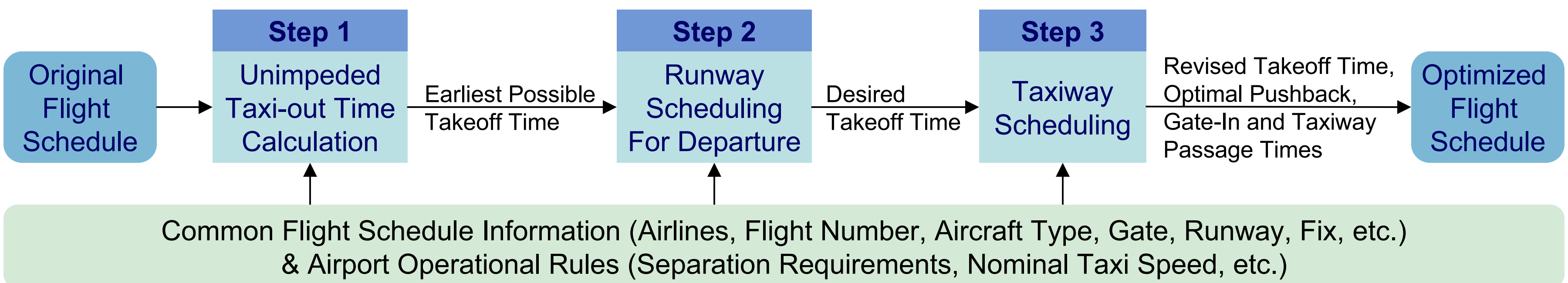
Runway Delay / Taxi-out Time / Taxi-in Time

$$\text{minimize} \sum_{i\in\mathcal{D}, r\in\mathcal{R}} \alpha_p(t_{i,r} - \text{EarliestOffT}_{i,r}) + \alpha_d\Big(\sum_{i\in\mathcal{D}, r\in\mathcal{R}} t_{i,r} - \sum_{i\in\mathcal{D}, g\in\mathcal{G}} t_{i,g}\Big) + \alpha_a\Big(\sum_{i\in\mathcal{A}, g\in\mathcal{G}} t_{i,g} - \sum_{i\in\mathcal{A}, r\in\mathcal{R}} t_{i,r}\Big)$$

subject to $z_{ij}^u + z_{ji}^u = 1, \forall i,j \in \mathcal{D}\cup\mathcal{A}, i \neq j, u \in \mathcal{I}$	: Sequencing constraint
$t_{i,v} \geq t_{i,u} + \text{MinTaxiT}_{uv}, \forall i \in \mathcal{D}\cup\mathcal{A}, (u,v) \in \mathcal{E}$	: Max taxi speed
$z_{ij}^u = z_{ij}^v, \forall i,j \in \mathcal{D}\cup\mathcal{A}, i \neq j, u,v \in \mathcal{I}, (u,v) \in \mathcal{E}$	: Overtaking avoidance
$z_{ij}^u + z_{ji}^v = 1, \forall i,j \in \mathcal{D}\cup\mathcal{A}, i \neq j, u,v \in \mathcal{I}, (u,v) \in \mathcal{E}$	: Head-on conflict avoidance
$t_{j,u} - t_{i,u} - (t_{i,v} - t_{i,u})\frac{\text{Dsep}_{ij}}{l_{uv}} \geq -(1 - z_{ij}^u)M, \forall i,j \in \mathcal{D}\cup\mathcal{A}, i \neq j, u \in \mathcal{I}, (u,v) \in \mathcal{E}$	: Min separation on taxiway (1)
$t_{j,v} - t_{i,v} - (t_{j,v} - t_{j,u})\frac{\text{Dsep}_{ij}}{l_{uv}} \geq -(1 - z_{ij}^v)M, \forall i,j \in \mathcal{D}\cup\mathcal{A}, i \neq j, v \in \mathcal{I}, (u,v) \in \mathcal{E}$	: Min separation on taxiway (2)
$t_{j,r} - t_{i,r} - \text{Rsep}_{ij} \geq -(1 - z_{ij}^r)M, \forall i,j \in \mathcal{D}, i \neq j, r \in \mathcal{R}$	: Min separation on runway
$t_{i,r} \leq \text{EarliestOffT}_{i,r} + \text{MaxRunwayDelay}_{i,r}, \forall i \in \mathcal{D}, r \in \mathcal{R}$	: Takeoff time window
$t_{i,g} \geq \text{OutT}_{i,g}, \forall i \in \mathcal{D}, g \in \mathcal{G}$	: Earliest possible pushback time
$t_{i,g} \leq \text{OutT}_{i,g} + \text{MaxGateHold}_{i,g}, \forall i \in \mathcal{D}, g \in \mathcal{G}$	: Latest possible pushback time
$t_{i,r} = \text{OnT}_{i,r}, \forall i \in \mathcal{A}, r \in \mathcal{R}$	: Landing time
$t_{i,u} = \text{FrozenT}_{i,u}, \forall i \in \mathcal{D}'\cup\mathcal{A}', u \in \mathcal{N}$	: Existing flights on taxiway
$z_{ij}^u \in \{0,1\}, \forall i,j \in \mathcal{D}\cup\mathcal{A}, i \neq j, u \in \mathcal{I}$	: Sequencing variable
$t_{i,u} \geq 0, \forall i \in \mathcal{D}\cup\mathcal{A}, u \in \mathcal{N}$	: Continuous time variable

Model 2: Three-Step Approach

- Step 1
  - Estimate the earliest runway arrival times for departures
    - Based on the distance from gate to runway along the taxi route
- Step 2
  - Optimize departure schedules using a CPS algorithm and initial takeoff times from Step 1
- Step 3
  - Optimize taxiway schedules using a MILP model and takeoff times from Step 1 & 2



CPS Algorithm for Runway Scheduling (Step 2)

- Runway scheduling under constrained position shifting (CPS)
  - Objectives
    - Minimize the sum of runway delays (*k*-CPSd)
      - Runway delay = Actual takeoff time – Earliest possible takeoff time
    - Minimize the makespan (*k*-CPSm)
      - Makespan: takeoff time of the last aircraft in the schedule
  - Dynamic programming
    - Fast computation time
  - Keep separation time requirements depending on weight classes of successive flights (in seconds)

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

  - Limited deviation from FCFS sequence under CPS

MILP Model for Taxiway Scheduling (Step 3)

- Decision variables
  - Passage time of flight *i* at node *u*, $t_{i,u}$
  - Sequencing variable between flight *i* and *j* at intersection *u*, $z^{u}_{i,j}$
- Objective
  - Minimize taxi-out/in times and <u>penalty for late takeoff</u>
    - A large penalty is applied, if a flight departs later than the optimized takeoff time in Step 2
- Constraints
  - Same constraints as the single MILP model in the integrated approach
  - Limit the excessive position changes in takeoff sequencing

