Integrated disruption management and flight planning to trade off delay and fuel burn

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Irregular operations and recovery

- Inherent uncertainty in airline operations
  - Delays, disruptions

- Disruption management and Operations recovery
  - *Reactive* approach to mitigating delay
  - Manages disruptions during execution of operations
  - Minimize additional operating costs due to delay

- Air delays cost $40 B in 2007
  - $19B to airlines
  - $9-12B to passengers

- 74.04% on-time in 2008 (83% in 2003)
Disruption management and Flight Planning

- **Disruption management**: get plan back on schedule with minimum cost
  - Network interactions: aircraft, crew and passengers
  - Swaps, re-timings, cancelations, etc.
  - More flexibility => better recoverability

- **Flight planning**: find best route (3D) and speed to minimize time + fuel costs
  - Mechanisms: Route and *speed change*
  - Travel time, arrival time and fuel burn cost
  - Impact block time and arrival time of flight
Opportunity: Flight speed changes and ground holds

Original flight plan for flight $a$

Alternative flight plans for flights $a, b, c, d$
Concept: Integration adds flexibility

- Re-allocate slack in block and ground times in the network
  - Recovery mechanisms
    - Swaps, cancelations, re-timing, reserve crew
  - Flight planning mechanisms
    - Speed changes and ground holds for passenger connections

- **Goal:** Decrease disruption costs and dynamically optimize tradeoffs between
  - flight and passenger delay costs
  - Fuel burn costs
• Flight Planning and choosing the right speed
  – Limitations of current practice
• Disruption management - re-arrangement of slack
  – Re-allocation of slack through integration
• Taking a dynamic and network perspective
• Mathematical model
• Computational results
• Summary
Flight Planning and Cost-Index (CI)

Cost Index: (Historical) cost of time/cost of fuel = 500
OR speed-based (431 min)

Rule of thumb
Max CI = 300

‘Normal’
CI=30

Cost Index = \( \frac{\text{dollars / min}}{\text{dollars / kg}} = \frac{\text{kg}}{\text{min}} \)
Amount of fuel (kg) worth burning to save one minute of time

CI: historically derived, ‘static’
Problem: cost of time non-linear

- *Current* airline system state not accounted for
  - *Network* perspective missing
  - Current practice uses a constant metric for entire network
  - Delay propagation, passenger connections not explicitly modeled

- The ‘optimal’ CI/speed to use is based on aircraft and passenger connectivity based on current network state
  - Interest from airlines with significant long-haul operations
Fuel-Time cost tradeoff dependent on system state

Optimal CI/speed based on current system state
Flight time - delay cost relationships

- Disruption scenario: Departure delay = 1 hour

Airline rules of thumb can be far from optimal
Dynamic, network perspectives

- **Dispatchers and pilots:**
  - Flight by flight view
  - Choice of CI far from optimal

- **Ops controlers:**
  - Network view
  - Swaps, cancelations, delays
  - More schedule flexibility improves recoverability
Enhanced recovery: Modeling framework

Planned schedule
Current disrupted state
Passenger itineraries
Flight holds Θ allowed

Possible flight plans (all flights)
1. Fuel burn
2. Flying time

Integrated Flight Planning and Disruption Management

All flights

Current flights +disruptions (State of the system)
Flights departing in 0.5-1 hour (optimize flight plans)
Flights departing after 1 hour (re-optimize before departure)

Optimization point

Time

Optimized recovery decisions
1. Optimized flight plans
2. Re-timing
3. Swaps
4. Cancelations
5. Fuel burn
Modeling Architecture

Aircraft connections impacted by swaps, re-timing, *speed changes*

Passenger connections impacted by speed changes, *holding flights*
Model

- Disrupted scenario:
  - Long-haul flight disrupted, departs late from origin
- Identify non-propagating time, or set of flights impacted due to connectivity
  - Aircraft and passenger connectivity
- Solve model for flight planning and recovery
- Assumptions:
  - Cannot depart before the actual (observed) departure time
  - En-route delays not taken into account
Notation

