Robust and Recoverable Maintenance Routing Schedules

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Introduction
Some numbers

- Huge economical impact\(^1\)
  - $1.7 billion loss of revenue for first week
  - $400 million a day for the first 4 days
  - 1.2 million affected passengers / day

- Spill out due to disrupted / blocked passengers

\(^1\) www.iata.org/pressroom, Press release No 15, 21 April 2010
Why robustness appeals for airline scheduling

- Airlines have low profitability
  - < 2% profit margin (US, 2007)

- High delays and implied delay costs
  - 4.3 Billion hours delay (US, 2008)
  - $41 Billion delay costs (US, 2008)

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2 Your flight has been delayed again (2008), Joint Economic Committee
www.jec.senate.gov
Worse is still to come

- **Growth:**
  - 2.5% more flights annually
  - Every 1% additional flights incur an additional 5% delays (Schaefer et al., 2005)
  - => Yearly increase of delays of 12.5%

- Europe: 50% of flights in 2030 depart or land at congested airports

- Airlines must react – we try to help
  - Improve operations in a congested network
Questions

- Are these (potential) costs considered at the planning phase?

- What would change?
Outline

- Optimization under uncertainty
  - In general
  - In airline scheduling

- Robust Maintenance Routing Problem
  - Definitions
  - “Robust” and “ Recoverable” models

- Simulation – preliminary results
  - Methodology to evaluate and compare robust solutions
  - Preliminary a priori and a posteriori results
General Optimization Problems

- Planning
- Observing
- Adapting
Other meanings of robustness

- Robustness is also used as a
  - “stability” measure
    - Absorbs disruptions
    - Does not require recovery
  - “flexibility” measure
    - Facilitates recovery
    - Reduces recovery costs

- We differentiate
  - ROBUSTNESS vs RECOVERABILITY
Our objectives

- Examine how robustness proxies and performance metrics are correlated

- Robustness proxies are structural a priori properties of the schedule
  - Expected propagated delay
  - Total slack in aircraft routes
  - Total passenger connection time
  - ...

- Performance metrics are a posteriori metric
  - Observed propagated delay
  - Total passenger delay
  - Recovery costs
  - ...
Airline Scheduling: An iterative Process

-60 to -6 months
- Route Choice

-6 months
- Fleet Assignment

-6 to -2 months
- Maintenance Routing

-6 to -2 months
- Crew Pairing

-2 to -1 months
- Crew Rostering

Day of Operations (Disruption Management)

Revenue Management (passenger booking)

-6 months to day D
Robust Maintenance Routing Problem (MRP)

- Deterministically known
  - Original schedule (1 maintenance route/aircraft)
- To determine
  - New routes for each aircraft
  - And/or new departure times for each flight
- Constraints
  - Maintenance routes are feasible for each aircraft
  - All flights are covered exactly once
  - Each flight is retimed by at most $\pm 15$
  - Total retiming of all flights of at most $C$ minutes (500 or 1000)
- Objective
  - Optimize robustness proxy
Used Uncertainty Feature Optimization (UFO)\(^3\) Models

- Use different UFs:
  - IT: maximize total idle time
  - MIT: maximize sum of minimal idle time of each route
  - CROSS: maximize nbr plane crossings
  - PCON: maximize passenger idle connection time
  - MinPCON: maximize minimal PCON

- Solved with CG algorithm (COIN-OR – BCP package)
  (Eggenberg et al., 2010)

\(^3\) Eggenberg et al. (2010b), *Uncertainty Feature Optimization: a implicit paradigm for problems with noisy data* (accepted for publication in Networks in June, 2010)
Robustness in airline scheduling – existing approach

Robust airline schedules are:

- Operationally more efficient
- Less sensitive to delay
  - i.e. with reduced delay propagation
Delay Propagation

- 2 types of delays for each flight
  - **Independent** delay: generated during a flight
    - At any stage (taxi, runway, landing,...)
  - **Propagated** delay
    - Delay due to previously delayed flight
    - Propagation is downstream (possibly to several flights)

- \[ \text{Del}(f) = \text{ID}(f) + \text{PD}(f) \]

- Robustness proxy = expected PD
  - To be minimized
Benchmark

Models from literature

- **EPD**: minimize expected propagated delay (Lan et al., 2006)
  - No retiming
  - Allow only plane swaps

