Balancing Reliability, Efficiency and Equity in Airport Scheduling Interventions

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Vikrant Vaze

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06/29/2017
Outline

- Introduction
  - Motivation and Background
  - Problem of Inter-airline Equity
- Model Formulation and Solution Approach
- Results
  - Theoretical Results
  - Computational Results
- Conclusion
The National Aviation System

→ Impacts on growth, fares, connectivity
→ Congestion, delays, unreliability (Ball et al., 2010)

Image credits: (Bonnefoy, 2008), aviationexplorer.com, airlines.org, airliners.net
The National Aviation System

→ Impacts on growth, fares, connectivity

→ Congestion, delays, unreliability (Ball et al., 2010)

Capacity limitations

Demand growth

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Cost of delays in 2007 (in $ billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost to Airlines</td>
<td>8.3</td>
</tr>
<tr>
<td>Cost to Passengers</td>
<td>16.7</td>
</tr>
<tr>
<td>Cost from Lost Demand</td>
<td>3.9</td>
</tr>
<tr>
<td>Impact on GDP</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>32.9</strong></td>
</tr>
</tbody>
</table>
Demand Management Policies

Outside the US:
- Administrative slot control policies
- 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)
Airport Congestion Mitigation

- Capacity Expansion
- Scheduling Interventions
- Capacity Utilization

![Graph showing number of scheduled operations over hours]

- Y-axis: Number of Scheduled Operations
- X-axis: Hour

Legend:
- Capacity Range
- Schedule
Airport Congestion Mitigation

Capacity Expansion

Scheduling Interventions

Capacity Utilization

Airport capacity planning
(Saatcioglu, 1982)
(Santos and Antunes, 2015)

Aircraft sequencing / spacing
(Balakrishnan and Chandran, 2010)
(Solveling et al., 2011)

Runway configurations / Service rates
(Gilbo, 1993)
(Bertsimas, Frankovich & Odoni, 2011)
(Jacquillat, Odoni & Webster, 2017)

Surface operations
(Pujet et al., 1999)
(Simaiakis et al., 2014)
Airport Congestion Mitigation

Capacity Expansion

Scheduling Interventions

Capacity Utilization

Airline scheduling under congestion
(Pita et al., 2012)

IATA schedule coordination
(Zografos, Salouras & Madas, 2012)
(Jiang and Zografos, 2016)
(Zografos et al., 2016)
(Ribeiro et al., 2016)

Scheduling at US airports
(Vaze & Barnhart, 2012)
(Swaroop et al., 2012)
(Pyrgiotis & Odoni, 2015)
(Jacquillat & Odoni, 2015)
What is the adequate level of scheduling interventions? (Vaze & Barnhart, 2012; Swaroop et al., 2012; Pyrgiotis & Odoni, 2015; Jacquillat & Odoni, 2015)

How to determine *which* flights to reschedule?
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  - Theoretical Results
  - Computational Results
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### Problem of Inter-airline Equity

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<tr>
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<th>Airline</th>
<th>Original schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival</td>
<td>Airline 1</td>
<td>8:00</td>
</tr>
<tr>
<td>Arrival</td>
<td>Airline 2</td>
<td>8:00</td>
</tr>
<tr>
<td>Departure</td>
<td>Airline 1</td>
<td>8:05</td>
</tr>
<tr>
<td>Departure</td>
<td>Airline 2</td>
<td>8:05</td>
</tr>
<tr>
<td>Departure</td>
<td>Airline 1</td>
<td>8:10</td>
</tr>
<tr>
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<td>Arrival</td>
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<tr>
<th></th>
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<tbody>
<tr>
<td># flights</td>
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<td>4</td>
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<tr>
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<td>Airline 2</td>
<td>8:00</td>
<td>8:00</td>
<td>8</td>
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<tr>
<td>Departure</td>
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<td>0</td>
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<tr>
<td>Displacement 2</td>
<td>3</td>
<td>3</td>
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Problem of Inter-airline Equity

Interventions may penalize a few airlines disproportionately
Quantification and optimization of inter-airline equity

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<tr>
<td>Displacement 2</td>
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<tr>
<td>Displacement 3</td>
<td>4</td>
<td>2</td>
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</table>
## Contributions

- Integration of inter-airline equity objectives in the modeling and optimization of airport scheduling interventions

