"Optimized" Airline Plans and Operational Realities

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Fields Lecture, 2008

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Overview

- Scheduling process
  - Classical OR models
- Disconnect between plans and operations
  - Causes of disruption
  - Impact of disruption
  - Propagation of delay
  - Mis-aligned incentives

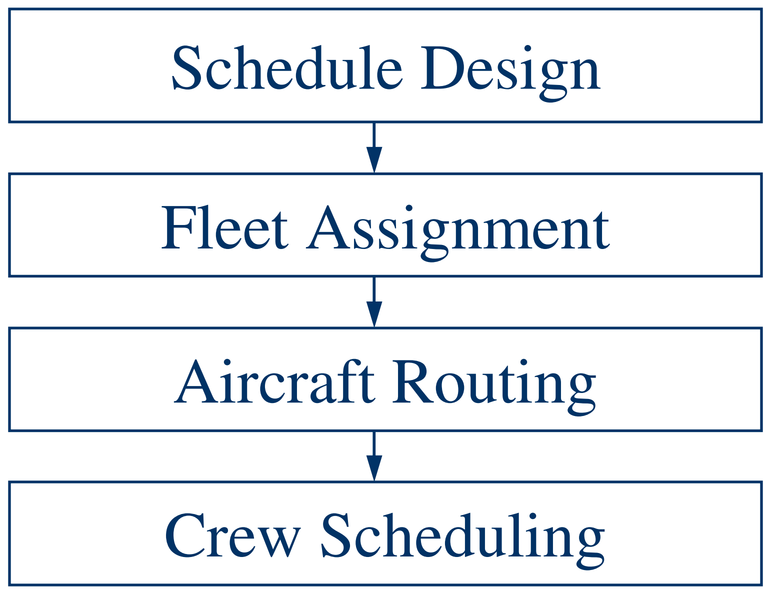
Overview, cont.

- New metrics and objectives for the planning process
  - What is robustness?
  - How do we measure it?
  - How do we value it?
  - How do we achieve it?
- Current successes
- Future challenges

Airline Planning

- Allocating and scheduling multiple scarce resources
  - Aircraft
  - Crew
  - Gates
  - Maintenance slots
- Complex, inter-dependent network
- Highly competitive environment

Airline Schedule Planning



- Pros and cons of disaggregation

Schedule Design

- Decide markets, frequency, time table
- Precedes (and drives) all other planning decisions
- Lots of qualitative decisions
- Feasibility difficulty to establish

Fleet Assignment

- For each flight, pick a fleet type
- Satisfy:
  - Cover constraints
  - Balance constraints
  - Count constraints
- Maximize expected revenue minus operating cost

Maintenance Routing

- For each flight assign a tail number
- Need to create cycles
- Need adequate maintenance opportunities
- Every tail flies every flight?
- No clear objective function
- Plan changes frequently – more a validation than a plan

Crew Scheduling

- For each flight assign a crew (cockpit, cabin)
- Need to respect lots of complex FAA and labor restrictions
- Minimize cost
- Crew pairing problem: Find a minimum cost set of feasible pairings such that each flight is included in exactly one pairing
- These pairings are then assigned to individual crew members (rostering, bidding)

Links Between Planning Problems

- Schedule determines flights to be covered
- Fleet assignment partitions flights into smaller sets that share common crews, common aircraft
- Maintenance routing restricts feasible crew connections

OR Contributions to Airline Planning

- Decades of OR research in airline planning
- Many important general OR techniques have evolved from airline applications
- Countless research projects, papers, models, algorithms, software tools, and Edelman awards
- A true OR success story in many ways

