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

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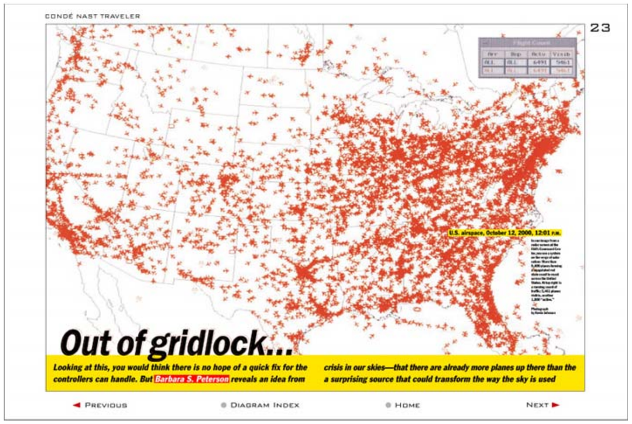
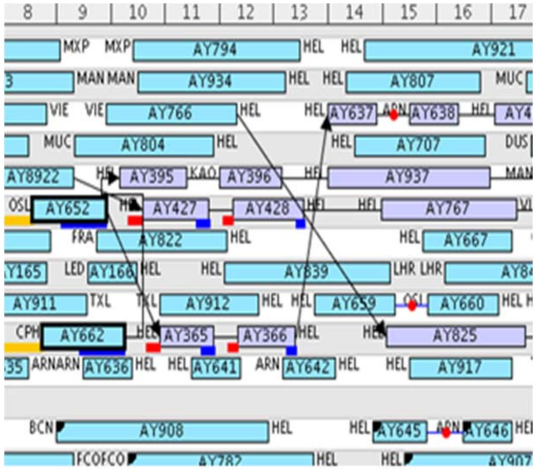
Irregular operations and recovery

- 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)

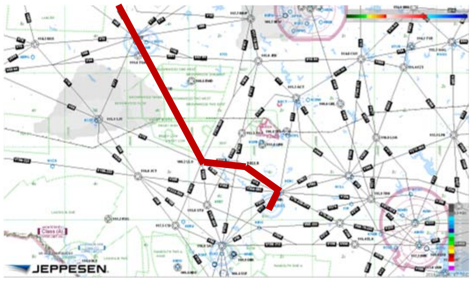


Disruption management and Flight Planning

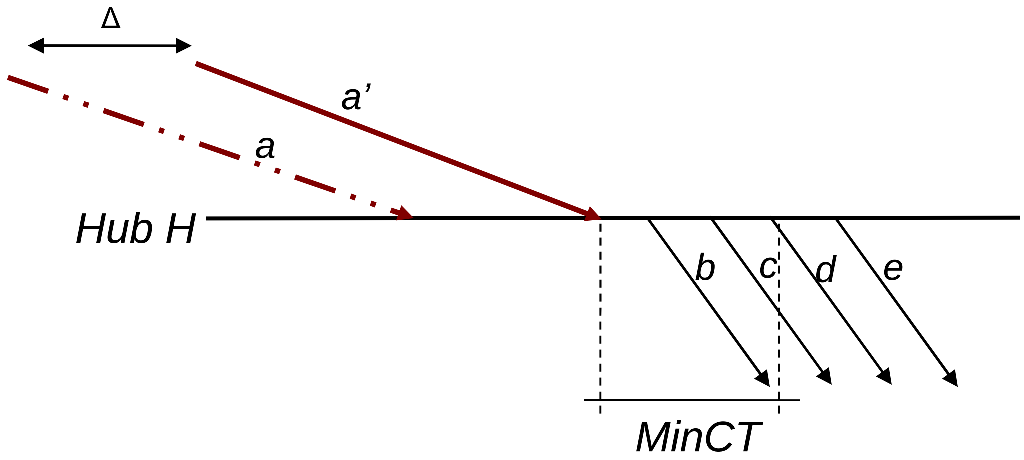
- *Disruption management*: get plan back on schedule with minimum cost
  - Network interactions: aircraft, crew and passengers
  - Swaps, re-timings, cancelations, etc.
  - More flexibility => better recoverability



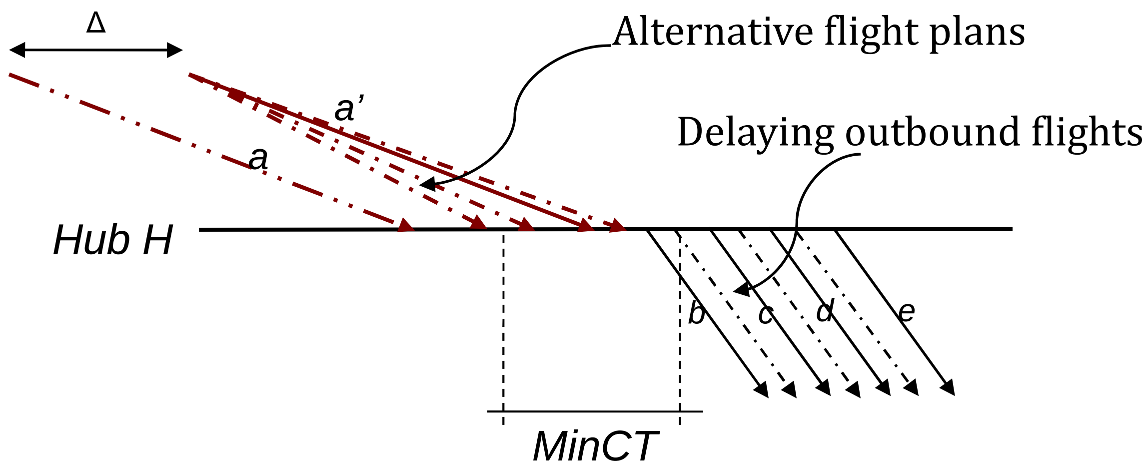
- *Flight planning*: find best route (3D) and speed to minimize time + fuel costs
  - Mechanisms: Route and *speed change*
  - Travel time, arrival time and fuel burn cost
  - Impact block time and arrival time of flight