- **F**: Set of flight legs \( f \) operated by the airline
- **A**: Set of aircraft \( a \) available to the airline
- **\( C_f \)**: Set of copies of flight \( f \). **Copies are flight plans or delayed flights.** The set also contains the original flight plan and flight plans with new equipment types
- **\( G_a \)**: Set of ground arcs in the aircraft flow network for aircraft \( a \)
- **\( N_a \)**: Set of nodes in the aircraft flow network for aircraft \( a \)
- **\( G_p \)**: Set of ground arcs in the pax flow network for pax itinerary \( p \)
- **\( N_p \)**: Set of nodes in pax flow network for pax itinerary \( p \)
- **\( n^-, n^+ \)**: Set of incoming and outgoing arcs to node \( n \) in time-space network
- **\( M \)**: Set of passenger itineraries \( m \)
- **\( p_m \)**: Number of pax on itinerary \( m \)
- **\( c^k_f \)**: Cost of operating copy \( k \) of flight \( f \); including fuel, delay and swap costs
- **\( \delta(f_1, f_2, m) \)**: indicator parameter; 1 if \( f_1, f_2 \) connect in itinerary \( m \)
- **\( c_g \)**: Cost of using ground arc \( g \)
- **\( c_f \)**: Cost of cancelling flight \( f \)
- **\( s^n_a \)**: Supply of aircraft \( a \) at node \( n \). A demand is specified as a negative supply.
- **\( x^k_f \)**: 1 if copy \( k \) of flight leg \( f \) is present in solution, 0 otherwise
- **\( y_g \)**: 1 if ground arc \( g \) is present in solution (applies to aircraft or pax networks)
- **\( z_f \)**: is 1 if flight \( f \) is cancelled in the solution and 0 otherwise
Aircraft and Passenger Recovery Formulation

\[ \text{Min} \sum_{f \in F} \sum_{k \in C_f} c_f^k x_f^k + \sum_{p \in P} c_p^r \rho_p^r \]

s.t.

\[ \sum_{k \in C_f} x_f^k + z_f = 1 \quad \forall f \in F \]

\[ \sum_{g \in n^-} y_g + \sum_{(f,k) \in n^-} x_f^k + s_a^n = \sum_{g \in n^+} y_g + \sum_{(f,k) \in n^+} x_f^k \quad \forall n \in N \]

\[ \sum_{r \in R(p)} \rho_p^r = n_p \quad \forall p \in P \]

\[ \sum_{p \in P} \sum_{r \in R(p)} \delta_f^r \rho_p^r \leq \text{Cap}_f (1 - z_f) \quad \forall f \in F \]

\[ x_f^k \in \{0,1\} \]

\[ z_f \in \{0,1\} \]

\[ \rho_p^r \in Z^+ \]

\[ y_g \geq 0 \]

Fuel + pax delay cost

Flight cover/ cancel

Aircraft flow balance

Passenger flow balance

Plane capacity

Integrality
Model capabilities

- Re-optimize pre-departure of each flight
- Allow/disallow swapping of aircraft within a fleet family
- Allows capture of maintenance constraints
  - If some planes have to be maintained today, do not allow swaps
- Capture passenger re-accommodations
Aircraft and Passenger Recovery

• Solving the full aircraft and passenger recovery model is hard in real-time
• Use a simpler model that captures passenger connectivity
  – Connections within the propagation boundary
  – Minimize passenger disruptions while allowing small deviation in aircraft recovery costs
  – Actual realized passenger costs calculated by implementing solution on Jeppesen’s GUI, which gives estimate of re-accommodation costs
Enhanced recovery with Fuel burn-
Passenger disruption trade-offs

