SARDA Surface Schedulers

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Outline

- Overview of airport surface management
- Single runway scheduling
  - One exact algorithm
  - Two heuristics-based algorithms
  - Simulation setup and results
- Multiple runway scheduling
  - CLT airport layout
  - Mixed Integer Linear Program Formulation
  - Simulation setup and results
Current Operations

Spots

Departure Runway

Arrival

E C A
Current Operations

Spots

Departure Runway

Arrival

Full Inner Outer
Current Operations

Spots

Departure Runway

Arrival

E C A
Inefficiencies in current operations:

- Aircraft are delayed in departure queues
- Excess taxi-out times, fuel consumption and emissions
Surface Optimization at NASA

- Spot and Runway Departure Advisor (SARDA) provides a departure metering capability by efficiently scheduling aircraft on airport surface

- Human-in-the-loop simulations (2010, 2012)
  - Dallas/Fort Worth Airport (DFW), East Tower
  - Advisories provided to tower controllers

- Human-in-the-loop simulations (2014)
  - Charlotte Douglas International Airport (CLT)
  - Advisories provided to ramp controllers
SARDA Concept

- Taxi Predictor
- Runway Scheduler
- Spot Release
- Ramp Tool

ASDE-X
Pushback time
Arrival ETA
ETA Runway
Runway Usage
Spot Time
Pushback Time
A collaborative decision support tool for airlines and tower controllers to enhance the efficiency of surface traffic
A collaborative decision support tool for airlines and tower controllers to enhance the efficiency of surface traffic

Provides advisories to Air Traffic Control Tower controllers and airline operators
SARDA Concept

- A collaborative decision support tool for airlines and tower controllers to enhance the efficiency of surface traffic
- Provides advisories to Air Traffic Control Tower controllers and airline operators
- Efficient Runway Scheduler that incorporates aircraft specific constraints, as well as arrivals
A collaborative decision support tool for airlines and tower controllers to enhance the efficiency of surface traffic.

- Provides advisories to Air Traffic Control Tower controllers and airline operators.

- Efficient Runway Scheduler that incorporates aircraft specific constraints, as well as arrivals.

- Both computation time and solution quality are critical factors in deciding a solution technique for Runway Scheduler.
Outline

‣ Overview of airport surface management

‣ **Single runway scheduling**
  ‣ One exact algorithm
  ‣ Two heuristics-based algorithms
  ‣ Simulation setup and results

‣ **Multiple runway scheduling**
  ‣ CLT airport layout
  ‣ Mixed Integer Linear Program Formulation
  ‣ Simulation setup and results
Single Runway Scheduling
Single Runway Scheduling

- Departures on taxiway form 3 queues
- Arrivals can be merged into a single queue
Departures on taxiway form 3 queues
Arrivals can be merged into a single queue
Spots needs to be considered as forming their own queue
**Single Runway Scheduling**

- Exact Dynamic Program (EDP)
- Restricted Dynamic Program (RDP)
- Insertion and Local Search (ILS)
Runway Scheduler: Inputs

- For each aircraft:
  - Earliest available time
  - Spot, surface route, position, and fix/exit
  - Weight class and operation type
- Wake-vortex separation criteria and RNAV separation
- Separation between arrivals and departures for mixed use runway
- Separation between arrivals and departures for runway crossings
- Individual time-windows of intended take-off times for departing aircraft — Expect Departure Clearance Time (EDCT) and Call For Release (CFR)
Exact Dynamic Program
Exact Dynamic Program

[(3,2)]

Partial solution:
Exact Dynamic Program

Partial solution: \{a_1\}
Exact Dynamic Program

Partial solution: \{b_1\}
Exact Dynamic Program

(1,2) → (2,2) → (3,2) → (3,1)

Partial solution: \{a_1, a_2\}
Exact Dynamic Program

Partial solution: \{a_1, b_1\}
Exact Dynamic Program

Partial solution: \{a_1, b_1\}, \{b_1, a_1\}
Exact Dynamic Program

Partial solution: \{b_1, b_2\}
Exact Dynamic Program
Exact Dynamic Program

- Definition of state may not be rich enough
- It does not carry enough process history to determine optimality of remaining decisions
- Enhance state definition or consider multiple objectives
Exact Dynamic Program

- **State Definition:**
  - heading of last departure
  - weight-class of last departure
  - last operation type
  - \#aircraft in queue 1
  - \#aircraft in queue 2
  - ...
  - ...
  - ...
  - \#aircraft in queue Q
Exact Dynamic Program

› State Definition:
  ⚫ heading of last departure
  ⚫ weight-class of last departure
  ⚫ last operation type
  ⚫ #aircraft in queue 1
  ⚫ #aircraft in queue 2
  ⚫ #aircraft in queue Q