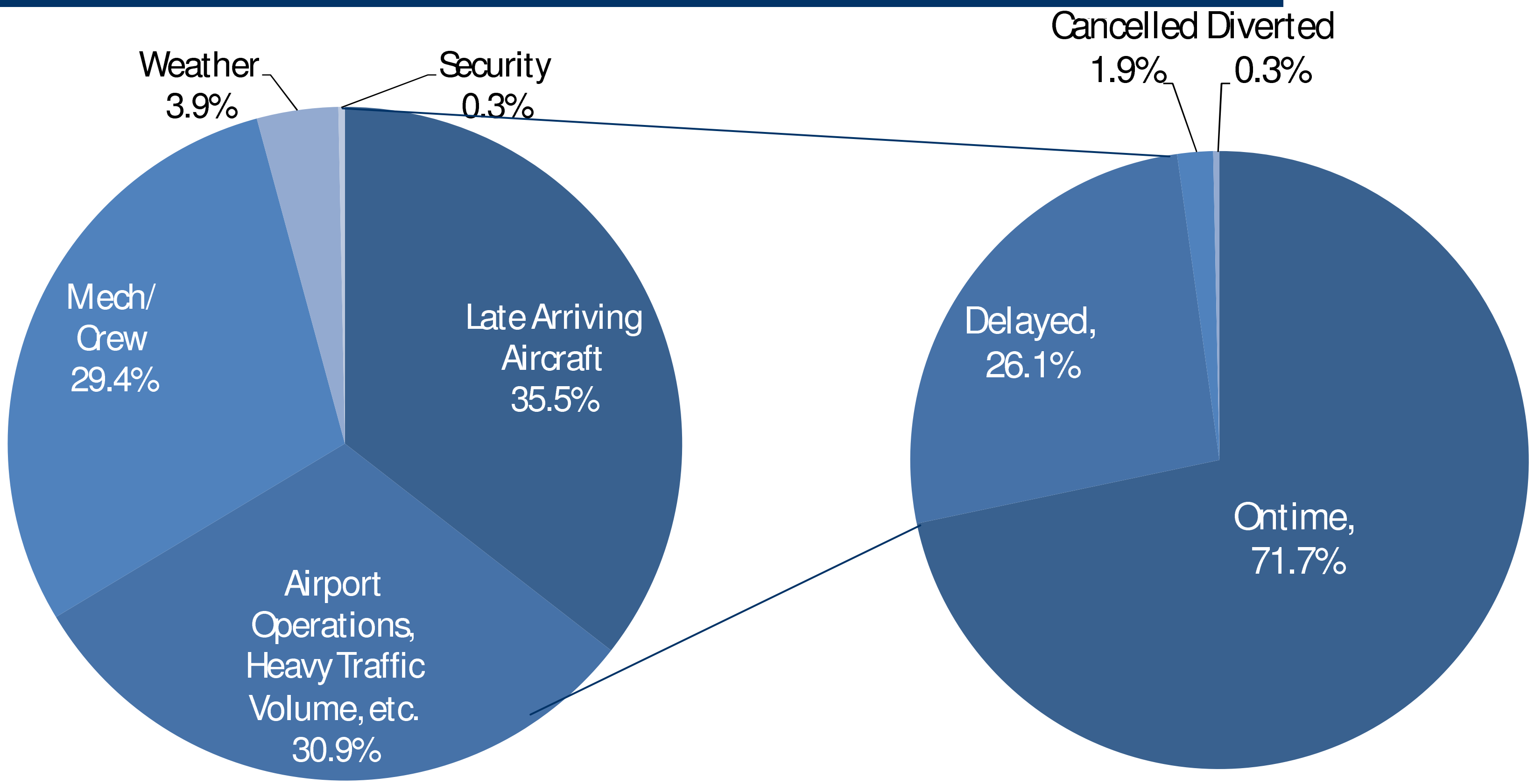
Limitations of These Successes

- Airline planning is largely based on static, deterministic data
- Does not directly and adequately address:
  - Daily fluctuations in demand
  - Uncertainty in resource availability
  - Uncertainty in flight times
  - …