Expected Benefits and Problems

Integrated approach

Benefit

• Optimal solution for integrated system considering both runway and taxiway schedules

Problem

• Long solution time during peak periods

• Fairness problem in takeoff sequencing

  − Allow excessive position shifting from the FCFS order

Three-step approach

Benefit

• Efficient runway scheduling

• Flexibility to change algorithms or objectives

  − Maximize runway throughput or minimize (weighted) takeoff delay

• Fairness in takeoff sequence

• Fast solution time

  − Runway scheduling is almost done in Step 2

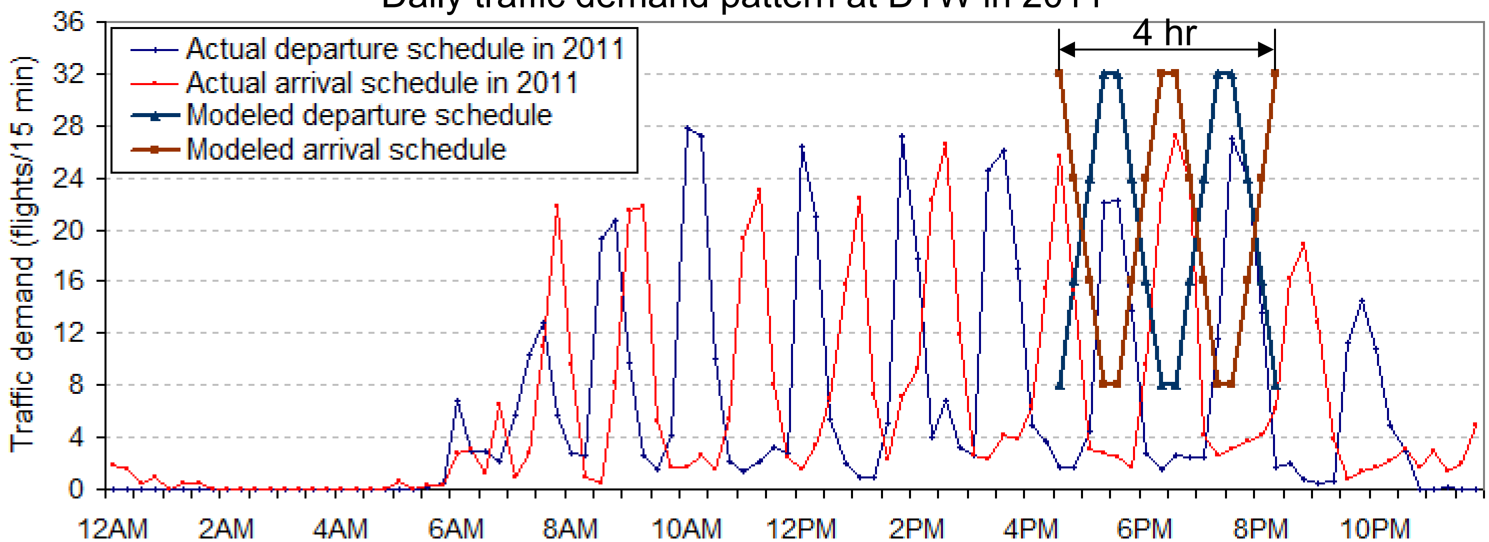
Problem

• Possible sub-optimality of the system objective

Flight Schedule Data for Evaluation

- 4-hr flight schedule having two peak times at Detroit airport (DTW)
  - Traffic patterns similar to the actual flight schedule at busy airports
  - Hourly demand rate: 160ac/hr (80 departures/hr + 80 arrivals/hr)
  - Constant fleet mix ratio (Heavy:B757:Large = 10% : 20% : 70%)
  - 27 datasets having different flight schedules, randomly generated by SIMMOD

Daily traffic demand pattern at DTW in 2011



Optimization Set-up

- CPS algorithm used in the three-step approach
  - 45 min time window, moving by 15 min for the next iteration
- MILP models used in both approaches
  - AMPL/CPLEX solver
  - 30 min rolling horizon with 15 min overlap
  - Runtime issue: 10 min of time limit to find optimal solutions
- Operational parameters at DTW
  - Runway configuration: (22R, 27L | 21R, 22L)
  - Nominal taxi speeds depending on the moving area
    - Gate area : ramp area : taxiway = 3 knots : 7 knots : 18 knots
  - Taxiway separation: 150 m
  - Runway separation: same as the table used in the CPS algorithm
  - Maximum gate-holding allowed: 15 min
    - To avoid gate conflicts with arrivals