<table>
<thead>
<tr>
<th>Modeling</th>
<th>A multi-objective architecture based on efficiency, equity and on-time performance objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical analysis</td>
<td>Guarantees of joint maximization of efficiency and inter-airline equity, and conditions of a trade-off</td>
</tr>
<tr>
<td>Computational analysis</td>
<td>Significant gains in inter-airline equity at no (or minimal) efficiency losses in realistic settings</td>
</tr>
<tr>
<td>Practical Impact</td>
<td>Incorporation of inter-airline equity objectives in scheduling and operating procedures in ATM</td>
</tr>
</tbody>
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Outline

- Introduction
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- Model Formulation and Solution Approach

- Results
  - Theoretical Results
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- Conclusion
Baseline Model

- Model of centralized scheduling interventions
  (Jacquillat & Odoni, 2015)

minimize Schedule Displacement
subject to: Scheduling constraints
Network connectivity constraints
Arrival queue length lower than $A_{\text{MAX}}$
Departure queue length lower than $D_{\text{MAX}}$
Baseline Model

- Model of centralized scheduling interventions (Jacquillat & Odoni, 2015)

  \[
  \begin{align*}
  & \text{minimize} \quad \text{Schedule Displacement} \\
  & \text{subject to:} \quad \text{Scheduling constraints} \\
  & \quad \text{Network connectivity constraints} \\
  & \quad \text{Arrival queue length lower than } A_{\text{MAX}} \\
  & \quad \text{Departure queue length lower than } D_{\text{MAX}}
  \end{align*}
  \]

- No flight eliminated

- Scheduled block times maintained

- Connections maintained

\[
\begin{align*}
  w_{i1}^{\text{Arr}} &= w_{i1}^{\text{Dep}} = 1 \\
  \sum_{t \in T} (w_{it}^{\text{arr}} - S_{it}^{\text{arr}}) &= \sum_{t \in T} (w_{it}^{\text{dep}} - S_{it}^{\text{dep}}) = u_i \\
  t_{i,j}^{\text{min}} &\leq \sum_{t \in T} (w_{jt}^{\text{dep}} - w_{it}^{\text{arr}}) \leq t_{i,j}^{\text{max}}
  \end{align*}
\]
Baseline Model

Model of centralized scheduling interventions (Jacquillat & Odoni, 2015)

\[
\begin{align*}
\text{minimize} & \quad \text{Schedule Displacement} \\
\text{subject to:} & \quad \text{Scheduling constraints} \\
& \quad \text{Network connectivity constraints} \\
& \quad \text{Arrival queue length lower than } A_{\text{MAX}} \\
& \quad \text{Departure queue length lower than } D_{\text{MAX}}
\end{align*}
\]

Scheduling model \rightarrow Modified schedule \rightarrow Expected delays

\[ q : (X_1, ..., X_T, Y_1, ..., Y_T) \rightarrow (a_1, ..., a_T, d_1, ..., d_T) \]

\[ \mathbb{E}(a_t) \leq A_{\text{MAX}} \quad \forall t \in \mathcal{T} \]
\[ \mathbb{E}(d_t) \leq D_{\text{MAX}} \quad \forall t \in \mathcal{T} \]

Solution algorithm to integrate these constraints in the model
Baseline Model

- **Model of centralized scheduling interventions (Jacquillat & Odoni, 2015)**

  \[
  \begin{align*}
  \text{minimize} & \quad \text{Schedule Displacement} \\
  \text{subject to:} & \quad \text{Scheduling constraints} \\
  & \quad \text{Network connectivity constraints} \\
  & \quad \text{Arrival queue length lower than } A_{\text{MAX}} \\
  & \quad \text{Departure queue length lower than } D_{\text{MAX}}
  \end{align*}
  \]

- **Modeling framework to optimize scheduling interventions**

- **However, centralized perspective does not necessarily balance costs of scheduling interventions equitably**

  → **A multi-objective architecture to balance objectives of reliability, efficiency and equity in scheduling interventions**
Performance Indicators

- **Efficiency:** Meeting airline scheduling preferences
  - Min-max efficiency
    \[ \delta = \max_{i \in \mathcal{F}} |u_i| \implies \min \delta \]
  - Total weighted efficiency
    \[ \Delta = \sum_{i \in \mathcal{F}} v_i |u_i| \implies \min \Delta \]