Sources of Delay/Disruption

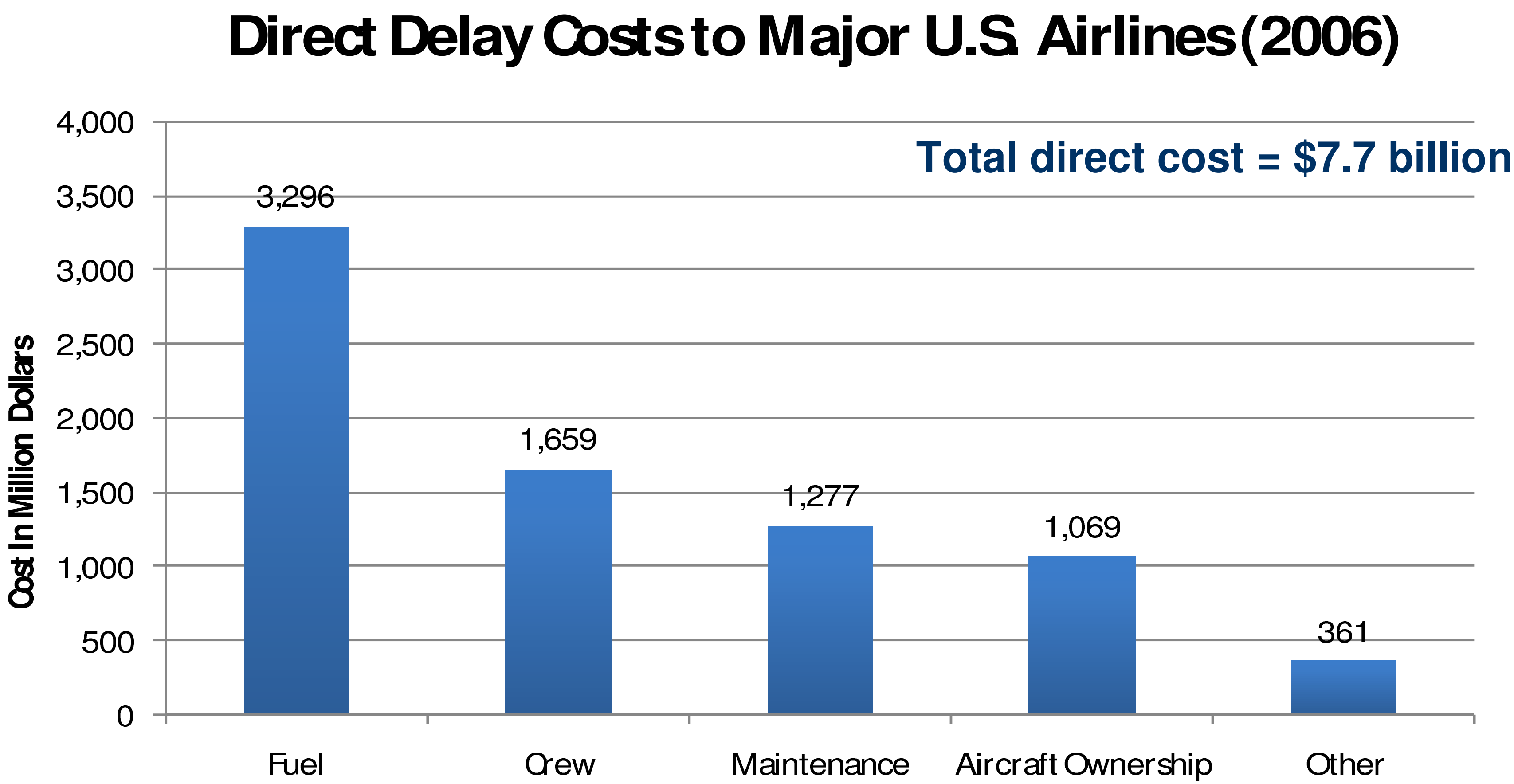
- Weather
- Mechanical
- Air traffic control
- Boarding delays
- Unavailable crew (cockpit, cabin, gate, ground)
- …

Delay Propagation Statistics



Source: U.S. Department of Transportation - Air Travel Consumer Report – Dec 2007