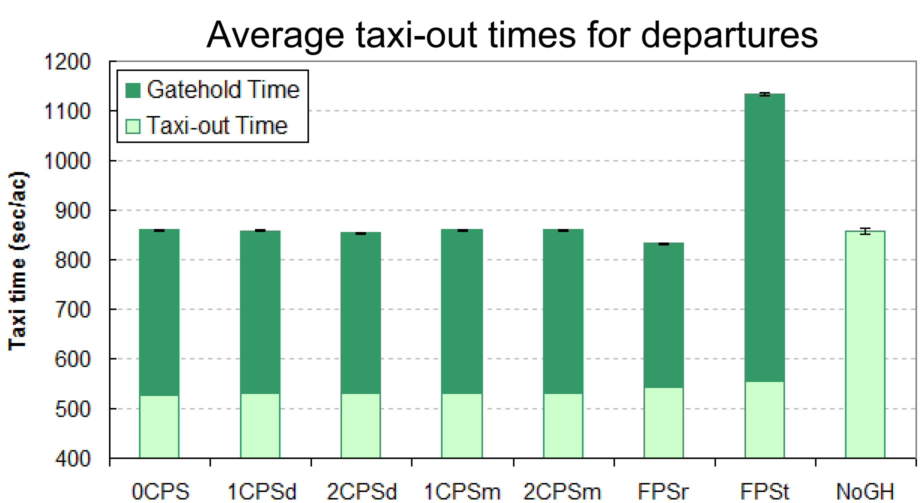
Optimization Cases for Comparison

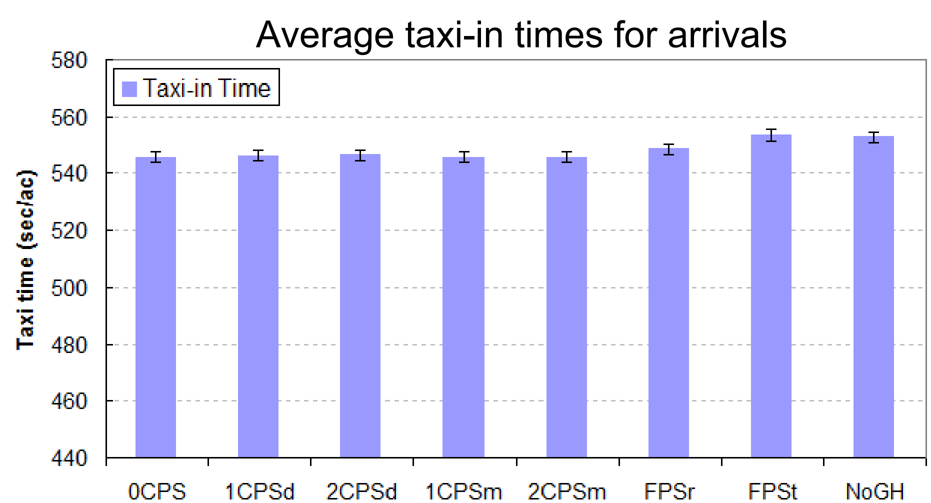
<table>
<tr><th>Case name</th><th>Optimization approach</th><th>Objective in runway scheduling</th><th>Position change limit in takeoff sequencing</th><th>Gate-holding strategy for departures</th><th>Objective in taxiway scheduling</th></tr>
<tr><td>0-CPS</td><td rowspan="5">Three-step approach</td><td>Not applied (FCFS)</td><td>0</td><td rowspan="7">Applied</td><td rowspan="8">Minimize total taxi-out/in times</td></tr>
<tr><td>1-CPSd</td><td rowspan="2">Minimize sum of runway delays</td><td>±1</td></tr>
<tr><td>2-CPSd</td><td>±2</td></tr>
<tr><td>1-CPSm</td><td rowspan="2">Minimize makespan</td><td>±1</td></tr>
<tr><td>2-CPSm</td><td>±2</td></tr>
<tr><td>FPSr</td><td rowspan="3">Integrated approach</td><td>Minimize total runway delay</td><td rowspan="3">No limit</td></tr>
<tr><td>FPSt</td><td rowspan="2">No objective for runway scheduling</td></tr>
<tr><td>NoGH</td><td>Not applied</td></tr>
</table>

Note) CPS: Constrained Position Shifting, FPS: Free Position Shifting, FCFS: First Come, First Served,
NoGH: No Gate-Holding for departures (runway & taxiway schedule optimization to resolve conflicts only)

Average Taxi-out/in Times

- Significant taxi-out time savings by gate-holding
- Small improvement on taxi-in times by optimization
- Similar taxi-out/in times when gate-holding applied

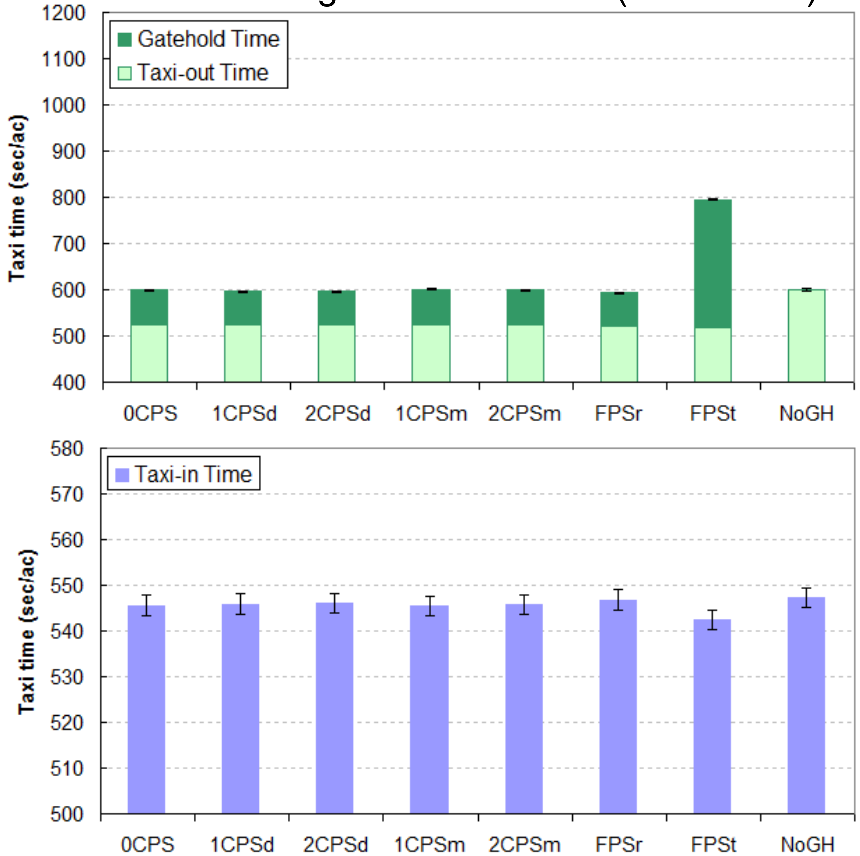




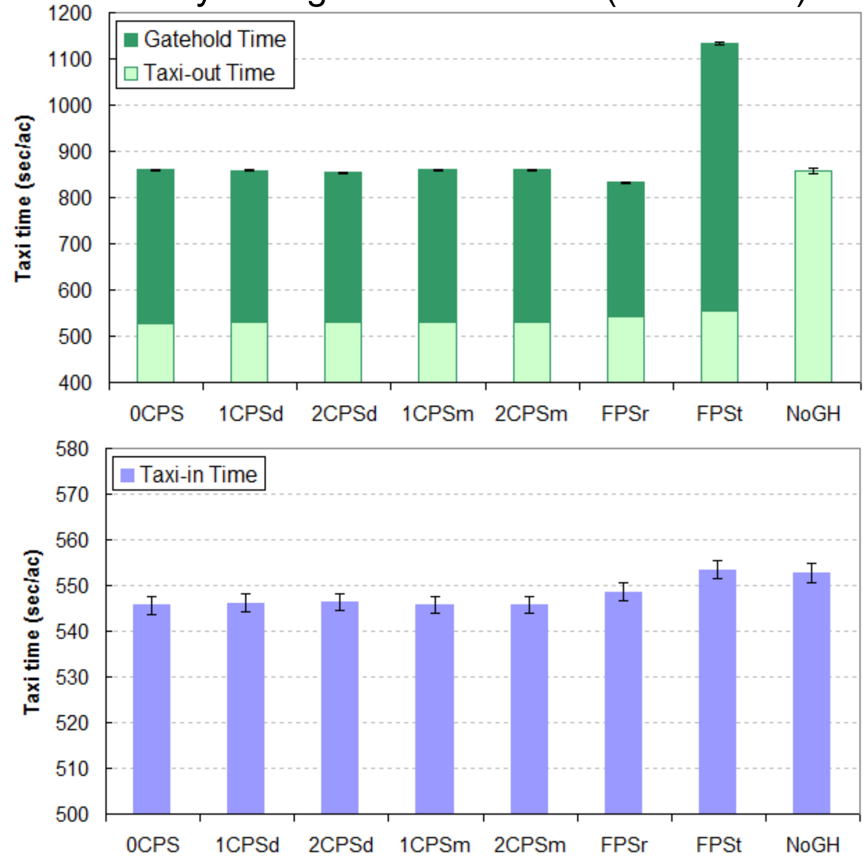
Effects of Cyclic Traffic Demand

- ❑ NoGH case: increased taxi-out/in times by traffic demand fluctuation
- ❑ Similar taxi-out/in times by optimization, but longer gate-holding time