- **Equity:** Balancing displacement fairly among the airlines
  \[ \mathcal{A} = \text{set of airlines, } \{1, \ldots, A\} \]
  \[ \mathcal{F}_a = \text{set of flights scheduled by airline } a \]
  \[ \sigma_a = \frac{1}{|\mathcal{F}_a|} \sum_{i \in \mathcal{F}_a} v_i |u_i|, \forall a \in \mathcal{A} \implies \text{lex min } \sigma \]

- **On-time performance:** Mitigating airport congestion
  \[ \min \left\{ g \left( A_1, \ldots, A_T, D_1, \ldots, D_T \right) \right\} \]
  \[ \rightarrow \text{Optimization of trade-off between performance attributes} \]
Lexicographic Architecture

1. Setting of on-time performance targets
   - Queuing limits $A_{\text{MAX}}, D_{\text{MAX}}$

2. Efficiency maximization
   - min-max displacement $\delta^*$
   - weighted displacement $\Delta^*$
   - aggregate schedule $\lambda_{t}^{\text{arr}}, \lambda_{t}^{\text{dep}}$

\[ \begin{align*}
\text{min} & \quad \delta \\
\text{s.t.} & \quad \text{Scheduling and network constraints}
\end{align*} \]
\[ E(A_t) & \leq A_{\text{MAX}}, \forall t \in \mathcal{T} \\
E(D_t) & \leq D_{\text{MAX}}, \forall t \in \mathcal{T} \]

\[ \begin{align*}
\text{min} & \quad \Delta \\
\text{s.t.} & \quad \text{Scheduling and network constraints}
\end{align*} \]
\[ E(A_t) & \leq A_{\text{MAX}}, \forall t \in \mathcal{T} \\
E(D_t) & \leq D_{\text{MAX}}, \forall t \in \mathcal{T} \\
|u_i| & \leq \delta^*, \forall i \in \mathcal{F} \]
Lexicographic Architecture

1. Setting of on-time performance targets

2. Efficiency maximization

   - min-max displacement \( \delta^* \)
   - weighted displacement \( \Delta^* \)
   - aggregate schedule \( \lambda_t^{arr}, \lambda_t^{dep} \)

3. Equity maximization

   \[
   \text{lex min } \sigma
   \]

   s.t. Scheduling and network constraints

   \[
   \lambda_t^{arr} \leq \lambda_t^{arr} \quad \forall t \in T
   \]

   \[
   \lambda_t^{dep} \leq \lambda_t^{dep} \quad \forall t \in T
   \]

   \[
   |u_i| \leq \delta^* \quad \forall i \in F
   \]

   \[
   \sum_{i \in F} v_i |u_i| \leq (1 + \rho) \Delta^*
   \]
Solution Approach

- Efficiency-maximizing schedule *(Jacquillat & Odoni, 2015)*

Original Schedule

Efficient, Inequitable Schedule
Solution Approach

- Efficiency-maximizing schedule \textit{(Jacquillat & Odoni, 2015)}
- Storage of aggregate schedule of flights at the airport
Solution Approach

- Efficiency-maximizing schedule \((\text{Jacquillat & Odoni, 2015})\)
- Storage of aggregate schedule of flights at the airport
- Efficiency/equity maximization, given aggregate schedule

Original Schedule

Efficient, Equitable Schedule
Efficiency/Equity Trade-off

→ When/How can efficiency and equity be jointly maximized?
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Overview of Results

<table>
<thead>
<tr>
<th>Theoretical results</th>
<th>Computational results</th>
</tr>
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<tbody>
<tr>
<td>Joint maximization of efficiency and equity</td>
<td>Maximizing efficiency alone does not maximize equity</td>
</tr>
<tr>
<td>- No network connection</td>
<td>- Optimal equity at no loss in efficiency in current settings (uniform valuations)</td>
</tr>
<tr>
<td>- Uniform flight valuations</td>
<td>- Strong equity improvements even under differentiated flight valuations</td>
</tr>
<tr>
<td>- Some scheduling conditions</td>
<td>- Low price of equity</td>
</tr>
<tr>
<td>Conditions of an efficiency/equity trade-off</td>
<td>- High price of efficiency</td>
</tr>
<tr>
<td>- Differentiated flight schedules</td>
<td>- Differentiated network connectivities</td>
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Theoretical results

- Joint maximization of efficiency and equity
  - No network connection
  - Uniform flight valuations
  - Some scheduling conditions

- Conditions of an efficiency/equity trade-off
  - Differentiated flight schedules
  - Differentiated network connectivities
  - Differentiated flight valuations