› Value Function:
  ⚫ Last time a departure took off
  ⚫ Makespan
  ⚫ Cumulative delay
**Exact Dynamic Program**

- **State Definition:**
  - heading of last departure
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  - last operation type
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  - #aircraft in queue 2
  - 
  - 
  - 
  - #aircraft in queue Q

- **Value Function:**
  - Last time a departure took off
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Pareto dominance can be applied
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Restricted Dynamic Program

- Number of nodes in DP is proportional to product of number of aircraft in each queue

- Some stages of the EDP formulation of the SRS could have a large number of states
Restricted Dynamic Program

- Number of nodes in DP is proportional to product of number of aircraft in each queue

- Some stages of the EDP formulation of the SRS could have a large number of states
In each stage, only a restricted subset of $H$ states with the smallest delay is kept.

Increasing the value of $H$ should yield better solutions, but will also result in higher computation times.
Insertion and Local Search

- Start with a First-Come-First-Served (FCFS) initial solution

\[ a_1 \ a_2 \ a_3 \ a_4 \ a_5 \ a_6 \ a_7 \ a_8 \ a_9 \ a_{10} \ a_{11} \ a_{12} \ a_{13} \]
Insertion and Local Search

- Find all permutations of ‘k’ free aircraft
Insertion and Local Search

- Find all permutations of ‘k’ free aircraft
- Select sequence which gives best objective value
Insertion and Local Search

- Fix first free aircraft
Insertion and Local Search

- Fix first free aircraft
- Find all permutations of next ‘k’ free aircraft
Insertion and Local Search

- Fix first free aircraft
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- Fix first free aircraft
- Find all permutations of next ‘k’ free aircraft
Insertion and Local Search

- If final sequence is different from starting sequence, repeat whole procedure (descent search)
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  - *Simulation setup and results*
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Simulation Setup

- DFW East-side in South-flow configuration
- 20 Departures and 15 runway crossings considered.
- Planning window of 15 minutes
- Earliest available times were uniformly distributed within 0-900 seconds
- 80% of type Large, 10% of type Heavy, 10% B75x
- Heading were randomly assigned to 0 or 1
Simulation Setup

- Scenarios were generated with varying numbers of queues (from 3 to 10)
- Hundred different scenarios generated for each queue number
- Three variants of RDP algorithm: RDP10K (H=10,000), RDP20K (H=20,000), RDP30K (H=30,000)
- ILS algorithm used a value of 7 for the neighborhood parameter k
Computation times

![Graph showing computation times with time on the y-axis and number of queues on the x-axis. The graph compares different queue sizes (EDP, RDP30K, RDP20K, RDP10K, ILS) and shows increasing time as the number of queues increases.]
Summary: Single Runway Scheduling

- Comparative study of three algorithms:
  - Exact Dynamic Programming (EDP)
  - Restricted Dynamic Programming (RDP)
  - Insertion and Local Search (ILS)
- Simulations conducted for the east side of the Dallas/Fort Worth International Airport (DFW)
- ILS heuristics is the most suitable candidate for application in tactical surface decision support tools
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Airport Layout

Airport capacity profile estimates were created using a standard set of performance characteristics and do not take into account non-runway constraints, unless otherwise noted. The capacity estimates developed for this report are not intended to replace the results of any detailed analysis that would precede an environmental, investment, or policy decision.

The list of Future Improvements and their expected effects on capacity does not imply FAA commitment to, or approval of, any item on the list.
Airport Layout

South Flow Configuration

Air Carrier Terminal
Airport Layout

North Flow Configuration

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In order to obtain an optimal solution for the airport runway operations it is necessary to formulate an algorithm that includes operations at all the runways.
Runway Scheduler: Inputs

- Estimated runway queue entry times (for departures)
- Estimated runway time (for arrivals)
- Spot, runway, position and fix/exit for each aircraft
- Type (weight class) of each aircraft
- Separation requirements between pair of aircraft
- Individual time-windows of intended take-off times for departing aircraft (EDCT, CFR)
Separation Requirements

- Between departures on same runway (wake vortex and RNAV separation)
- Between arrivals and departures for mixed use runway, runway crossings and converging runway operations
- Separation between departure from parallel runways going to same fix
- Separation between departures going to same constraint fix (MIT)
Separation Requirements

- Between departures on same runway (wake vortex and RNAV separation)
- Between arrivals and departures for mixed use runway, runway crossings and converging runway operations
- Separation between departure from parallel runways going to same fix
- Separation between departures going to same constraint fix (MIT)

These separations are converted to time-based separations for use in the MILP
MILP Runway Scheduler

Decision Variables

- Let $t_i$ denote the calculated time at which the aircraft uses the runway (take-off, land or cross)

- Let $Z_{i,j}$ be a binary sequencing variable
  
  $$Z_{i,j} = \begin{cases} 
    1 & \text{if aircraft } i \text{ uses runway before } j \\
    0 & \text{otherwise}
  \end{cases}$$
MILP Runway Scheduler