Constant high traffic demand (Scenario 2)

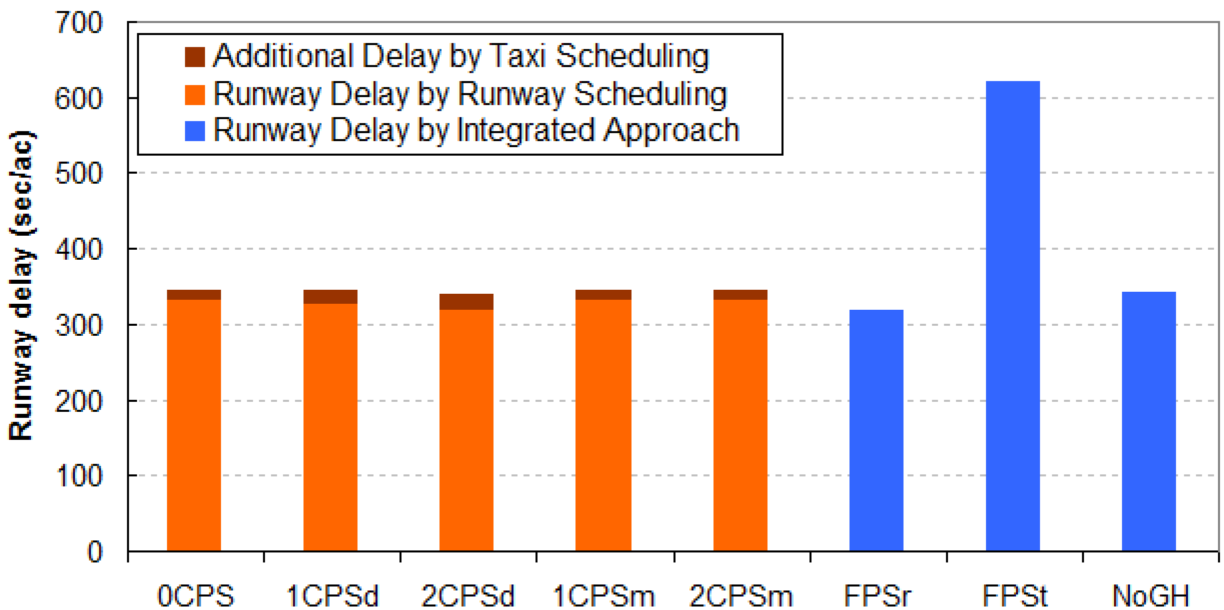


Cyclic high traffic demand (Scenario 3)



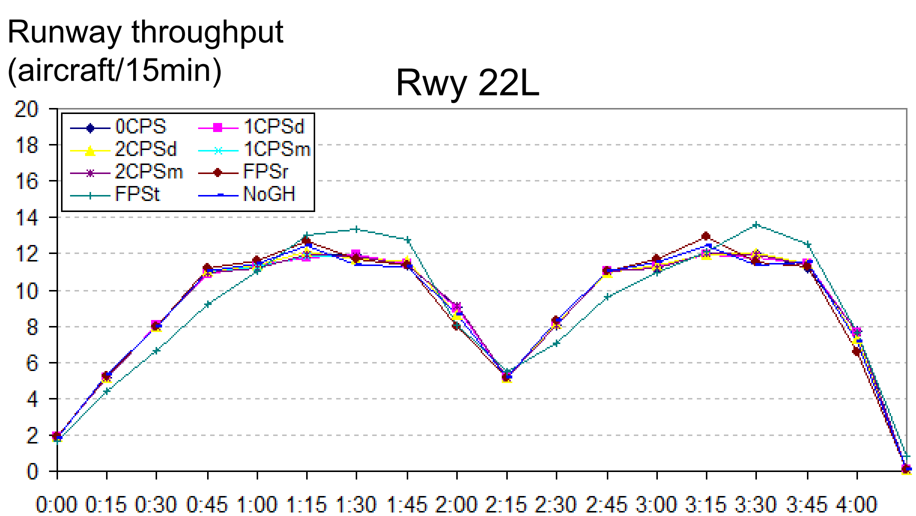
Runway Delay for Departures

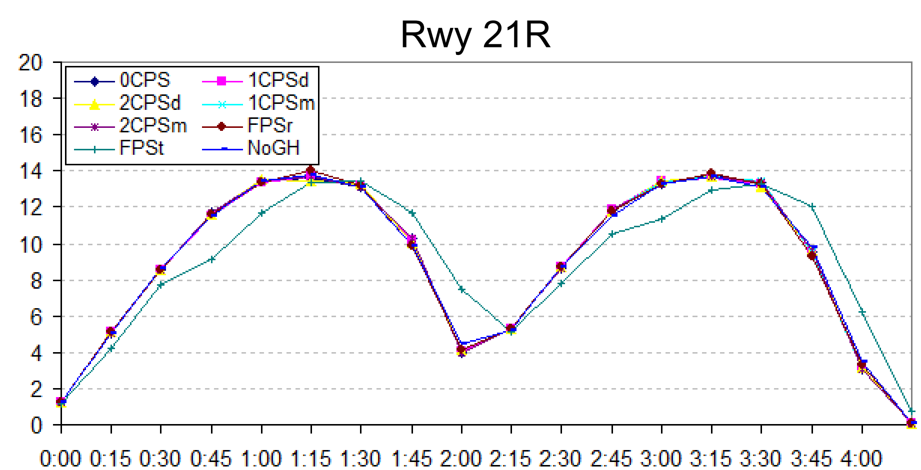
- Runway delay = Actual takeoff time – Earliest runway arrival time
  - Mainly due to the separation requirements
- Three-step approach: similar runway delay to the NoGH case
  - Small increase in the runway delay by taxiway scheduling (Step 3)
- Integrated approach (FPSr) : lower runway delay by free position changes in takeoff sequence