Impact of Disruptions

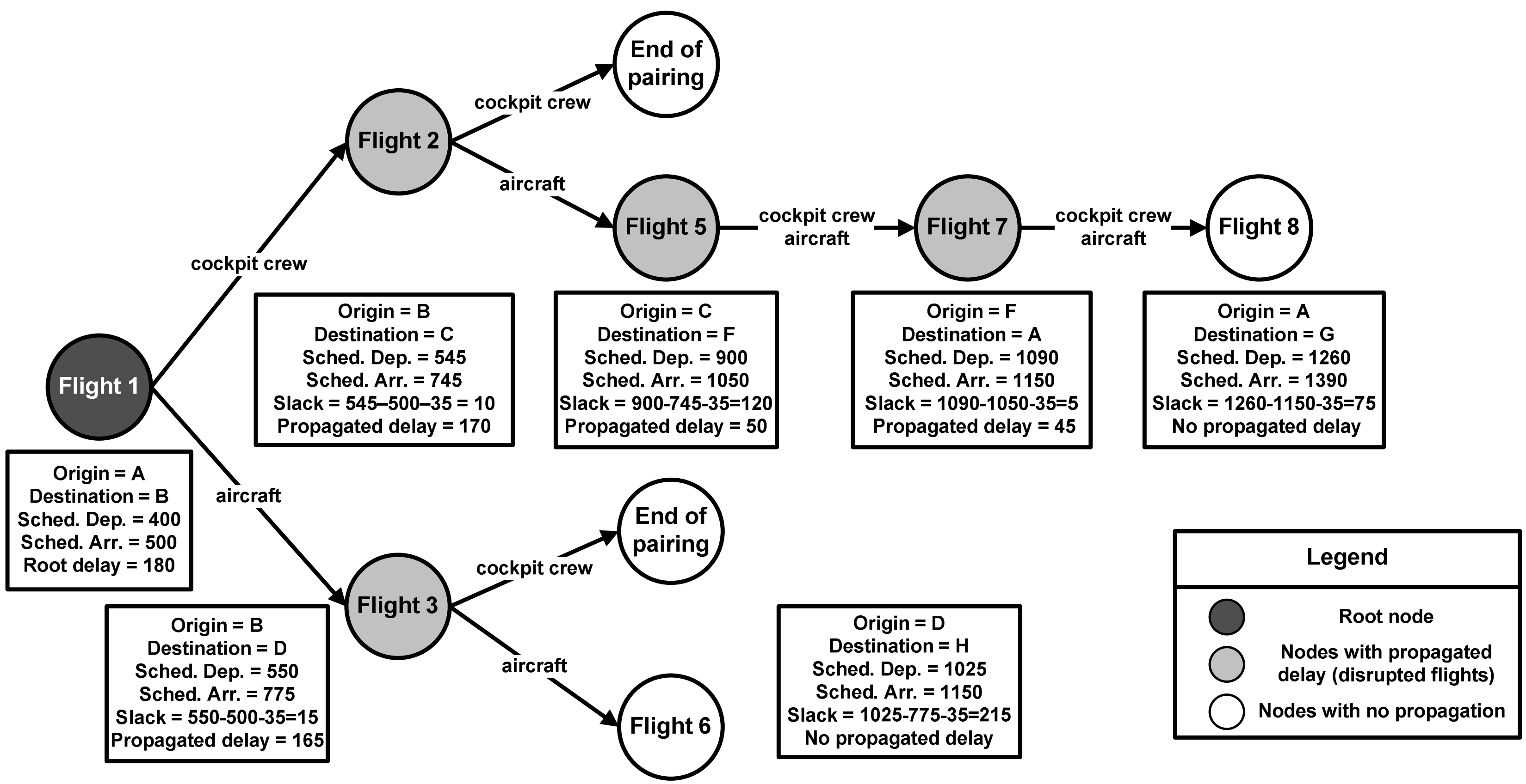


Delay Propagation

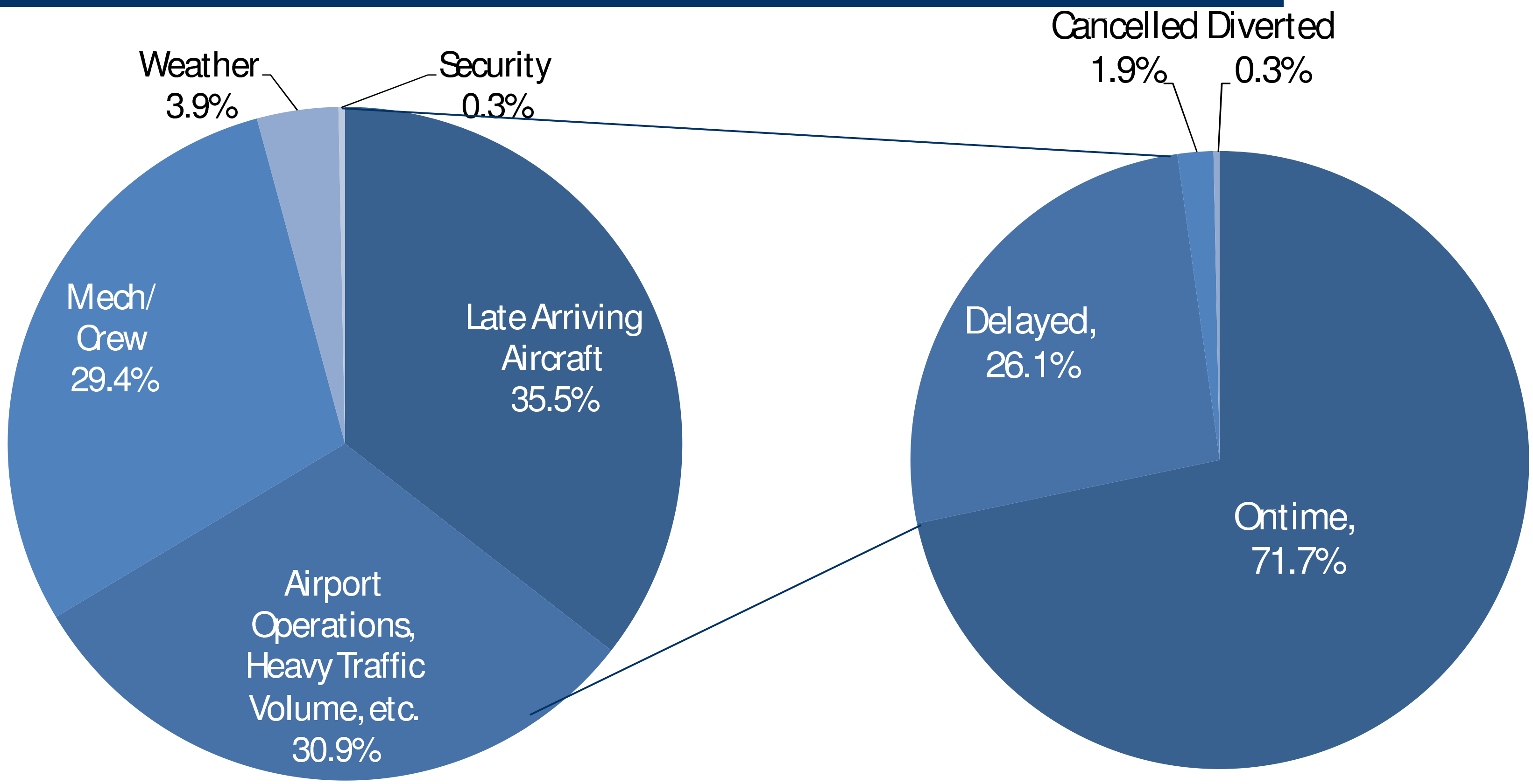
- In addition to root causes of delay, many delays are caused by upstream delays
  - Awaiting aircraft
  - Awaiting crew
  - Awaiting connecting passengers
  - Awaiting gates
  - …

