A Model-based Approach to the Setting of Declared Capacities and Flight Schedules

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Airport Stakeholders’ Workshop
Outline

☐ Motivation and Framing

☐ Airport Operations and Delays

☐ Impact of Declared Capacity on Performance

☐ Targeted Scheduling Interventions Approach

☐ Implications for Busy Airports Worldwide

☐ Conclusion
The National Aviation System

Capacity limitations

Demand growth

<table>
<thead>
<tr>
<th>Cost Component (Ball et al., 2010)</th>
<th>Cost of delays in 2007 (in $ billion)</th>
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Airport Congestion Mitigation

- Capacity expansion
- Demand management
- Operating enhancements

Airports Commission: Final Report

July 2015
Demand Management Policies

- **Outside the US:**
  - Administrative slot control
  - Lower capacity utilization
  - Lower, more predictable delays

- **At US airports**
  - Limited demand management
  - Higher capacity utilization
  - Higher, more variable delays

Scheduling at European airports (FRA; 2007)
Scheduling at US airports (JFK; 05/25/2007)
Demand Management Process

- Setting of declared capacities varies across airports
- Typical declared capacity: Number of slots per hour
  - Can vary by time of the day
  - Can include separate limits on number of arrivals and departures
  - Can include limits per 5/15/30-minute period, or per week/month/year

### Declared capacity at LHR in Summer 2015

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Trade-off in Declaring Capacities

- On-time performance, level of service vs.
- Intensity of scheduling interference, and capacity utilization

1. Schedule-coordinated airports can solve this trade-off through the setting of declared capacities
2. We propose a *Targeted Scheduling Interventions* approach that provides flexibility by treating declared capacities as *variables*
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Airport Throughput Capacity

- Airport throughput is stochastic and variable, as a function of:
  - Operating conditions (e.g., weather conditions)
  - Operating procedures (e.g., active runways, human factors)
  - Flight mix (e.g., arrivals vs. departures, aircraft mix)

*Airport Throughput Capacity:* expected number of movements that can be performed per unit of time, under continuous demand

Not possible to equate declared capacity (a fixed, administrative quantity) with operating capacity (an unknown, variable quantity)
Model of Airport Congestion

- Complex, stochastic, nonlinear relationship between flight schedules, airport capacity, and flight delays
  - A descriptive model of congestion based on queuing theory
Schedules and Capacity (2007)
Validation: Average Queues

![Graphs showing average queues at JFK, EWR, and LGA over time of day.](image-url)
Validation: Queue Variability

![Graph showing queue variability between JFK, EWR, and LGA airports.](image)
Application: LGA in 2000

- Slot “lottery” at LGA in 2000 to reduce congestion
Application: LGA in 2000

- Slot “lottery” at LGA in 2000 to reduce congestion
- Small scheduling reduction led to very large delay reduction

Average delay (mins per flight)

Time of day

Graph showing average delay over time for Nov, 00 and Aug, 01.
Application: New York, 2007-10

- Small changes in flight schedules between 2007 – 2011
  - Schedule limits at JFK & EWR in 2008
  - 5%-10% reduction in demand between 2008 and 2010
- Substantial delay declines: 30%-50%

→ Delay reductions mostly due to changes in flight schedules
Takeaways

- Airport throughput is highly variable, and depend on (unknown) operating conditions at the airport
  - Declared capacities cannot be equal to throughput capacity in all operating scenarios

- At near-capacity operating levels, flight delays are very sensitive to even small changes in:
  - Number of flights (“traffic volume”)
  - Distribution of traffic over the course of the day
  - Declared capacities can have a strong impact on airport operating performance

Integration of airport capacity and operations into the optimization and evaluation of declared capacities and flight schedules
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Modeling Approach

- **Inputs**
  - **Supply:** Capacity estimates and model of airport operations
  - **Demand:** Airline scheduling requests for a given day

- **Objective:** Simulating the effects of declared capacities on flight schedules & delays

- **Approach:** Minimizing *displacement* from airline scheduling requests

- **Impact of declared capacity on flight schedules & delays?**
Model Formulation

minimize Schedule Displacement
subject to: Scheduling constraints
          Network connectivity constraints
          Schedule limits constraints

\[ S_{\text{arr}} = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \]
\[ S_{\text{dep}} = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{pmatrix} \]
\[ w_{\text{arr}} = \begin{pmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \]
\[ w_{\text{dep}} = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{pmatrix} \]
Model Formulation

minimize Schedule Displacement
subject to: Scheduling constraints
        Network connectivity constraints
        Schedule limits constraints

1. min. largest displacement
   \[ \min \left\{ \max_{i \in F} |u_i| \right\} \]