Runway Throughput

- Same throughput curves for all the cases (excluding FPSt)
  - No impacts on runway throughput by optimization, compared to NoGH
  - FPSt: delayed runway throughput curves by long gate-holding
  - Note that heavy aircraft can use Rwy 22L only, leading to a little lower runway throughput on Rwy 22L during peak times



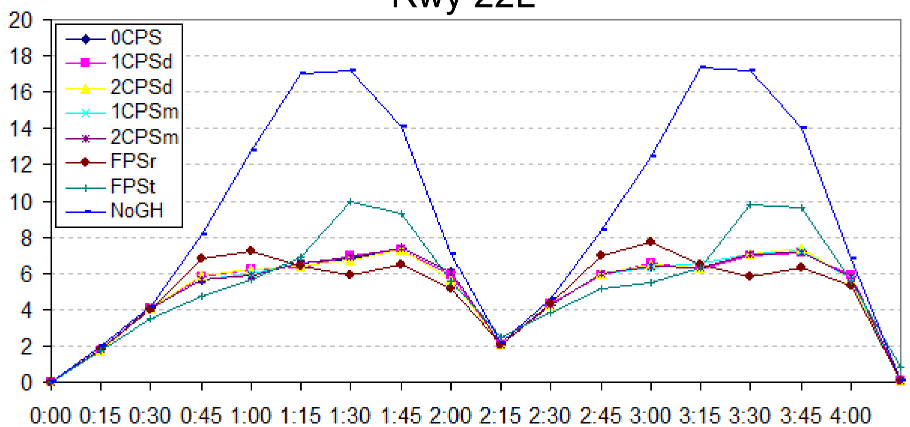


Number of Taxiing Aircraft, N

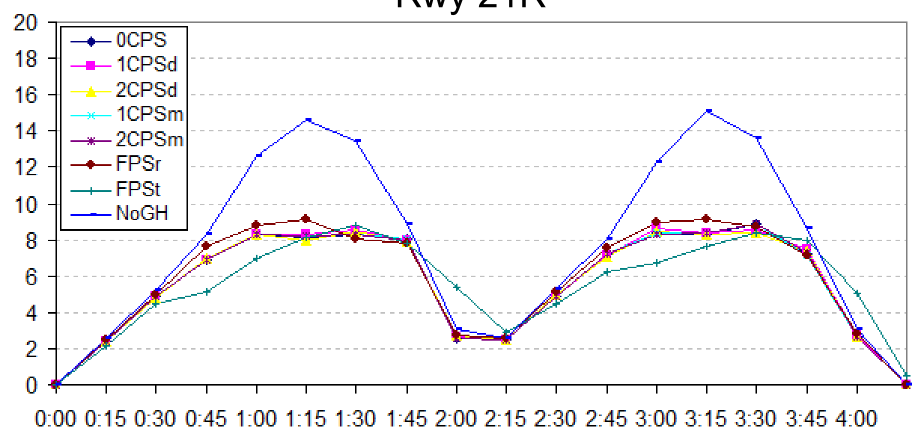
- ❑ Mitigated taxiway congestion by both approaches
  - N values are maintained less than 10 aircraft for each departure runway
  - No difference among five cases from the three-step approach
  - FPSr: different behavior from three-step approach cases
  - FPSt: delayed pushback for minimizing taxi times only
- ❑ NoGH: long queues are observed for both departure runways

No. of taxiing aircraft
(aircraft)

Rwy 22L

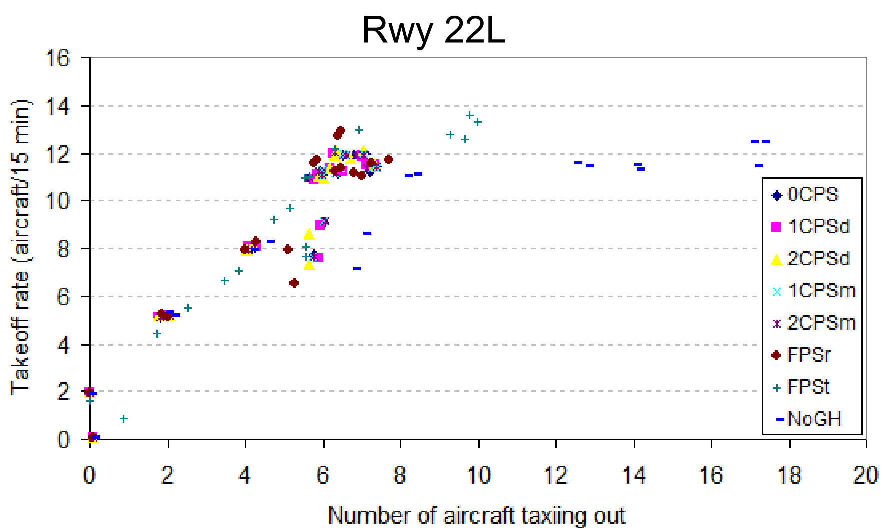


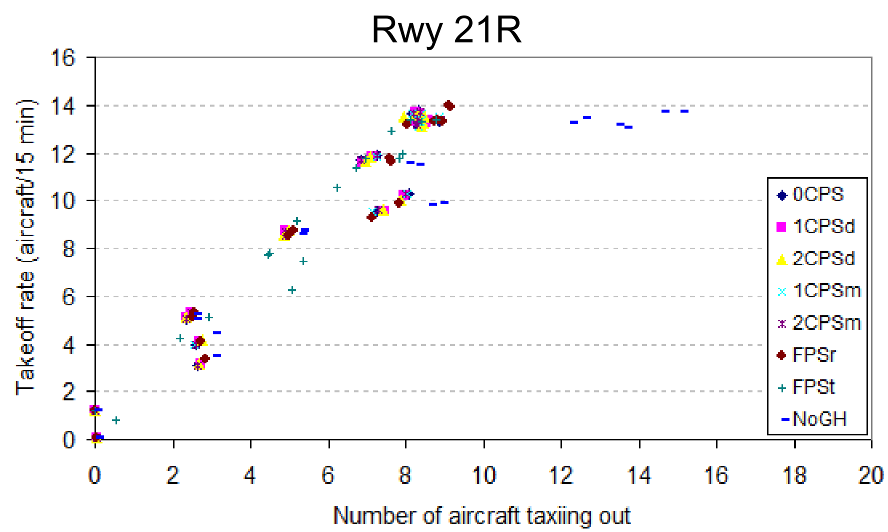
Rwy 21R



Runway Throughput vs. Taxiing Aircraft

- NoGH case follows typical patterns from the actual traffic statistics
- Clustering in the other optimization cases
  - During peak times, the data points are concentrated on the specific region (maximum runway throughput, but limited size of taxiing aircraft)
  - In normal traffic, the number of taxiing aircraft is minimized