Objective Function

- System Delay - cumulative waiting time of all aircraft
- Let $\alpha_i$ be a earliest available time

System Delay:

$$\min \sum_{i \in F} (t_i - \alpha_i)$$
MILP Formulation
MILP Formulation

- Linear ordering constraints: \( Z_{i,j} + Z_{j,i} = 1 \)
MILP Formulation

- Linear ordering constraints: \( Z_{i,j} + Z_{j,i} = 1 \)
- Runway use after earliest time: \( t_i \geq \alpha_i \)
MILP Formulation

- Linear ordering constraints: \( Z_{i,j} + Z_{j,i} = 1 \)
- Runway use after earliest time: \( t_i \geq \alpha_i \)
- Arrival landing time cannot be changed: \( t_i \leq \alpha_i + \delta \)
MILP Formulation

- Linear ordering constraints: \[ Z_{i,j} + Z_{j,i} = 1 \]
- Runway use after earliest time: \[ t_i \geq \alpha_i \]
- Arrival landing time cannot be changed: \[ t_i \leq \alpha_i + \delta \]
- Time-Window constraints: \[ TMIL \leq t_i \leq TMIH \]
MILP Formulation

- Linear ordering constraints: \( Z_{i,j} + Z_{j,i} = 1 \)
- Runway use after earliest time: \( t_i \geq \alpha_i \)
- Arrival landing time cannot be changed: \( t_i \leq \alpha_i + \delta \)
- Time-Window constraints: \( TMI_L \leq t_i \leq TMI_H \)
- Separation requirements: \( Z_{i,j}(t_j - t_i - \Delta_{i,j}) \geq 0 \)
MILP Formulation

- Linear ordering constraints: \( Z_{i,j} + Z_{j,i} = 1 \)
- Runway use after earliest time: \( t_i \geq \alpha_i \)
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- Separation requirements: \( Z_{i,j}(t_j - t_i - \Delta_{i,j}) \geq 0 \)
- FCFS constraints on crossing aircraft: \( Z_{i,j} = 1, \text{ if } \alpha_i < \alpha_j \)
MILP Formulation

- Linear ordering constraints:  \( Z_{i,j} + Z_{j,i} = 1 \)
- Runway use after earliest time:  \( t_i \geq \alpha_i \)
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- FCFS constraints on MIT aircraft:  \( Z_{i,j} = 1, \) if \( \alpha_i < \alpha_j \)
MILP Formulation

- Linear ordering constraints: \( Z_{i,j} + Z_{j,i} = 1 \)
- Runway use after earliest time: \( t_i \geq \alpha_i \)
- Arrival landing time cannot be changed: \( t_i \leq \alpha_i + \delta \)
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- FCFS constraints on crossing aircraft: \( Z_{i,j} = 1, \text{ if } \alpha_i < \alpha_j \)
- FCFS constraints on MIT aircraft: \( Z_{i,j} = 1, \text{ if } \alpha_i < \alpha_j \)
- Constrained Position Shift (CPS) constraint on sequence of departures only
Simulation Setup

- Mixed operation runway with arrivals, departures and crossing traffic
- Another stream of arrivals was modeled to simulate converging runway operations
- Planning window of 15 minutes
- Number of aircraft in the scenarios was varied from 10 to 35 in increments of 5
- Hundred different scenarios generated for each aircraft count
Simulation Setup

- Earliest available times were uniformly distributed within 0-900 seconds
- Sixty percent of the traffic was chosen to be departures, 20% arrivals and 20% crossing aircraft
- 80% of type Large, 10% of type Heavy, 10% B75x
- Departure fix assigned randomly from 6 discrete choices
Simulation Setup

- Earliest available times were uniformly distributed within 0-900 seconds
- Sixty percent of the traffic was chosen to be departures, 20% arrivals and 20% crossing aircraft
- 80% of type Large, 10% of type Heavy, 10% B75x
- Departure fix assigned randomly from 6 discrete choices
- MILP formulation is compared with a FCFS to examine the benefits of the proposed algorithm
- The MILP is solved using Gurobi
Solution Quality

Total Delay Improvement over FCFS

Aircraft count

MPS=0
MPS=1
MPS=2
MPS=3
Computation times

![Computation times graph](image-url)

- **Run time (seconds)**
- **Aircraft count**
- **MPS=0**
- **MPS=1**
- **MPS=2**
- **MPS-3**
Summary: Multiple Runway Scheduling

- A MILP formulation for multiple runway scheduling
- 30% average improvement in total delay over FCFS
- Maximum position shift (MPS) parameter value of 2 is a good trade-off between solution quality and computation times
- MPS value of 0 and 1 are also good for cases with limited computational resources