2. min. total displacement
   \[ \min \left\{ \sum_{i \in F} |u_i| \right\} \]

\[ S_{arr} = \begin{pmatrix} 1, 1, 0, 0, 0, 0, 0, 0, 0, 0 \end{pmatrix} \]
\[ S_{dep} = \begin{pmatrix} 1, 1, 1, 1, 1, 1, 0, 0, 0, 0 \end{pmatrix} \]
\[ w_{arr} = \begin{pmatrix} 1, 1, 1, 1, 1, 0, 0, 0, 0, 0 \end{pmatrix} \]
\[ w_{dep} = \begin{pmatrix} 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 \end{pmatrix} \]
Model Formulation

minimize Schedule Displacement

subject to:
Scheduling constraints
Network connectivity constraints
Schedule limits constraints

- No flight eliminated
  \[ w_{i1}^{\text{Arr}} = w_{i1}^{\text{Dep}} = 1 \]

- Scheduled block times maintained
  \[ \sum_{t \in T} (w_{it}^{\text{arr}} - S_{it}^{\text{arr}}) = \sum_{t \in T} (w_{it}^{\text{dep}} - S_{it}^{\text{dep}}) = u_i \]

- Connections maintained
  \[ t_{i,j}^{\text{min}} = \sum_{t \in T} (w_{jt}^{\text{dep}} - w_{it}^{\text{arr}}) \leq t_{i,j}^{\text{max}} \]

\[
\begin{align*}
S^{\text{arr}} &= \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \\
S^{\text{dep}} &= \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{pmatrix} \\
w^{\text{arr}} &= \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \\
w^{\text{dep}} &= \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{pmatrix}
\end{align*}
\]
Model Formulation

minimize Schedule Displacement

subject to:

Scheduling constraints

Network connectivity constraints

Schedule limits constraints

Schedule aggregation

\[ \sum_{i \in F_{\text{arr}}} (w_{it}^{\text{arr}} - w_{i,t+1}^{\text{arr}}) = \lambda_t^X \]

\[ \sum_{i \in F_{\text{dep}}} (w_{it}^{\text{dep}} - w_{i,t+1}^{\text{dep}}) = \lambda_t^Y \]

Declared capacities

\[ \lambda_t^X + \lambda_t^Y \leq C_t \]

\[ \lambda_t^X \leq C_{\text{arr}}^t \]

\[ \lambda_t^Y \leq C_{\text{dep}}^t \]
Impact on Scheduling

- Smoothing of flight schedules, based on declared capacities
- “Flattens” peak scheduling profiles, extends peak period

Max disp.: 1 15-min period
Total disp.: 127 15-min periods
Impact on Scheduling

- Smoothing of flight schedules, based on declared capacities
- “Flattens” peak scheduling profiles, extends peak period

Max disp.: 1 15-min period
Total disp.: 292 15-min periods
Impact on Scheduling

- Smoothing of flight schedules, based on declared capacities
- “Flattens” peak scheduling profiles, extends peak period

Max disp.: 2 15-min periods
Total disp.: 810 15-min periods
Impact on Flight Delays

- Large, and non-linear effect of declared capacities on airport on-time performance
  → Trade-off: delay reductions vs. small scheduling interference
Outline

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Main observation: “Best” schedule does not have to be flat at peak hours

Targeted Scheduling Interventions

- Declared capacity
- Airline requests
- Schedule coordination
- Flight schedule
- On-time performance
Main observation: “Best” schedule does not have to be flat at peak hours

No reliance on pre-specified value of declared capacity
Targeted Scheduling Interventions

- Main observation: “Best” schedule does not have to be flat at peak hours
- No reliance on pre-specified value of declared capacity
- Optimization and elicitation of the trade-off between

  On-time performance **vs.** Schedule displacement
Model Formulation

minimize Schedule Displacement
subject to: Scheduling constraints
Network connectivity constraints
Scheduling limits constraints
Model Formulation

minimize Schedule Displacement
subject to: Scheduling constraints
Network connectivity constraints
Operating capacity constraints

- Arrival queue length lower than $A_{\text{MAX}}$
- Departure queue length lower than $D_{\text{MAX}}$

- Modified schedule $\rightarrow$ Capacity utilization $\rightarrow$ Queue lengths

$$q : (\lambda^X_1, ..., \lambda^X_T, \lambda^Y_1, ..., \lambda^Y_T) \mapsto (A_1, ..., A_T, D_1, ..., D_T)$$

$$E(A_t) \leq A_{\text{MAX}} \quad \forall t \in T$$
$$E(D_t) \leq D_{\text{MAX}} \quad \forall t \in T$$