Propagation Tree: Example

Nodes: Flights **Arcs**: Connections due to transfer of resources



Delay and Disruption Statistics



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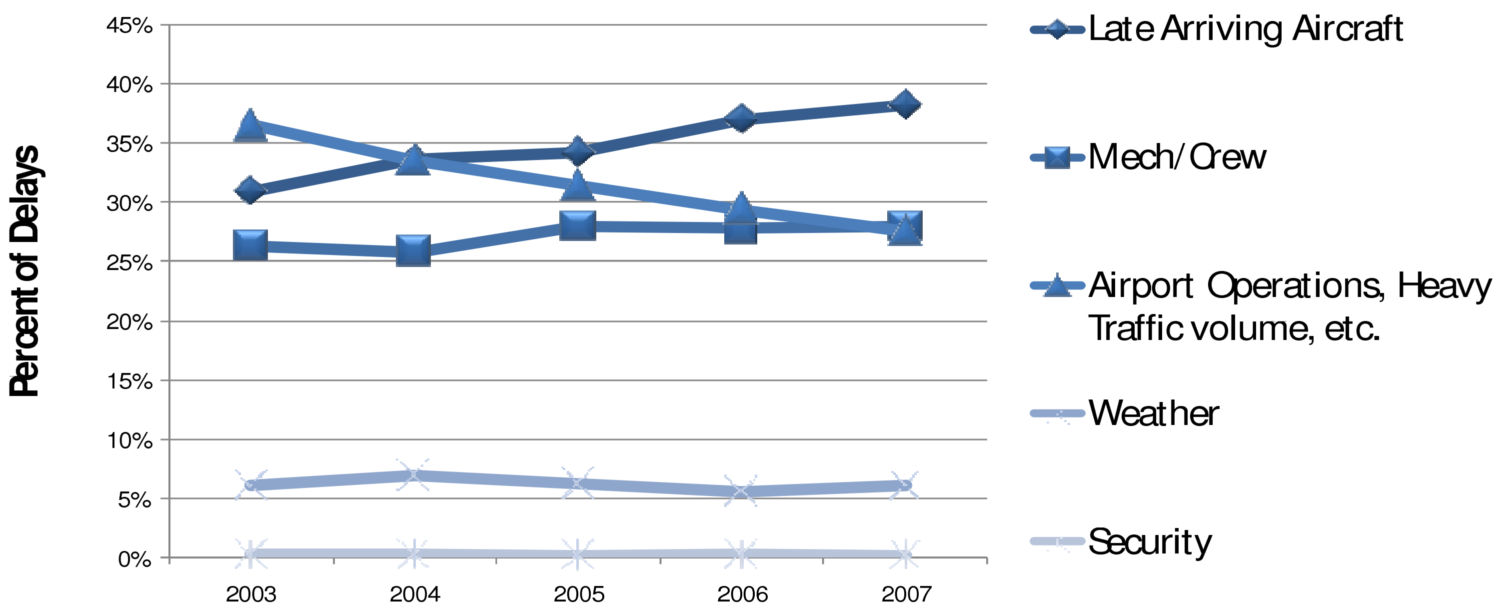
Delay and Disruption Trends