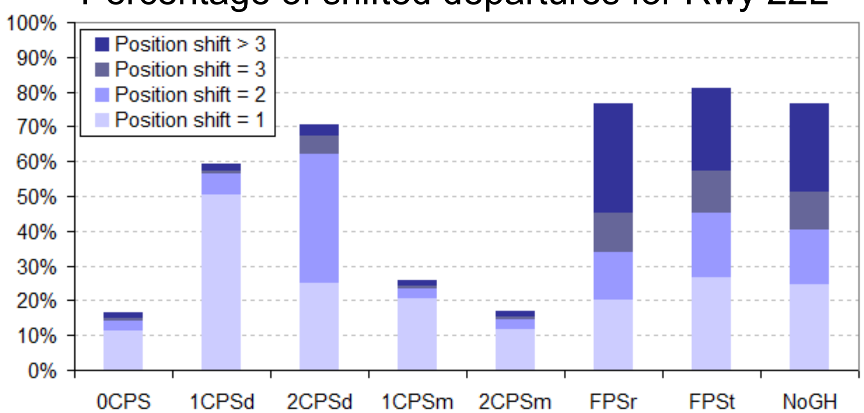




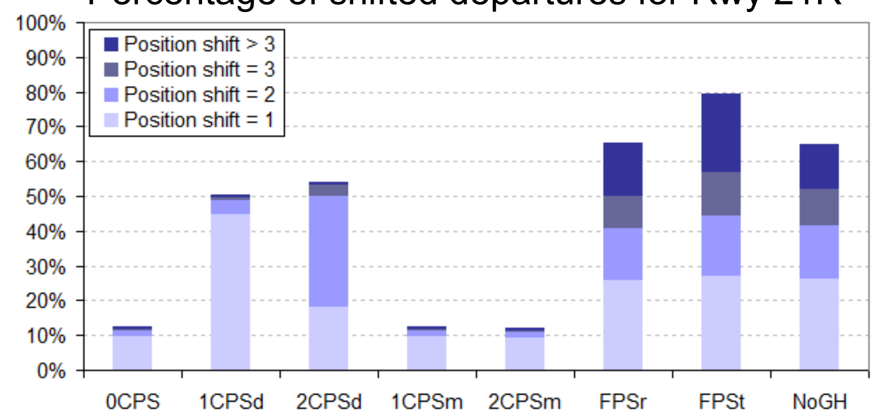
Takeoff Sequence Changes

- The number of position changes from the initial takeoff sequence based on the earliest runway arrival time
  - Affected by both runway scheduling and taxiway conditions
  - Three step approach: depending on the objective in Step 2
    - Minimizing runway delay: over half of flights experience position changes
    - Minimizing makespan: less frequent position changes
  - Integrated approach: excessive position changes observed frequently

Percentage of shifted departures for Rwy 22L



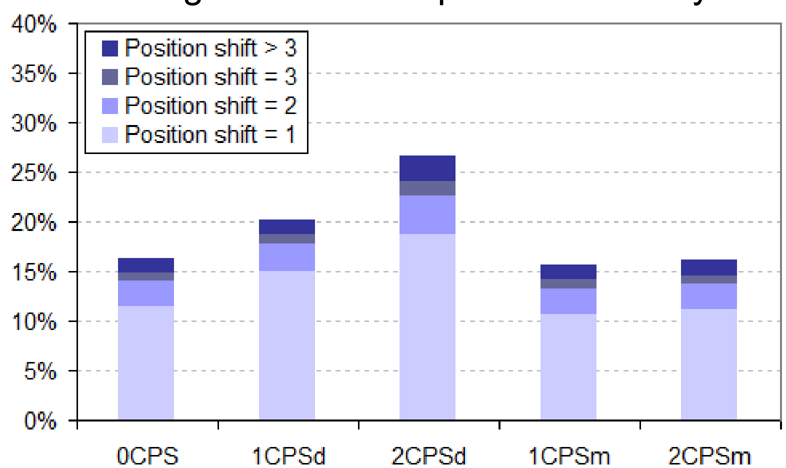
Percentage of shifted departures for Rwy 21R



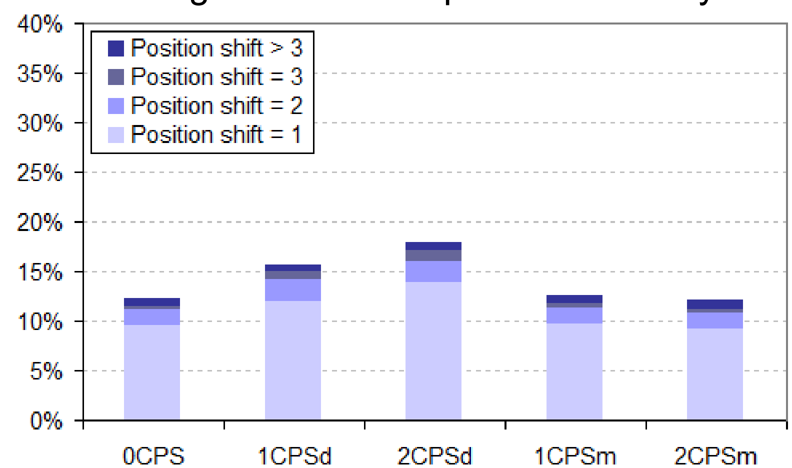
Takeoff Sequence Changes between Step 2 and Step 3

- The number of position changes from the optimized takeoff sequence in Step 2 for the three-step approach
  - 12~27% departures affected by taxiway conditions
  - More impacts on runway 22L
  - In most cases, the takeoff slot is shifted by one position