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

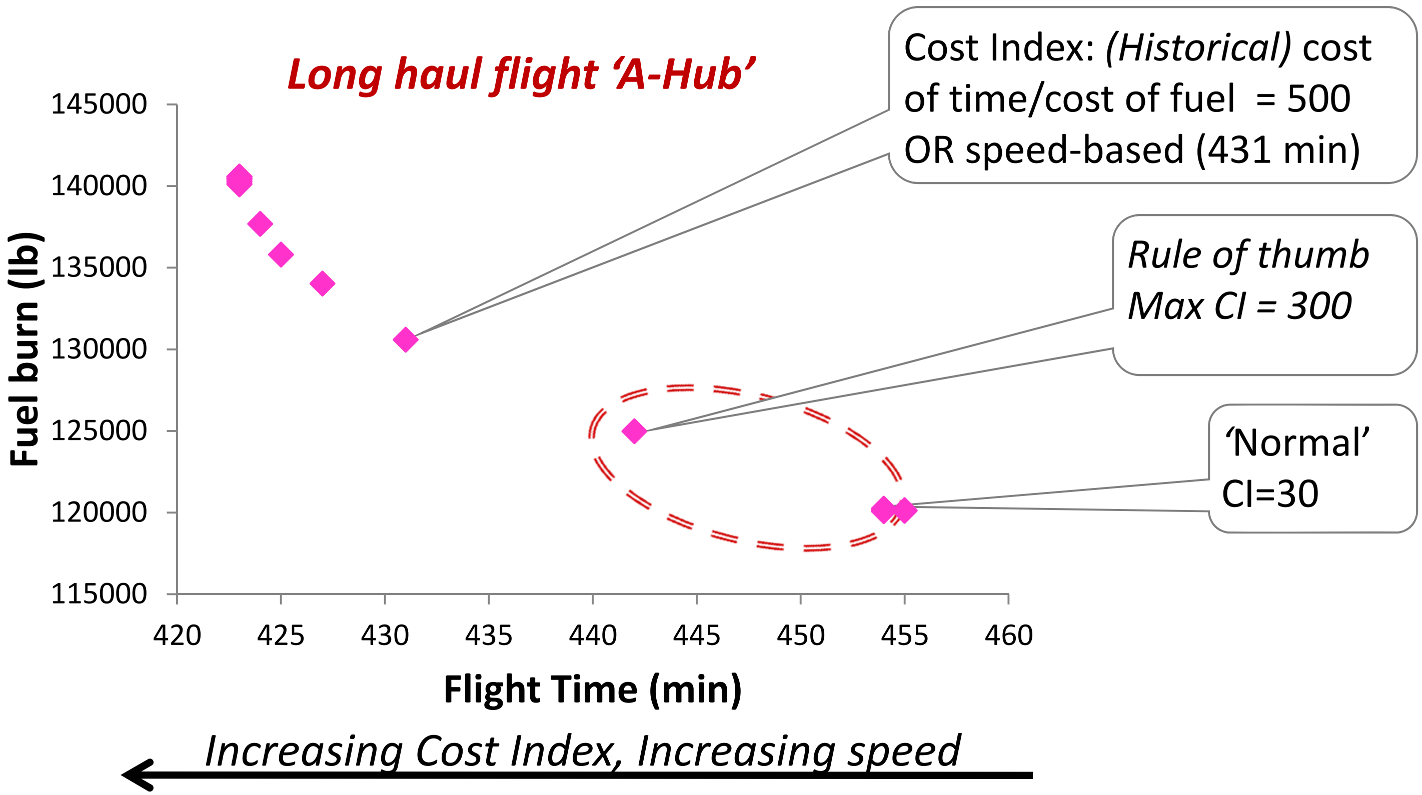
- Re-allocate slack in block and ground times in the network
  - Recovery mechanisms
    - Swaps, cancelations, re-timing, reserve crew
  - Flight planning mechanisms
    - Speed changes and ground holds for passenger connections

- *Goal:* Decrease disruption costs and dynamically optimize tradeoffs between
  - flight and passenger delay costs
  - Fuel burn costs

Agenda

- 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*)



$$\text{Cost Index} = \frac{\text{dollars / min}}{\text{dollars / kg}} = \frac{\text{kg}}{\text{min}}$$