Source: Bureau of Transportation Statistics: *http://www.bts.gov/*

Key Conflict

- Slack is fundamentally "bad" in planning and fundamentally "good" in operations
- In planning, wastes a scarce resource
- In operations, provides an opportunity to absorb delay and prevent propagation
- How should this conflict be resolved? Does it impact the way plans are built?

Beyond Delay Propagation

- Not all delays propagate
- Alternatives for recovery
  - Swapping aircraft
  - Swapping crew
  - Canceling flights
  - Spare aircraft, ferrying
  - …

New Objectives for Airline Planning

- Focusing solely on deterministic objectives doesn't make sense
- There are *NO* "clear-blue sky" days
- What should the planning objectives be?
  - Min expected cost
  - Min worst case
  - Maximize robustness
  - Trade off between cost and robustness

Minimize Expected Cost

- Several major obstacles:
  - Integrated planning
  - Stochastic
  - Data
  - Recovery codification

Maximize Robustness

- Several major obstacles:
- What is robustness?
  - How do we measure it?
  - How do we value it?
  - How do we achieve it?

Another Question: Boundaries

- What should be addressed in planning?
- What should be addressed in operations?

Alternative Approaches to Robustness

- Don't try to achieve "the Holy Grail"
- Incremental, iterative approaches
  - Decreasing propagation
  - Providing opportunities for recovery

Example One

- Ellis Johnson and Barry Smith
- Impose "station purity" in the fleet assignment problem to improve robustness of solution
  - Limit number of fleet types into spoke stations
  - Greater flexibility for recovering crews, aircraft
  - Impact on computational performance – need to develop new methodologies
  - Need to make cost-benefit trade-offs

Example Two

- Cindy Barnhart, Shan Lan, and John-Paul Clarke
- Focus on decreasing passenger disruption
- Two approaches
  - Taking into account stochasticity when construcing aircraft rotations by strategically choosing aircraft connections
  - Re-timing flight departures to decrease passenger mis-connects

Example Three

- Sergey Shebalov and Diego Klabjan
- Focus on crew scheduling
- Consider secondary objective criteria: maximizing number of “move-up crews”
- How much increase in planned crew costs should be incurred to have more options for crew recovery?

Example Four

- David Ryan and Oliver Weide
- Look at the link between crew scheduling and maintenance routing
  - Linked together via short turns
- Work to improve robustness by decreasing tight turns
- Begin with least-cost solution and iteratively increase robustness with minor increases in cost

Example Five

- Jay Rosenberger, Ellis Johnson, and George Nemhauser
- Methods to increase flexibility for recovery via fleet assignment/maintenance routing
  - Hub isolation
  - Short cycles
- Cost trade-offs

Our Research: Motivation

- **How can we mitigate delay propagation?**
- One approach is to add more slack to the connections
  - But adding more slack increases cost
  - How to trade-off between improved robustness and increased cost?
- Re-distribute the slack that is already in the network!
  - No additional costs incurred

Our Research: Problem Statement

- **Objective**:
  - Minimize the expected delay propagation
- **Constraints**:
  - Change the departure times of the flights within a given time window
  - Keep the original connections still feasible with respect to the crew assignment
- Other uses of time windows:
  - Levin (1971), Rexing et al (2000), Lan et al (2003)

Our Research: Notation

- **Sets**:
  - Set of flights (nodes) F
  - Set of connections (arcs) A
    - Union of two sets: cockpit crew (P) and aircraft (C) connections
    - $A = P \cup C$
  - Set of possible delay values (minutes) M

- **Parameters**:
  - Probability of the root delay $0 \leq p_f^m \leq 1 \quad \forall f \in F, \forall m \in M$
  - The original slack on each arc $s_{f_1,f_2} \geq 0 \quad \forall (f_1, f_2) \in A$

Our Research: Decision Variables

- