Robust Efficiency of Airline Resource Schedules

Lucian Ionescu
DoWoNO – Magdeburg 05/30/2013
Delays are a considerable Problem for Airlines

1.25 billion Euros overall costs due to delays in Europe

81 Euro on average per minute of delay in Europe

(Report worked out for the Performance Review Unit, EUROCONTROL, Brussels)
Minimizing the Real Costs of Airline Operations

- Robust Efficiency of Airline Resource Schedules

Real Costs

- Recovery Costs
- Planned Costs

High Utilization

High Robustness
Practical Goal Conflicts in Regular Daily Operations

**Robust Efficiency**
Construct schedules which...

**Cost-Efficiency**
...use resources at high utilization levels.

**Stability**
...absorb disruptions due to changes of environment.

**Flexibility**
...offer simple possibilities to react to disruptions.
Scope of the Project

- Delay Prediction Models
- Data Analysis

- Schedule Simulation
- Simulation

- Robust Scheduling
- Stochastic Optimization
Data Analysis
How do we realistically model Delays?
Knowledge Discovery in Databases (KDD)

Target: A Prediction Model for Flight Departure Delays

Historical Data → Data Analysis → Delay Prediction Model → Disruption Generator → Delay Scenarios

We do not need to know why but where and when delays occur.
Available Data

- 2.2 million real-world flight delay records
- Selected time span is 2003-2007
Slicing the Data using the Example of Daytime

Are these results repeatable when combining the dimensions?
Combining the Dimensions

Average delay per daytime differs by month!
Combining the Dimensions (2)

Average delay per daytime does not differ by workday!
• We have a high correlation between the first three moments (Mean, Standard Deviation, Skewness)

Correlation between Mean and SD

Adj-$R^2 = 0.8021$

Use the mean value as a location parameter for distributions?
Prediction Models for Delays

1. Build Decision Trees (Training Set)
2. Predict unknown Data (Validation Set)
3. Goodness-of-Fit can be tested by
   - Akaike Information Criterion (AIC)
   - Kullback-Leibler-Divergence (KLIC)

1. too generalized
2. 
3. overfitted
Simulation

How do we evaluate the Robustness of Schedules?
Evaluating Airline Resource Schedules by Simulation

• How will schedules perform in Operations?

• Regular Operations vs. Irregular Operations

• Simulated Recovery Actions
  – Delay Propagation / Delay Absorption
  – Swaps of Resources
  – Cancellations
  – Reserve Crews
  – Repositioning
  – Rescheduling

• Mutual impacts and interdependencies of Crew Pairings and Aircraft Rotations
Measuring the Delay Absorption Capacity of a Schedule

• How many delays can be absorbed by buffers during simulation?

• Model for propagation over several network layers, e.g. crew and aircraft

\[
\begin{align*}
    r_f &= \max\{ s_f^A, d_f + t_f \}, \quad \forall f \in F \\
    d_f &= \max\left\{ s_f^D, \max\left\{ r_{a(f)} + g_{a(f),f}^a, r_{c(f)} + g_{c(f),f}^c \right\} \right\} + X_f, \quad \forall f \in F \\
    D_f &= r_f - s_f^A, \quad \forall f \in F \\
    R_f &= D_f - X_f, \quad \forall f \in F
\end{align*}
\]

Simulating rule-based Recovery for Crew and Aircraft

Aircraft Only (AC)

\[ g_{b,s}^a(b) \]

\[ s^a(b) \]

Crew Only (CR)

\[ g_{b,s}^c(b) \]

\[ s^c(b) \]

Crew Changes Aircraft (CCA)

\[ g_{b,s}^c(b) \]

\[ s^c(b) \]

\[ g_{b,s}^a(b) \]

\[ s^a(b) \]

Crew Follows Aircraft (CFA)

\[ g_{b,s}^c(b) \]

\[ s(b) \]

\[ g_{b,s}^a(b) \]

\[ s(b) \]
Simulating rule-based Recovery for Crew and Aircraft (2)

**CFA-CFA**

- \( g^c_{b,s^e(b)} \)
- \( g^a_{b,s^o(b)} \)
- \( g^c_{m,s^e(m)} \)
- \( g^a_{m,s^o(m)} \)

**CFA-CCA**

- \( g^c_{b,s^e(b)} \)
- \( g^a_{b,s^o(b)} \)
- \( g^c_{m,s^e(m)} \)
- \( g^a_{m,s^o(m)} \)