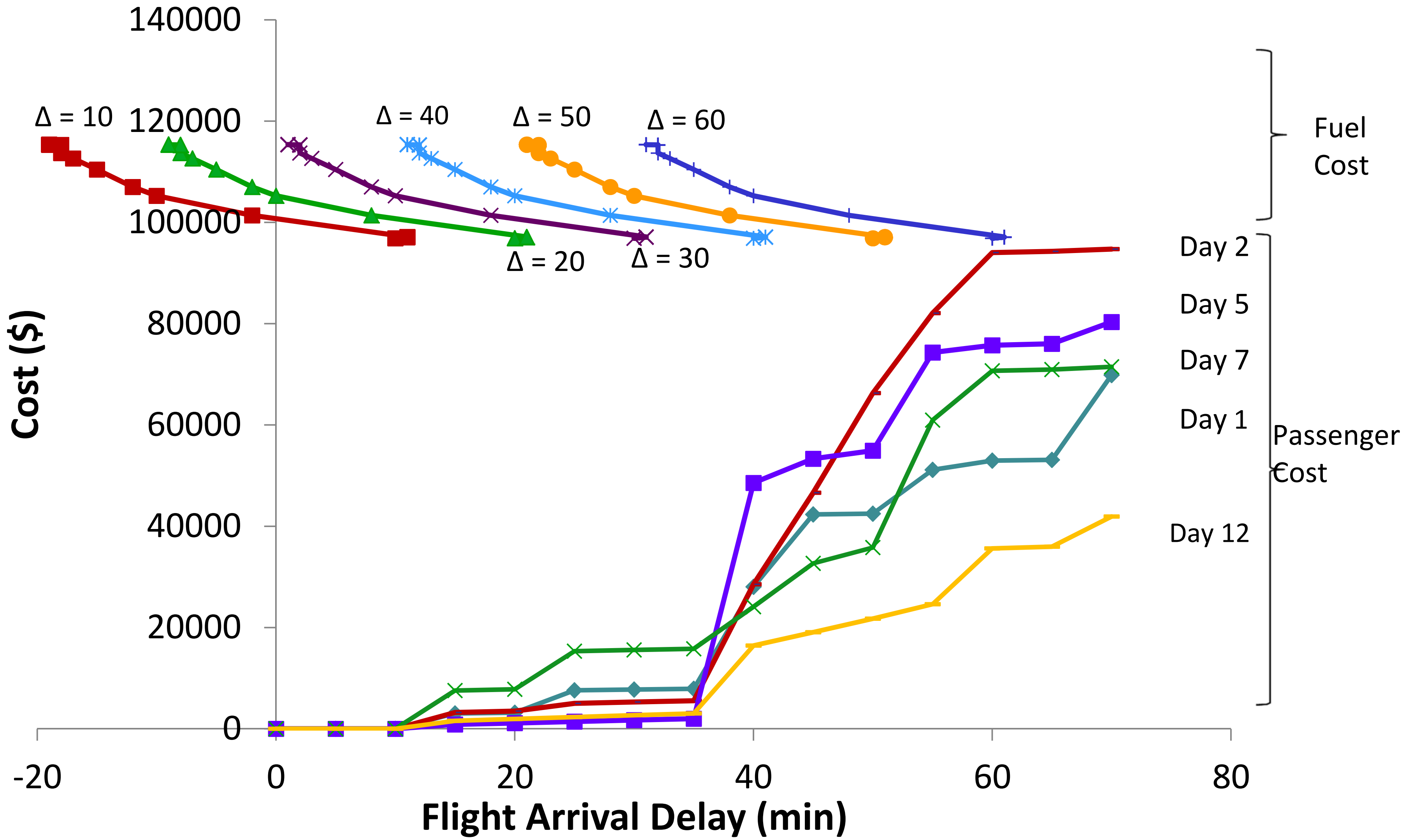
Amount of fuel (kg) worth burning to save one minute of time

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

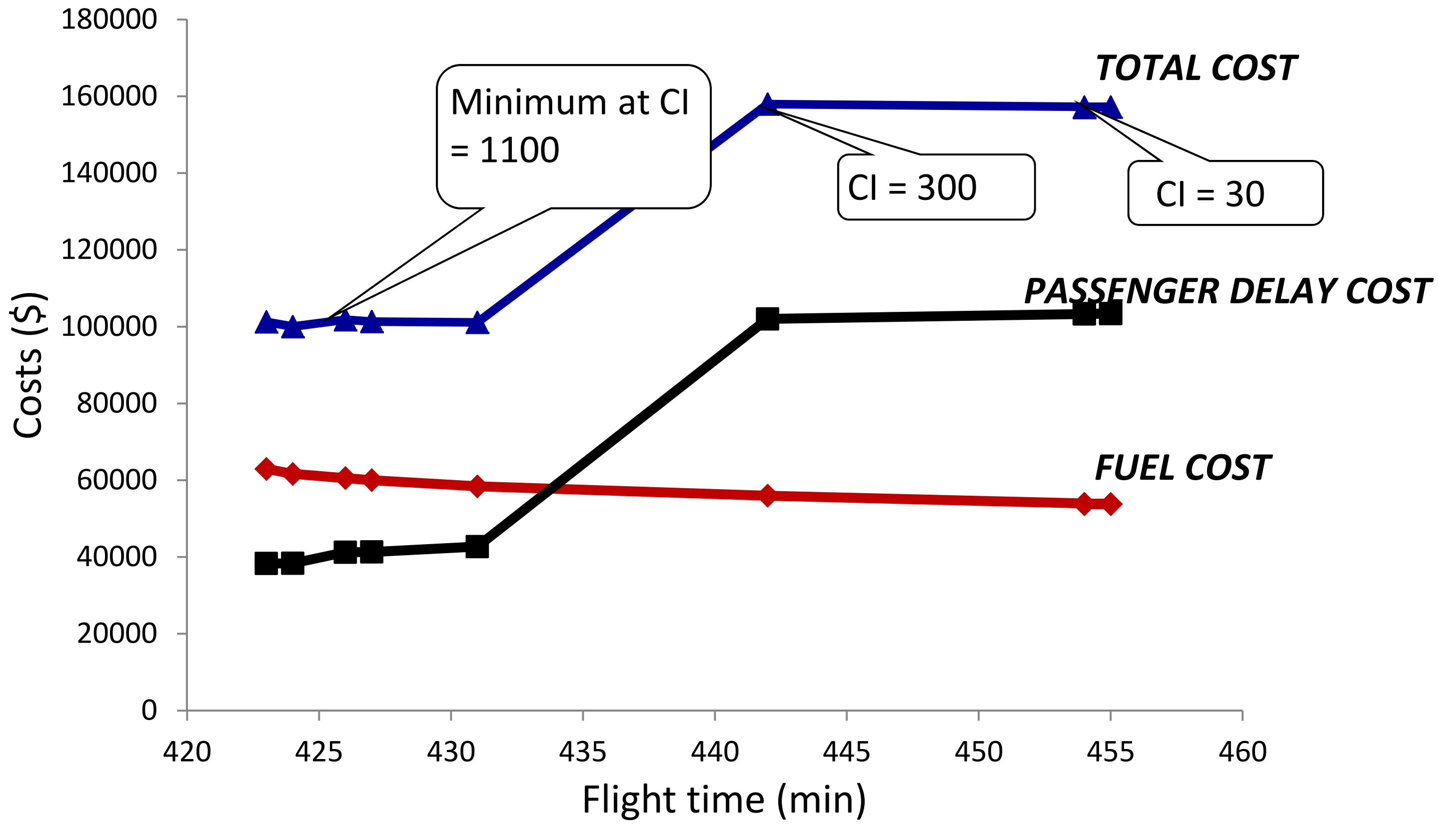
Fuel-Time cost tradeoff dependent on system state