Computational results

- Maximizing efficiency alone does not maximize equity
- Optimal equity at no loss in efficiency in current settings (uniform valuations)
- Strong equity improvements even under differentiated flight valuations
  - Low price of equity
  - High price of efficiency
Framing

- Theoretical guarantees of joint maximization of efficiency and inter-airline equity under
  - No network connection
  - Uniform flight valuations
  - Some scheduling conditions

**Efficiency maximization**

\[
\begin{align*}
\text{min} & \quad \sum_{i \in F} |u_i| \\
\text{s.t.} & \quad w_{it} \geq w_{i,t+1}, \forall i \in F, \forall t \in \mathcal{T} \\
& \quad w_{i1} = 1, \forall i \in F \\
& \quad \sum_{t \in \mathcal{T}} (w_{it} - S_{it}) = u_i, \forall i \in F \\
& \quad \sum_{i \in F} (w_{it} - w_{i,t+1}) \leq \hat{\lambda}_t, \forall t \in \mathcal{T}
\end{align*}
\]

**Equity maximization**

\[
\begin{align*}
\text{lex min} & \quad \left( \frac{1}{|F_a|} \sum_{i \in F_a} |u_i| \right)_{a \in A} \\
\text{s.t.} & \quad w_{it} \geq w_{i,t+1}, \forall i \in F, \forall t \in \mathcal{T} \\
& \quad w_{i1} = 1, \forall i \in F \\
& \quad \sum_{t \in \mathcal{T}} (w_{it} - S_{it}) = u_i, \forall i \in F \\
& \quad \sum_{i \in F} (w_{it} - w_{i,t+1}) \leq \hat{\lambda}_t, \forall t \in \mathcal{T}
\end{align*}
\]

- Is there a solution that is optimal for the two problems?
Proposition 1: If demand falls below capacity for any set of three consecutive periods, then there exists a solution that solves (EFF) and (EQ) simultaneously.

- Problem can be treated as a series of independent one-period cases
- There is no value (in terms of equity) in displacing an extra flight
Efficiency/Equity Maximization

**Proposition 2**: If each airline’s share of flights is identical across all periods, then there exists a solution that solves *(EFF)* and *(EQ)* simultaneously.

- The centralized decision-maker can “pick” which flights to reschedule to satisfy inter-airline equity objectives.

![Bar chart showing flights by airline across time periods](chart.png)
Overview of Results

Theoretical results

- Joint maximization of efficiency and equity
  - No network connection
  - Uniform flight valuations
  - Some scheduling conditions
- Conditions of an efficiency/equity trade-off
  - Differentiated flight schedules
  - Differentiated network connectivities
  - Differentiated flight valuations

Computational results

- Maximizing efficiency alone does not maximize equity
- Optimal equity at no loss in efficiency in current settings (uniform valuations)
- Strong equity improvements even under differentiated flight valuations
  - Low price of equity
  - High price of efficiency
Efficiency/Equity: Schedules

- Trade-off due to inter-airline variations in flight schedules

**Efficient Solution**
- Total displacement: 4
- Airline disutilities: (4/26, 0)

**Equitable Solution**
- Total displacement: 6
- Airline disutilities: (3/26, 3/26)
Efficiency/Equity: Connections

- Trade-off due to inter-airline variations in connections

**Efficient Solution**
- Total displacement: 4
- Airline disutilities: (4/13, 0)

**Equitable Solution**
- Total displacement: 6
- Airline disutilities: (3/13, 3/13)
Trade-off due to inter-airline variations in flight valuations

**Efficient Solution**
- Total displacement: 3.3
- Airline disutilities: (0.3/13, 3/10)

**Equitable Solution**
- Total displacement: 4.2
- Airline disutilities: (2.2/10, 2/10)
Summary of Insights

- Under some conditions, it may be possible to guarantee **inter-airline equity at no loss in efficiency**

- In contrast, there may be instances where there may be a trade-off between efficiency and equity...
  