Robust Efficiency of Airline Resource Schedules
Robust Scheduling
How do we increase the Robustness of Schedules?
Delay Risk Evaluation of Flights

- Risky connections between flights
- Follow-ons of flights may have different contexts

### Aircraft Change with History (Flight1, Flight9)

- **Rotation A**
  - Flight 1
  - Flight 2
  - Flight 3

- **Rotation B**
  - Flight 8
  - Flight 9
  - Flight 10

- **Rotation C**
  - Flight 15
  - Flight 16
  - Flight 17

**Sequence (1;9) (9;17) propagates a Delay**

### Aircraft-Change without History

- **Rotation A**
  - Flight 1
  - Flight 2
  - Flight 3

- **Rotation B**
  - Flight 8
  - Flight 9
  - Flight 10

- **Rotation C**
  - Flight 15
  - Flight 16
  - Flight 17

**Sequence (8;9) (9;17) propagates no Delay**
Increasing Stability – Integrated Solution Approach

**Crew Scheduling**

<table>
<thead>
<tr>
<th>Route 1</th>
<th>Route 2</th>
<th>Route 3</th>
<th>Route 4</th>
<th>∑</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg 123</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Leg 435</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Leg 52</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Leg 344</td>
<td></td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Check termination criteria
2. Increase Penalty Costs

**Aircraft Routing**

<table>
<thead>
<tr>
<th>Route 1</th>
<th>Route 2</th>
<th>Route 3</th>
<th>Route 4</th>
<th>∑</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg 123</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Leg 435</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Leg 52</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Leg 344</td>
<td></td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Preprocessing**

- Aircraft Rotations
- Delay Scenarios

**Data preparation**

**Column Generation**

- Pricing Problem
- Restricted Master Problem

**Propagation Module**

- Costs
- Sequences
- Propagation
- Evaluation

**IP Phase**

- Model
- IP Solver


Motivation for Flexibility by Swap Opportunities

- High marginal costs for stability
- Uncertainty of the real delays during scheduling
- Do swap opportunities provide a reasonable enhancement to stable scheduling?
Increasing Flexibility by Swap Opportunities

- If a follow-on \([f, s(f)]\) is likely to be disrupted in a specific context \(h\)
  - Insert penalty variable \(z \in \{0,1\}\):
    \[
    \frac{|\omega \in \Omega: \delta_{[f s(f)]_h} > t_\delta|}{|\Omega|} \cdot c \cdot z
    \]
  - Insert constraints for all pairings containing this follow-on:
    \[
    x - \sum_i y_i - z \leq 0, \quad \forall x \in P, [f, s(f)]_h \in p
    \]

Symbols
- \(x\): pairing containing a risky follow-on
- \(y\): pairings that offer a swap opportunity for \(x\)
- \(\omega \in \Omega\): delay scenarios
- \(t_\delta\): delay tolerance
- \(c\): cost multiplicator
Increasing Flexibility – Integrated Solution Approach

Crew Scheduling

1. Check termination criteria
2. Increase Penalty Costs

Preprocessing
- Aircraft Rotations
- Delay Scenarios

Column Generation
- Pricing Problem
- Restricted Master Problem
- Constraint Generation

Aircraft Routing

Duals

Routes

Table:

<table>
<thead>
<tr>
<th>Route 1</th>
<th>Route 2</th>
<th>Route 3</th>
<th>Route 4</th>
<th>∑</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg 123</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Leg 435</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Leg 52</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Leg 344</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Duals

Routes

Table:

<table>
<thead>
<tr>
<th>Route 1</th>
<th>Route 2</th>
<th>Route 3</th>
<th>Route 4</th>
<th>∑</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg 123</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Leg 435</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Leg 52</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Leg 344</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

1. Check termination criteria
2. Increase Penalty Costs

Robust Efficiency of Airline Resource Schedules
Summary & Outlook

Explorative Data Analysis ✓
Decision Tree Modeling ×
Propagation Model ✓
Rule-based Recovery ✓
Stochastic Modeling ✓
Column Generation ✓

Delay Prediction Models
Data Analysis

Schedule Simulation
Simulation

Robust Scheduling
Stochastic Optimization

Put it all together and start final tests...?
Thank you for your attention!

Robust Efficiency of Airline Resource Schedules

Lucian Ionescu
Dipl. Wirt.-Inf.
Information Systems Department
School of Business Administration
Freie Universität Berlin

mail: lucian.ionescu@fu-berlin.de
phone: +49 (30) 838 54057