\( \text{Min} \sum_{f \in F} \sum_{k \in C_f} (c^k_f + s^k_f + d^k_f)x^k_f + \sum_{f \in F} c_f z_f + \sum_{p \in P} c_p n_p \lambda_p \)

s.t.
\( \sum_{k \in C_f} x^k_f + z_f = 1 \quad \forall f \in F \)
\( \sum_{g \in n^-} y^k_g + \sum_{(f,k) \in n^-} x^k_f + s^n_f = \sum_{g \in n^+} y^k_g + \sum_{(f,k) \in n^+} x^k_f \quad \forall n \in N_a \)
\( x^I_T(p,1) + \sum_{m \in MC(p,IT(p,1),k)} x^m_{IT(p,2)} - \lambda_p \leq 1 \quad \forall k \in C_{IT(p,1)}, k \neq 0 \)
\( \lambda_p \geq z_f \quad \forall f \in IT(p), \forall p \in P \)
\( x^k_f \in \{0,1\} \)
\( z_f \in \{0,1\} \)
\( \lambda_p \in \{0,1\} \)
\( y_g \geq 0 \)

Fuel + swap + delay cost + pax disruption cost
Flight cover/cancel
Aircraft balance
Passenger misconnects
Integrality
Solution time capped at 2 min
Solution structure

- Dep delay 50 mins
- CI 900 Catch-up 40 mins
- Hold 15 mins 22 misconnects from Flight 030 avoided
- CI 300: no need to speed up too much
- Arrival delay 35 mins
Computational experiments

- Disruptions into hub airport
  - Flights delayed going into hub
  - Focus on long-haul flights
- 60 scenarios, 3 months of historic data
  - Grouped by severity of disruption
- Optimize flight plans pre-departure each flight
- Compare via simulation:
  - Baseline disruption management
  - Integrated disruption management + flight planning
Improvements in multiple delay metrics

**Pax misconns reduced [%]**

- Small: 100%
- Medium: 90%
- Large: 80%
- Very Large: 70%
- Total: 60%

**Fuel Savings per operated LH flight [%]**

- Small: -0.5%
- Medium: -0.4%
- Large: -0.3%
- Very Large: -0.2%
- Total: -0.1%

**OTP improvement [%]**

- Small: 10%
- Medium: 8%
- Large: 6%
- Very Large: 4%
- Total: 2%

**Total cost savings [%]**

- Small: 0%
- Medium: 2%
- Large: 4%
- Very Large: 6%
- Total: 8%
Improvements in multiple delay metrics

**Pax misconnects reduced [%]**

**Fuel burn per LH flight [%]**

**OTP improvement [%]**

**Total airline cost savings [%]**
Savings significant for large disruptions

- **Low and medium levels of disruption:**
  - Slack in system + flight holds helps absorb disruptions
  - Large % of flights can be slowed down
  - 60-98 % of passenger misconnections saved

- **Large and very-large disruptions:**
  - Delay *propagation* controlled
  - Swap opportunities increased, cancelations decreased
  - 57-81% decrease in passenger misconnects
  - Cost savings to airline: 2% for large disruptions, 18% for very large disruptions
Enhanced recovery models decrease overall delays and costs

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<thead>
<tr>
<th></th>
<th>Enhanced recovery: don’t hold connecting flights</th>
<th>Enhanced recovery: hold connecting flights up to 15 min</th>
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</thead>
<tbody>
<tr>
<td>Passenger misconnections decreased</td>
<td>66.4%</td>
<td>83.3%</td>
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<tr>
<td>Fuel burn (CO₂) increase</td>
<td>0.155%</td>
<td>0.152%</td>
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<tr>
<td>Passenger delay costs decreased</td>
<td>58.2% ($17.5 M/60 days)</td>
<td>77.5% ($17.9M /60 days)</td>
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<tr>
<td>OTP (traditional recovery 88%)</td>
<td>95%</td>
<td>95%</td>
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<tr>
<td>Total airline cost savings</td>
<td>5.9%</td>
<td>5.7%</td>
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Extensions and Future work

• Dynamic airline scheduling to match passenger demand
  – Tradeoffs between schedule, passenger revenue and fuel burn

• Re-routing under airport/airspace congestion
  – Flight planning to enhance slot/route availability and relationship to fuel burn