- **EPD2**: minimize expected propagated delay (AhmadBeygi et al., 2008)
  - No plane swaps
  - Allow for retiming by ± 15 minutes
  - Total retiming bounded (500 or 1000 minutes)

Solved with same CG algorithm (COIN-OR – BCP package) (Eggenberg et al., 2010)
Measuring Recoverability: Methodology

- Solve Robust MRP using different robust models

- Simulate different disruption scenarios
  - Differentiate *independent* and *propagated* delay
  - Update propagated delay according to schedule

- Solve the recovery problem
  - Using same recovery algorithm (Eggenberg et al., 2010)

- Evaluation with external recovery cost evaluator
  - Data and cost-evaluator provided by the *ROADEF Challenge 2009* (challenge.roadef.org/2009)
Scenario Generation

- Use historical data of 2 year and separate it by season
  - Winter (October – March)
  - Summer (April – September)

- For each airport, we have arrival and departure delays

- Generate delays for flight f from A to B drawing from empirical distribution by

\[
\text{Del} = 0.5 \times [\text{depDel}(A) + \text{arrDel}(A)]
\]
Generated schedules

- UFO solutions are the same for Winter and Summer
  - UFs are non-predictive models

- EPD solutions are different
  - Solution depends on estimated delay distribution
  - Based on average delay of each flight, which is different in Winter and in Summer
Notation for models

- **Model of** Lan et al., 2006 (minimize expected propagated delay)
  - EPD_W: use average delay of Winter
  - EPD_S: use average delay of Summer

- **Model of** AhmadBeygi et al., 2008 (minimize expected propagated delay)
  - EPD2_W: use average delay of Winter
  - EPD2_S: use average delay of Summer

- **Model name + “_XXX”**
  - XXX is the value of C (maximum allowed retiming in min.)
Simulation Overview – UFO solutions

<table>
<thead>
<tr>
<th>Scenario/Schedules</th>
<th>Winter Schedules</th>
<th>Summer Schedules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Scenarios</td>
<td>NEUTRAL</td>
<td>NEUTRAL</td>
</tr>
<tr>
<td>Summer Scenarios</td>
<td>NEUTRAL</td>
<td>NEUTRAL</td>
</tr>
</tbody>
</table>
# Simulation Overview – EPD and EPD2

<table>
<thead>
<tr>
<th>Scenario/Schedules</th>
<th>EPD_W &amp; EPD2_W</th>
<th>EPD_S &amp; EPD2_S</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Winter Scenarios</strong></td>
<td>OK</td>
<td>WRONG DISTRIBUTION</td>
</tr>
<tr>
<td><strong>Summer Scenarios</strong></td>
<td>WRONG DISTRIBUTION</td>
<td>OK</td>
</tr>
</tbody>
</table>
Comparison Criteria

- Compare a priori AND recovery statistics
- A priori proxies (= objective functions of different models)
  - UF values
  - EPD
- Recovery statistics
  - Recovery costs
  - Aircraft statistics
    - Total aircraft delay
    - Canceled flights
  - Passenger statistics
    - Total / average passenger delay
    - Rerouted passengers
    - Canceled passengers
Used Instance – Derived from instance A01 of the Roadef Challenge 2009

- 608 flights
- 85 aircraft
- 36010 passengers
- 1 day
Robustness Proxies: Correlations

<table>
<thead>
<tr>
<th>WINTER</th>
<th>IT</th>
<th>MIT</th>
<th>PCON</th>
<th>EPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIT</td>
<td>0.293</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCON</td>
<td>0.851</td>
<td>0.251</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>EPD</td>
<td>-0.318</td>
<td>0.458</td>
<td>-0.04</td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SUMMER</th>
<th>IT</th>
<th>MIT</th>
<th>PCON</th>
<th>EPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIT</td>
<td>0.293</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCON</td>
<td>0.865</td>
<td>0.248</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>EPD</td>
<td>-0.392</td>
<td>0.381</td>
<td>-0.082</td>
<td>X</td>
</tr>
</tbody>
</table>