Percentage of shifted departures for Rwy 22L

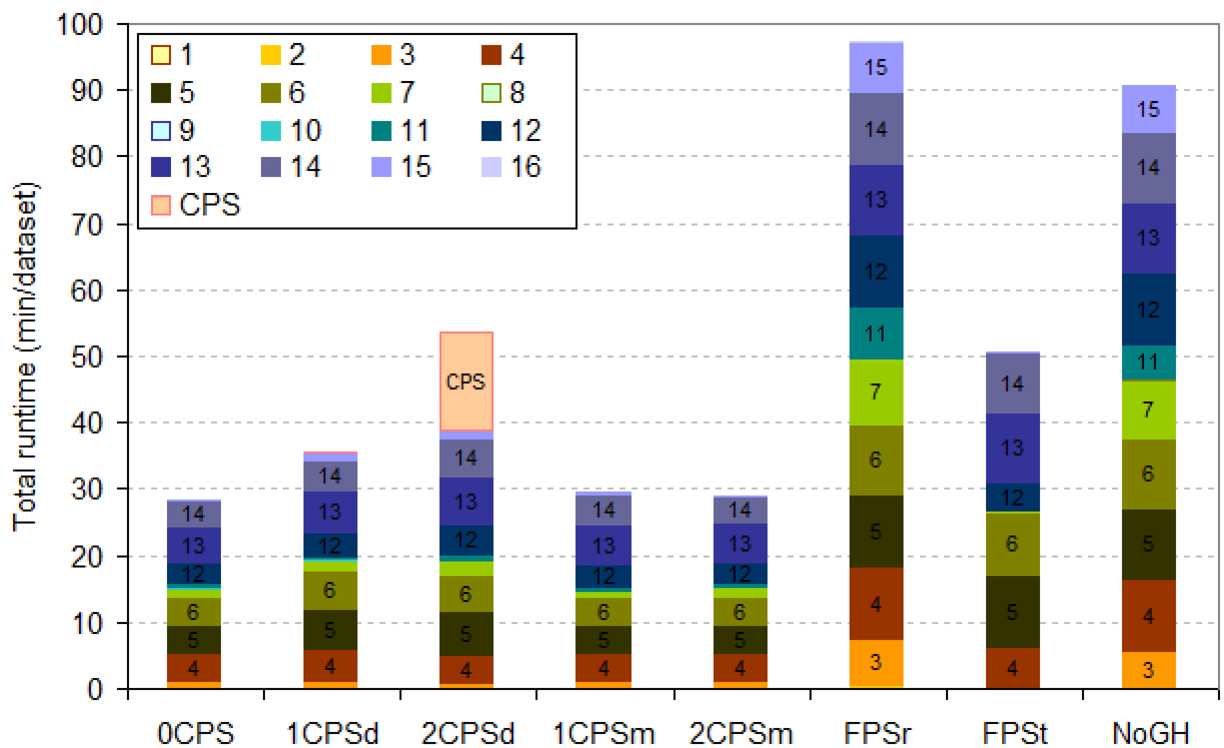


Percentage of shifted departures for Rwy 21R



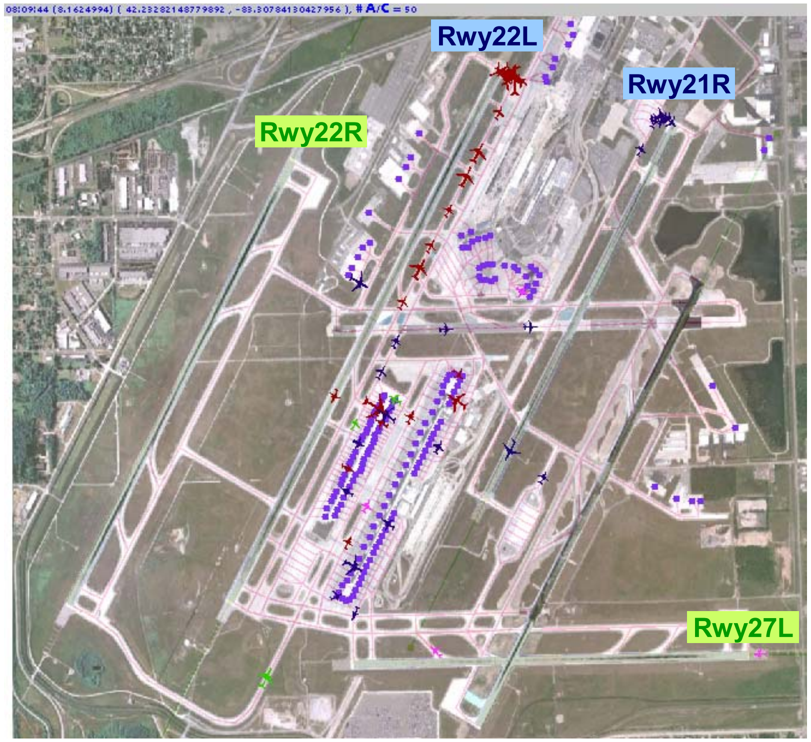
Computational Performance

- Total runtime for a 4-hr flight schedule by optimization time window
  - Weak computational performance in the FPSr case
    - Reach the time limit (10 min) set in the CPLEX solver more frequently

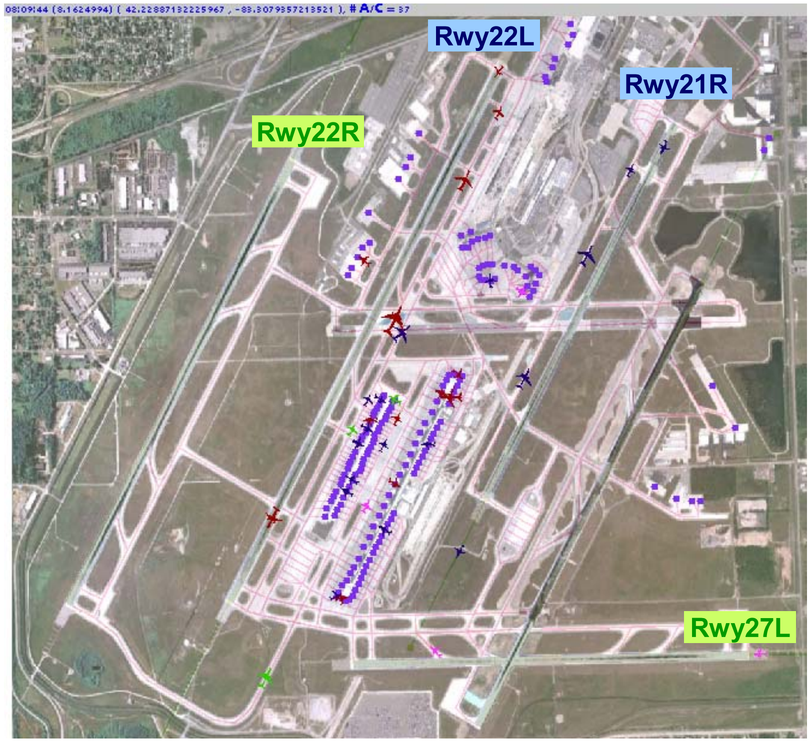


Air Traffic Flow on the Surface

- Long queue for takeoff at Rwy 22L in the NoGH case
- Enough space between flights moving toward the same departure runway in the FPSr case