Optimal CI / speed based on current system state

Flight time - delay cost relationships

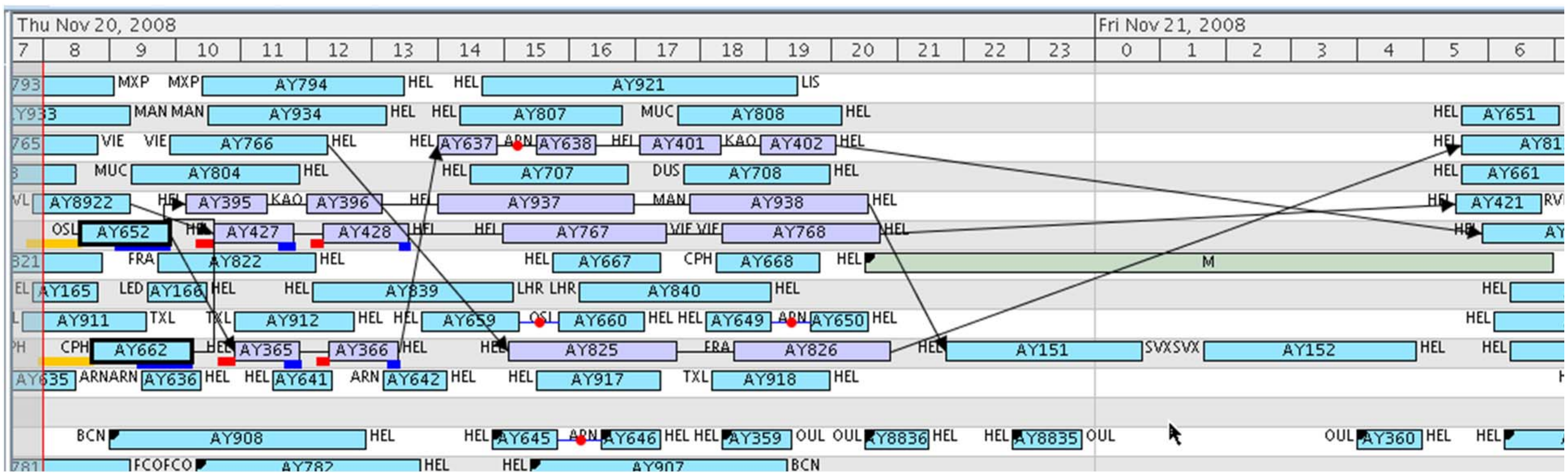
- Disruption scenario: Departure delay = 1 hour



Airline rules of thumb can be far from optimal

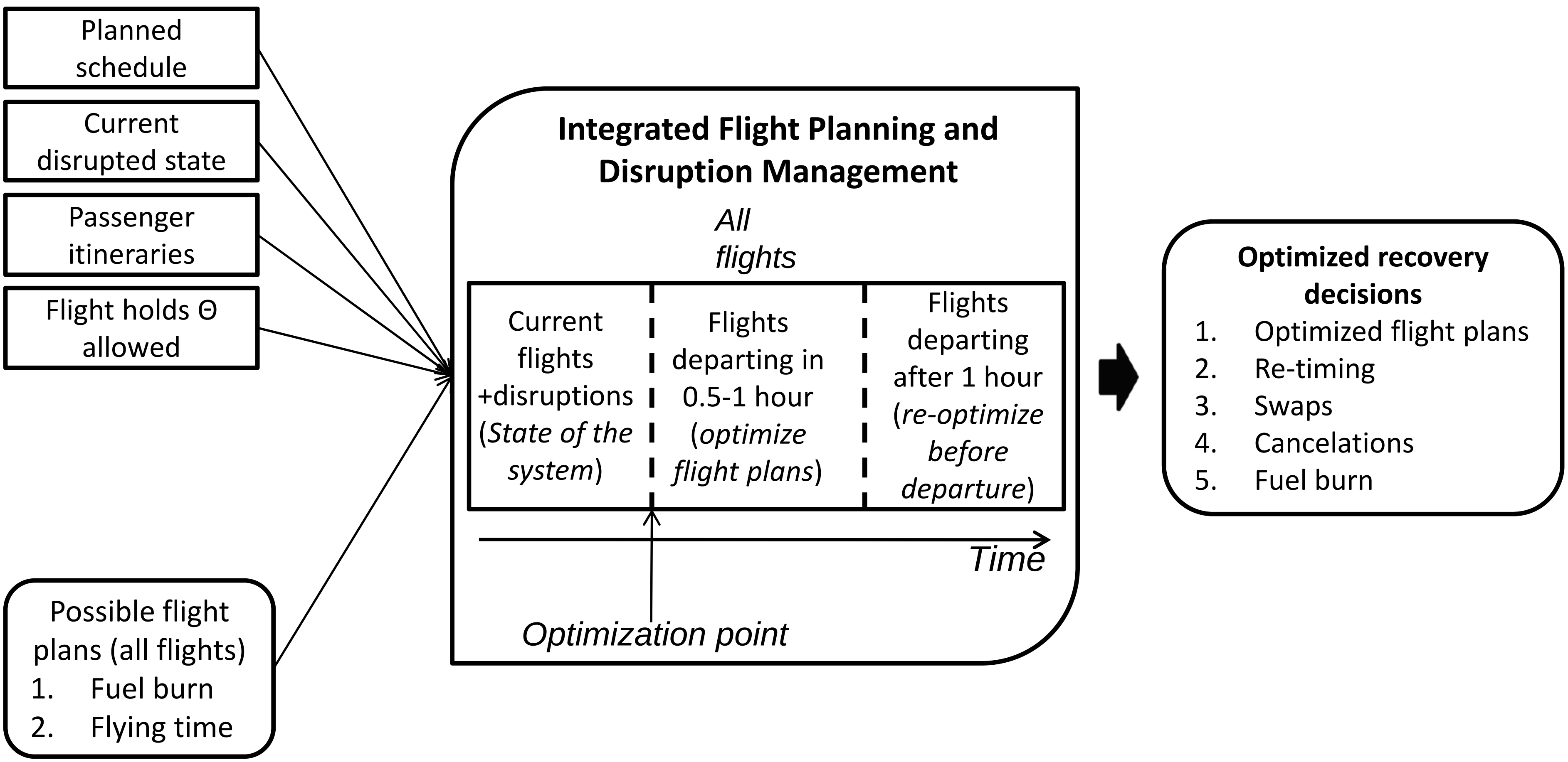
Dynamic, network perspectives

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

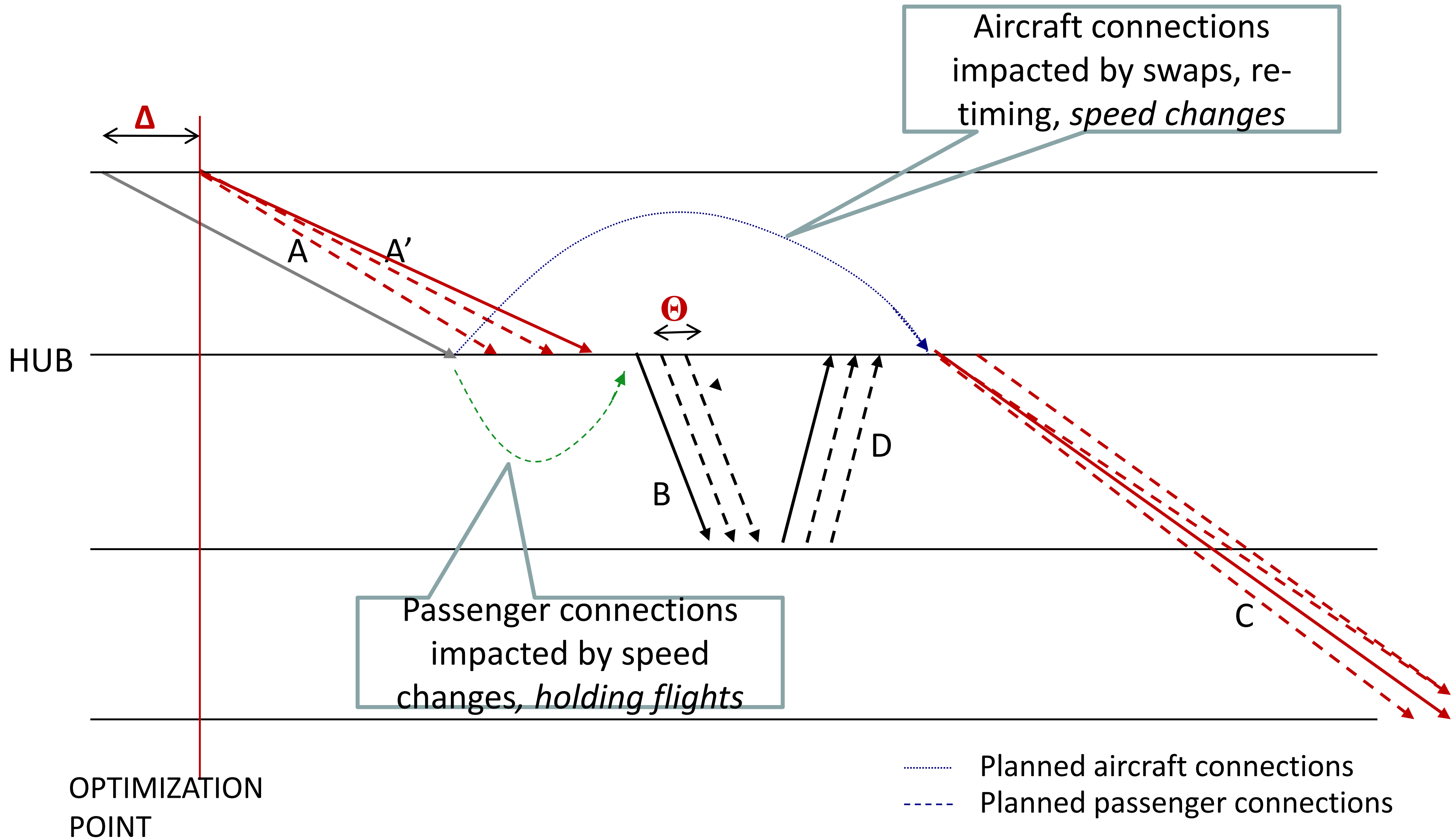


- Ops controlers:
  - Network view
  - Swaps, cancelations, delays
  - More schedule flexibility improves recoverability

Enhanced recovery: Modeling framework



Modeling Architecture



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* *a*vailable 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

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

Fuel + pax delay cost

$$s.t.$$

$$\sum_{k \in C_f} x_f^k + z_f = 1 \qquad \forall f \in F$$

Flight cover/ cancel

$$\sum_{g \in n^-} y_g + \sum_{(f,k) \in n^-} x_f^k + s_a^n = \sum_{g \in n^+} y_g + \sum_{(f,k) \in n^+} x_f^k \qquad \forall n \in N_a, \forall a \in A$$

Aircraft flow balance

$$\sum_{r \in R(p)} \rho_p^r = n_p \qquad \forall p \in P$$

Passenger flow balance

$$\sum_{p \in P} \sum_{r \in R(p)} \delta_f^r \rho_p^r \le Cap_f (1 - z_f) \qquad \forall f \in F$$

Plane capacity

$$x_f^k \in \{0,1\}$$

$$z_f \in \{0,1\}$$

$$\rho_p^r \in Z^+$$

$$y_g \ge 0$$

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

$$Min \sum_{f \in F} \sum_{k \in C_f} \left(c_f^k + s_f^k + d_f^k\right) x_f^k + \sum_{f \in F} c_f z_f + \sum_{p \in P} c_p n_p \lambda_p$$

Fuel + swap + delay cost + pax disruption cost

$$s.t.$$

$$\sum_{k \in C_f} x_f^k + z_f = 1 \qquad \forall f \in F$$

Flight cover/cancel

$$\sum_{g \in n^-} y_g + \sum_{(f,k) \in n^-} x_f^k + s_a^n = \sum_{g \in n^+} y_g + \sum_{(f,k) \in n^+} x_f^k \qquad \forall n \in N_a,$$

Aircraft balance

$$x_{IT(p,1)}^k + \sum_{m \in MC(p, IT(p,1), k)} x_{IT(p,2)}^m - \lambda_p \le 1 \qquad \forall k \in C_{IT(p,1)}$$

$$\lambda_p \ge z_f \qquad \forall f \in IT(p), \forall p \in P$$

Passenger misconnects

$$x_f^k \in \{0,1\}$$

$$z_f \in \{0,1\}$$

$$\lambda_p \in \{0,1\}$$

$$y_g \ge$$

Integrality

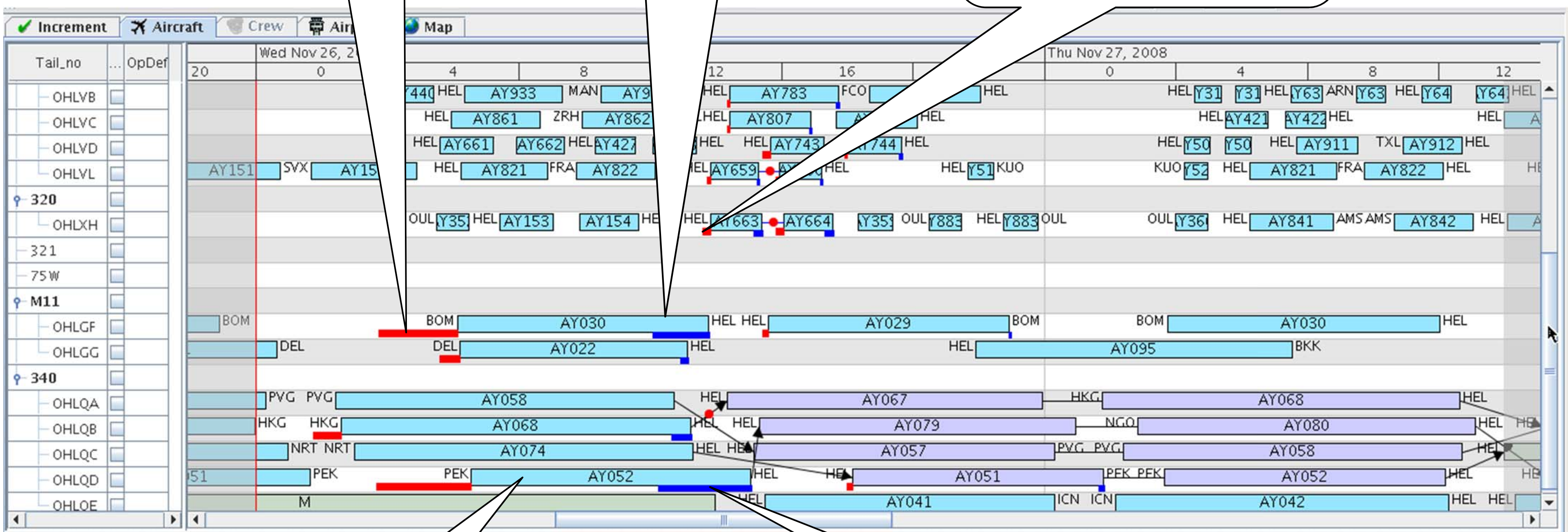
Solution time capped at 2 min

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

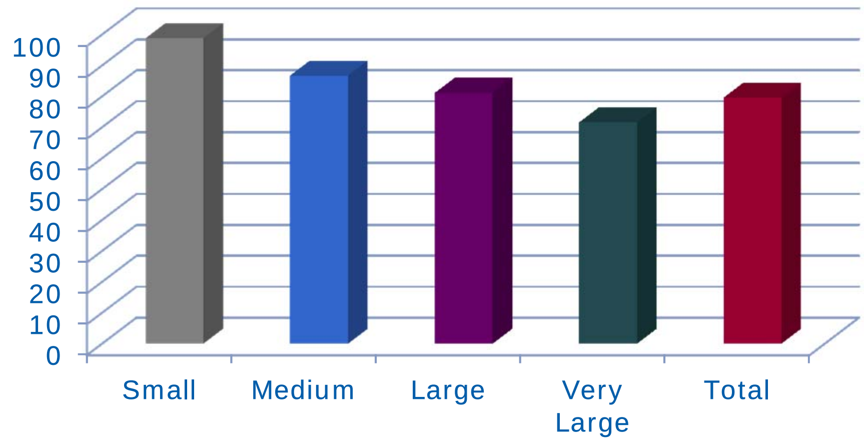
Arrival delay
35 mins

Computational experiments

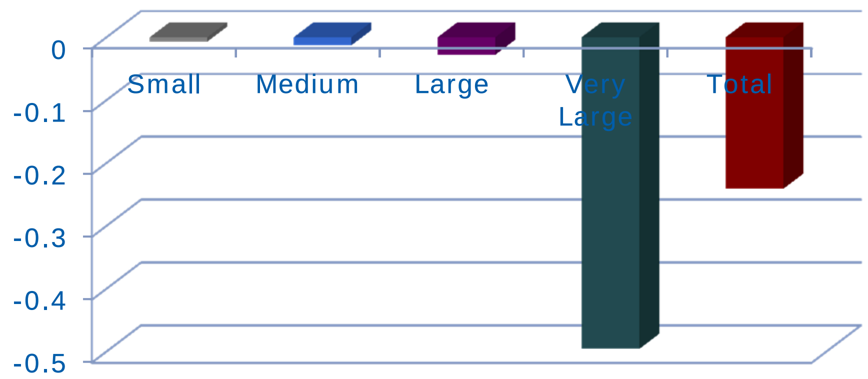
- Disruptions into hub airport
  - Flights delayed going into hub
  - Focus on long-haul flights
- 60 scenarios, 3 months of historic data
  - Grouped by severity of disruption
- Optimize flight plans pre-departure each flight
- Compare via simulation:
  - Baseline disruption management
  - Integrated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

Improvements in multiple delay metrics

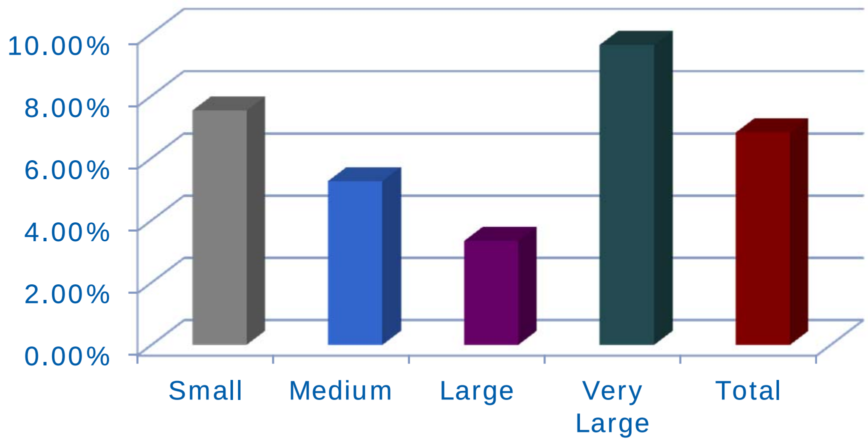
Pax misconns reduced [%]



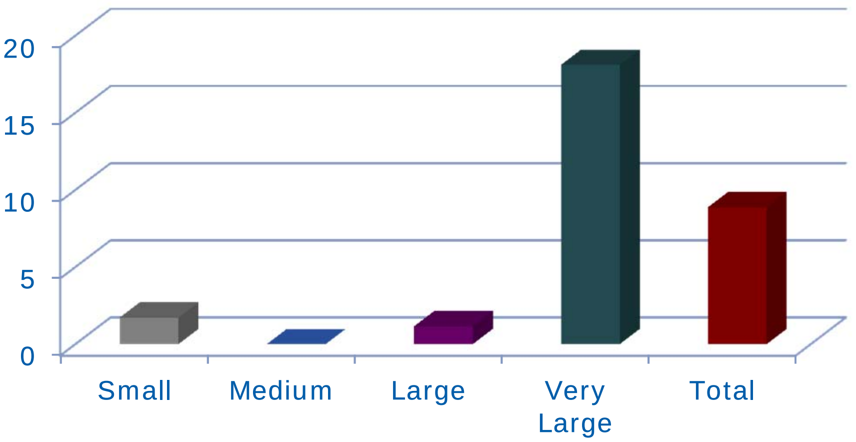
Fuel Savings per operated LH flight [%]



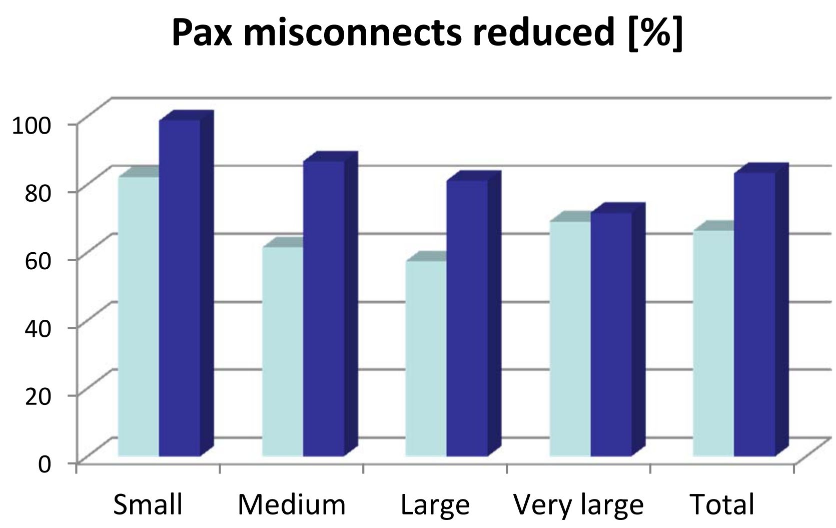
OTP improvement [%]