Bold values are significant with confidence level $\alpha = 0.001$
Performance Profiles
Over all 25 instances (Winter only)
Performance Profiles
Over all 25 instances (Summer only)
Recovery Performance Metrics – Overall (Winter + Summer)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Original</th>
<th>IT_1000</th>
<th>MIT_500</th>
<th>PCON_1000</th>
<th>EPD2_W_1000</th>
<th>EPD2_S_1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rec. Costs [k€]</td>
<td>249.2</td>
<td>197.4</td>
<td>241.1</td>
<td>249.6</td>
<td>248.6</td>
<td>239.8</td>
</tr>
<tr>
<td>Nbr Canc. Pax</td>
<td>137</td>
<td>104</td>
<td>123</td>
<td>137</td>
<td>139</td>
<td>129</td>
</tr>
<tr>
<td>Avg. Pax delay [min]</td>
<td>33.42</td>
<td>31.55</td>
<td>34.6</td>
<td>33.33</td>
<td>32.97</td>
<td>31.80</td>
</tr>
<tr>
<td>Nbr Cancelled Flights</td>
<td>2.98</td>
<td>2.36</td>
<td>3.08</td>
<td>2.98</td>
<td>2.84</td>
<td>2.94</td>
</tr>
<tr>
<td>Nbr Delayed Flights</td>
<td>53.7</td>
<td>50.6</td>
<td>55.2</td>
<td>53.8</td>
<td>53.1</td>
<td>45.8</td>
</tr>
<tr>
<td>Propagated Delay [min]</td>
<td>9405</td>
<td>7632</td>
<td>9732</td>
<td>9382</td>
<td>9069</td>
<td>6108</td>
</tr>
</tbody>
</table>
Recovery Performance Metrics: Correlations

<table>
<thead>
<tr>
<th>Overall</th>
<th>Recovery Costs</th>
<th># Cancelled Pax</th>
<th>Average Pax Delay</th>
<th># Cancelled Flights</th>
<th>Propagated Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery Costs</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># Cancelled Pax</td>
<td>0.961</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Pax Delay</td>
<td>0.683</td>
<td>0.621</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td># Cancelled Flights</td>
<td>0.786</td>
<td>0.779</td>
<td>0.469</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Propagated Delay</td>
<td>0.548</td>
<td>0.467</td>
<td>0.815</td>
<td>0.427</td>
<td>X</td>
</tr>
</tbody>
</table>

Bold values are significant with confidence level $\alpha = 0.001$
Recoverability: Correlation between a priori proxies and performance metrics

<table>
<thead>
<tr>
<th>Overall</th>
<th>Total Slack IT</th>
<th>Minimum Slack MIT</th>
<th>Passenger Connection Time PCON</th>
<th>Expected Propagated Delay EPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery Costs</td>
<td>-0.135</td>
<td>-0.021</td>
<td>-0.135</td>
<td>0.092</td>
</tr>
<tr>
<td># Cancelled Pax</td>
<td>-0.135</td>
<td>-0.016</td>
<td>-0.134</td>
<td>0.082</td>
</tr>
<tr>
<td>Average Pax Delay</td>
<td>-0.084</td>
<td>0.058</td>
<td>-0.086</td>
<td>0.137</td>
</tr>
<tr>
<td># Cancelled Flights</td>
<td>-0.072</td>
<td>-0.014</td>
<td>-0.073</td>
<td>0.056</td>
</tr>
<tr>
<td>Propagated Delay</td>
<td>-0.155</td>
<td>0.171</td>
<td>-0.152</td>
<td>0.409</td>
</tr>
</tbody>
</table>

Bold values are significant with confidence level $\alpha = 0.05$
Conclusions

- We propose a methodology to evaluate the relevance of robustness proxies.
- We show that these proxies are inter-correlated and indeed improve the recoverability of the schedule.
- We show that expected propagated delay:
  - is not a good indicator for recoverability
  - is sensitive to errors in the uncertainty model.
Open Research Directions

- Exploit the correlation structure to combine the different robustness proxies

- Explore correlations on wider instance set with disruptions including
  - Imposed flight cancellations
  - Aircraft unavailability periods
  - Airport capacity modifications

- Study other proxies
  - Possible way to partially integrate downstream operational decisions

- Evaluate performances using other recovery algorithms
  - To identify whether correlations are due to the recovery algorithm or if they are globally improving recoverability
The End

Thank you for your attention!