Air traffic flow based on the *initial* schedule



Air traffic flow based on the *optimized* schedule

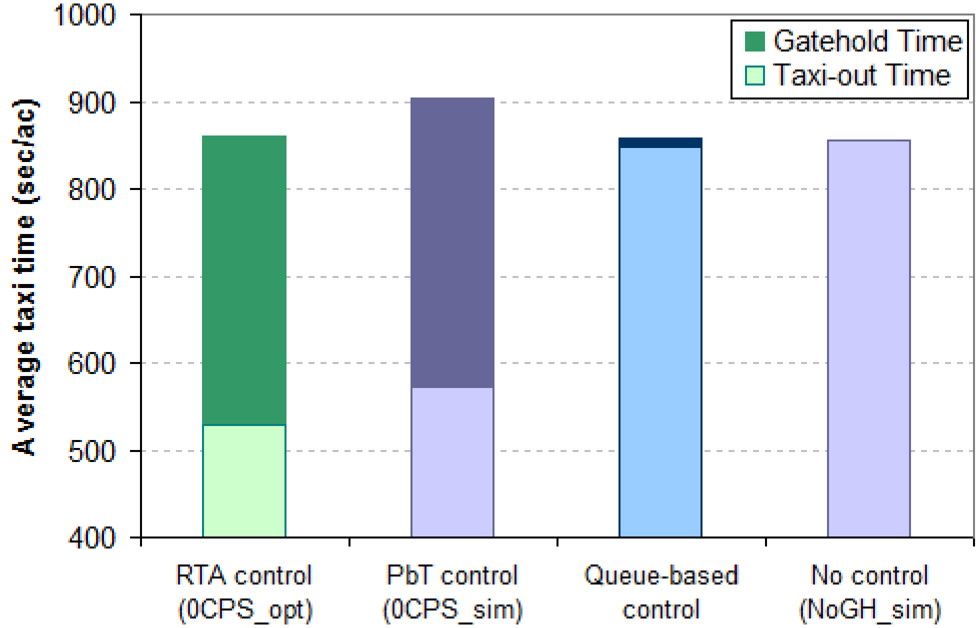
Aircraft Trajectory-based Control vs. Aggregate Queue-based Control

- Trajectory-based optimization
  - Optimize taxiway schedules along the given taxi routes
  - Determine the Required Times of Arrival (RTAs) at significant points on the taxiway
    - Need enhanced technologies for realizing the RTA control
  - Pushback time control only is possible in the current operational environment
    - Can be simulated in SIMMOD
    - Pushback time inputs from optimization results

- Queue-based control (N-control)
  - Model taxiways and runways as queue systems
  - Count the number of active departures on the taxiway, N
    - Consider taxiway congestion
  - Control pushback times of departures by gate-holding strategy
    - maintain N under the queue capacity threshold (N_{ctrl})

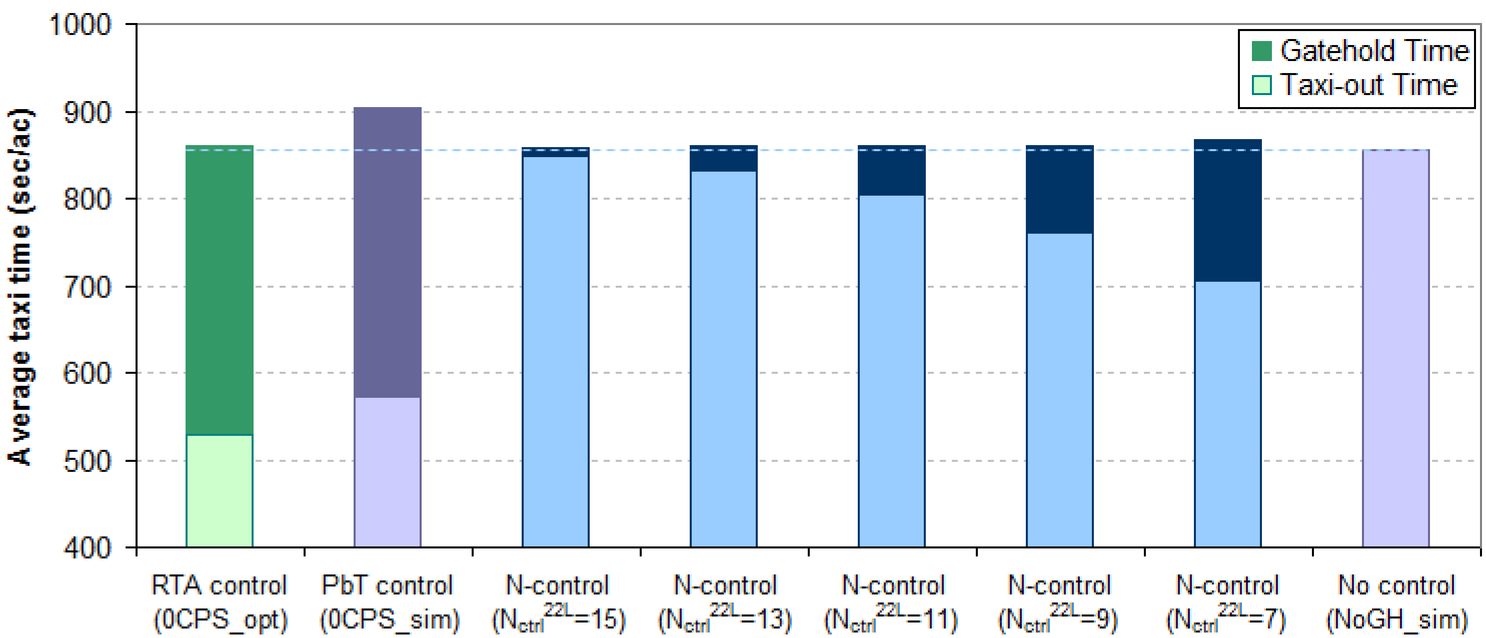
Taxi-out Time Comparison

- Trajectory-based control
  - RTA control: significant taxi-out time saving (5.4 min/aircraft)
  - Pushback time control: reduced taxi-out time (4.7 min/aircraft), but delayed takeoff (0.8 min/aircraft)
- Queue-based control (N-control with $N_{ctrl}^{22L} = 15$ and $N_{ctrl}^{21R} = 14$)
  - Small taxi-out time savings (0.1 min/aircraft) by limited gate-holding



Queue-based Control Study

- Aggressive queue control by reducing queue capacity
  - Simulation with various departure queue control parameters, N_{ctrl}
    - N_{ctrl}^{22L} = 7~15 (variable), N_{ctrl}^{21R} = 14 (fixed)
  - As N_{ctrl} decreases, taxi-out time decreases
  - Gate-holding time translates to taxi-out time savings
    - When N_{ctrl}^{22L} = 7, the average taxi time is reduced by 2.5 min/aircraft



Conclusions

- Developed two different optimization approaches for taxiway and runway scheduling
  - Three-step approach using a CPS algorithm and a MILP model
  - Integrated approach using a single MILP model
- Evaluated the optimization approaches with realistic flight schedules
  - Both approaches showed significant improvements on surface traffic operations without affecting runway delays and throughput
  - During peak times, the integrated approach provided the better optimal schedule at the cost of computational performance
- Compared the trajectory-based control with N-control
  - More taxi-out time savings could be obtained by RTA control
  - However, RTA control requires enhanced onboard equipment