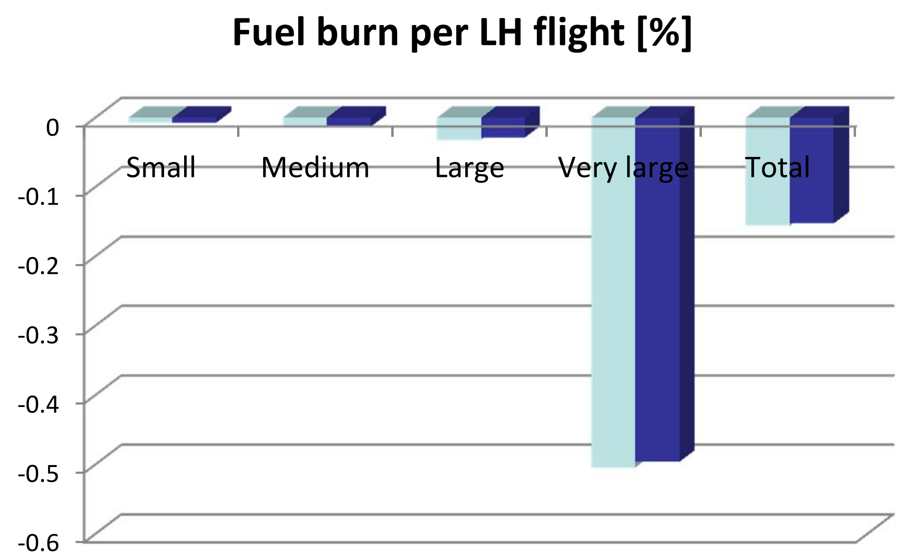


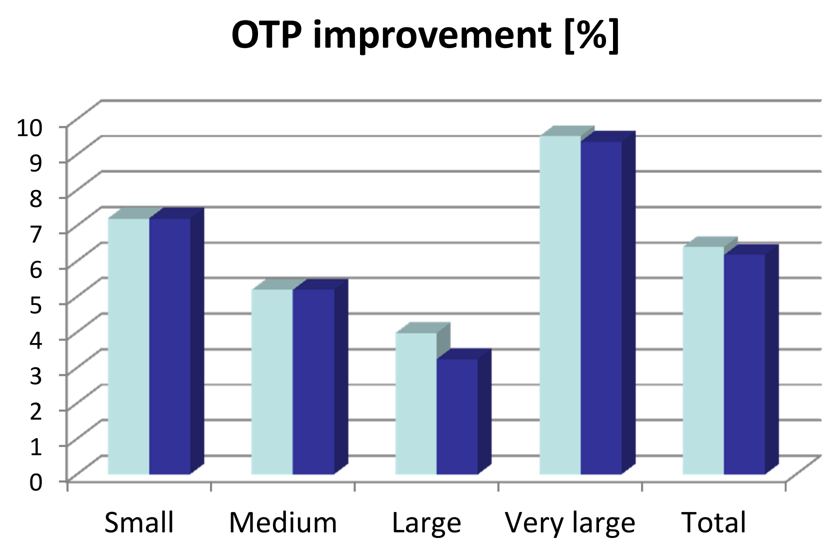
Total cost savings [%]

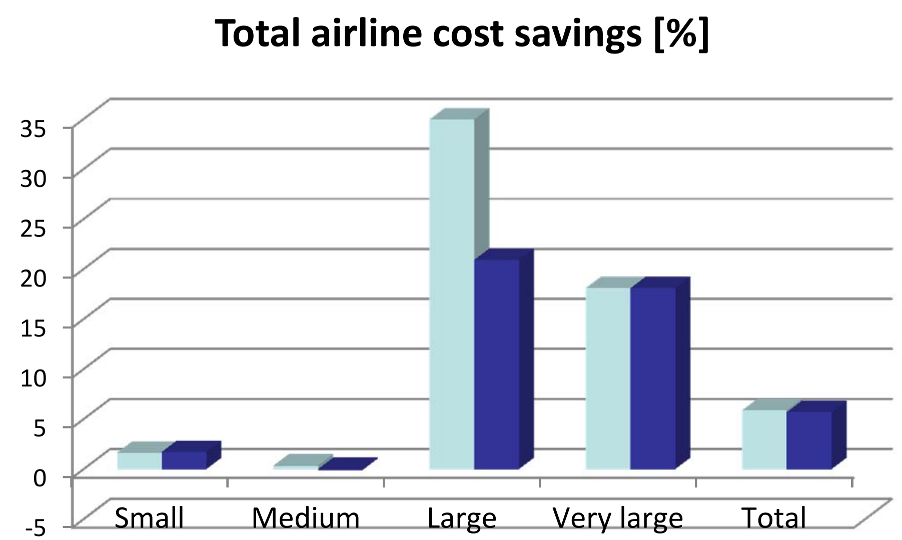


Improvements in multiple delay metrics









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

	Enhanced recovery: don't hold connecting flights	**Enhanced recovery: hold connecting flights up to 15 min**
Passenger misconnections decreased	66.4%	83.3%
Fuel burn (CO_2) increase	0.155%	0.152%
Passenger delay costs decreased	58.2% ($17.5 M/60 days)	77.5% ($17.9M /60 days)
OTP (traditional recovery 88%)	95%	95%
Total airline cost savings	5.9%	5.7%

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