  1. if airline schedules exhibit **different intra-day patterns**: more efficient to displace the flights at peak hours, but may be inequitable
  2. if airline schedules exhibit **different connectivity patterns**: more efficient to displace the least-connected flights, but may be inequitable
  3. if airline schedules exhibit **different flight valuation patterns**: more efficient to displace the low-valuation flights, but may be inequitable

→ How will this play out in realistic settings?
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Experimental Setup

- Use of historical scheduling data at JFK airport
  - Flight schedules from ASPM database
  - 4 airline groups: DAL, AAL, JBU, Others
  - Aircraft connections from ASPM database and (Pyrgiotis, 2011)
  - Passenger connections from (Barnhart, Fearing, Vaze, 2014)

1. Uniform flight valuations: all flights are equally valued
   → Current setting: “a flight is a flight” paradigm

2. Sampled flight valuations: differentiated valuations, with identical mean valuation for all airlines
   → Setting where airlines provide preferences re: which flights to reschedule

3. Profit-based flight valuations: differentiated valuations, which approximate marginal profit contribution of each flight
   → Hypothetical setting where flight valuations are known (e.g., auction)
Overview of Results

<table>
<thead>
<tr>
<th>Theoretical results</th>
<th>Computational results</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Joint maximization of efficiency and equity</td>
<td></td>
</tr>
<tr>
<td>■ No network connection</td>
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<tr>
<td>■ Uniform flight valuations</td>
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<tr>
<td>■ Some scheduling conditions</td>
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<td>□ Conditions of an efficiency/equity trade-off</td>
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<tr>
<td>■ Differentiated flight schedules</td>
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<td>■ Differentiated network connectivities</td>
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<tr>
<td>■ Differentiated flight valuations</td>
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<tr>
<td>□ Maximizing efficiency alone does not maximize equity</td>
<td></td>
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<tr>
<td>□ Optimal equity at no loss in efficiency in current settings (uniform valuations)</td>
<td></td>
</tr>
<tr>
<td>□ Strong equity improvements even under differentiated flight valuations</td>
<td></td>
</tr>
<tr>
<td>■ Low price of equity</td>
<td></td>
</tr>
<tr>
<td>■ High price of efficiency</td>
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</table>
Results: Uniform Valuations

Maximizing efficiency alone does not maximize equity
Optimal equity at no, or small, efficiency loss in realistic cases

<table>
<thead>
<tr>
<th>$A_{\text{MAX}}$</th>
<th>$D_{\text{MAX}}$</th>
<th>Model</th>
<th>DAL</th>
<th>AAL</th>
<th>JBU</th>
<th>Others</th>
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Disutility: $\sigma_a = \frac{1}{|F_a|} \sum_{i \in F_a} |u_i|$
Overview of Results

Theoretical results

Joint maximization of efficiency and equity
- No network connection
- Uniform flight valuations
- Some scheduling conditions

Conditions of an efficiency/equity trade-off
- Differentiated flight schedules
- Differentiated network connectivities
- Differentiated flight valuations

Computational results

- Maximizing efficiency alone does not maximize equity
- Optimal equity at no loss in efficiency in current settings (uniform valuations)
- Strong equity improvements even under differentiated flight valuations
  - Low price of equity
  - High price of efficiency
# Results: Sampled Valuations

<table>
<thead>
<tr>
<th>Scenario</th>
<th>For variations in DAL’s flight valuations</th>
<th>For variations in AAL’s flight valuations</th>
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### Results: Profit-based Valuations

- Efficient solution achieves inequitable outcome
- Equitable solution results in similar disutilities across airlines
- High price of efficiency, low price of equity

<table>
<thead>
<tr>
<th>(A_{\text{MAX}})</th>
<th>(D_{\text{MAX}})</th>
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<th>(\delta^*)</th>
<th>(\Delta_0)</th>
<th>(\Delta^*)</th>
<th>(\text{DAL})</th>
<th>(\text{AAL})</th>
<th>(\text{JBU})</th>
<th>(\text{Others})</th>
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Outline

- Introduction
  - Motivation and Background
  - Problem of Inter-airline Equity
- Model Formulation and Solution Approach
- Results
  - Theoretical Results
  - Computational Results
- Conclusion
Conclusion

- Integration of inter-airline equity objectives in the modeling and optimization of airport scheduling interventions

**Modeling**

A multi-objective architecture based on efficiency, equity and on-time performance objectives

**Theoretical analysis**

 Guarantees of joint maximization of efficiency and inter-airline equity, and conditions of a trade-off

**Computational analysis**

Significant gains in inter-airline equity at no (or minimal) efficiency losses in realistic settings

**Practical Impact**

Incorporation of inter-airline equity objectives in scheduling and operating procedures in ATM
Next Steps

- Overall objective: Design mechanisms to make the outcomes of airport scheduling interventions consistent with airports’, airlines’ and passengers’ preferences

  → Toward a multi-stakeholder approach to airport scheduling interventions that balances centralized (airport) and distributed (airline) objectives
Thank you!