$\rightarrow$ Integration of airport capacity and operating patterns into the optimization of schedule coordination
Effect on Flight Schedules

- Smoothing of flight schedules – as in previous case
- Optimal schedules may not be “flat”; exhibit peaks & valleys based on airline scheduling requests and delay dynamics

Max disp.: 1 15-min period
Total disp.: 63 15-min periods

Original Schedule

Modified Schedule – $A_{\text{MAX}}=13$, $D_{\text{MAX}}=23$
Effect on Flight Schedules

- Smoothing of flight schedules – as in previous case
- Optimal schedules may not be “flat”; exhibit peaks & valleys based on airline scheduling requests and delay dynamics

Original Schedule

Modified Schedule – $A_{\text{MAX}}=12$, $D_{\text{MAX}}=20$

Max disp.: 1 15-min period
Total disp.: 105 15-min periods
Effect on Flight Schedules

- Smoothing of flight schedules – as in previous case
- Optimal schedules may not be “flat”; exhibit peaks & valleys based on airline scheduling requests and delay dynamics

Original Schedule

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Max disp.: 2 15-min periods
Total disp.: 356 15-min periods

Modified Schedule – $A_{\text{MAX}}=11$, $D_{\text{MAX}}=15$

![Graph](image)
Effect on Flight Schedules

- Smoothing of flight schedules – as in previous case
- Optimal schedules may not be “flat”; exhibit peaks & valleys based on airline scheduling requests and delay dynamics

Original Schedule

Modified Schedule – $A_{\text{MAX}}=11$, $D_{\text{MAX}}=15$

Max disp.: 2 15-min periods
Total disp.: 1,129 15-min periods
Effect on On-time Performance

- Maximum flight displacement: 0 15-minute period
- Total schedule displacement: 0 15-minute period
Effect on On-time Performance

- Maximum flight displacement: 1 15-minute period
- Total schedule displacement: 37 15-minute period
Effect on On-time Performance

- Maximum flight displacement: 1 15-minute period
- Total schedule displacement: 105 15-minute period
Effect on On-time Performance

- Maximum flight displacement: 2 15-minute period
- Total schedule displacement: 356 15-minute period
Effect on On-time Performance

- Maximum flight displacement: 2 15-minute period
- Total schedule displacement: 1,129 15-minute period
Effect on On-time Performance

- Maximum flight displacement: 2 15-minute period
- Total schedule displacement: 1,129 15-minute period

→ Trade-off: delay reductions vs. small scheduling interference
Benefits of Scheduling Flexibility

- Targeted scheduling interventions vs. schedule limits
Benefits of Scheduling Flexibility

- Targeted scheduling interventions vs. schedule limits
  - For given schedule displacement, smaller resulting delays

![Arrival queue](image1)
![Departure queue](image2)
Benefits of Scheduling Flexibility

- Targeted scheduling interventions vs. schedule limits
  - For given schedule displacement, smaller resulting delays
  - For given delay reduction targets, smaller schedule displacement

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Short-term Implications

- Airport scheduling and operating performance is highly sensitive to declared capacities and flight schedules.

- At slot-controlled airports: Standardization and optimization of declared capacities based on:
  - airport capacity and operations patterns
  - airline scheduling requests
  - on-time performance objectives

  → Declared capacities may not be “flat”, but depend on time of day and balance of arrivals and departures

  → Fewer flights rejected and/or displaced at many airports

- At US airports: A scheduling mechanism that mitigates excessive delays through limited scheduling adjustments.
Long-term Implications

- Creation of a flexible, transparent and model-based scheduling mechanism: *Targeted scheduling interventions*
- Implementation in a CDM environment: Airlines, airport operators and ANSPs selecting the preferred tradeoff of:
  - On-time performance
  - Schedule displacement (e.g., flights rejected, flights rescheduled)
- Decisions with full knowledge of the Pareto-optimal frontier
- Approach can be extended to capture additional guidelines (e.g., slot series, slot priorities, secondary trading, etc.)

Treatment of declared capacities as *variables* that can vary over the day or from day to day based on airport demand and capacity
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Conclusion

- Scheduling levels must consider simultaneously the supply side and the demand side of the airport
  - Supply: Throughput is variable, and unknown in advance
  - Supply: On-time performance is highly sensitive to demand and capacity
  - Demand: Airline schedules may exhibit strong peaks and valleys

On-time performance vs. Schedule displacement

→ Review of declared capacity levels based on records of schedule displacement and on-time performance
→ Enhancements in setting declared capacities (e.g., intra-day variations, inter-day variations, arrival/departure limits, etc.)
→ Long-term: A more flexible approach to schedule coordination based on Targeted Scheduling Interventions
Thank you!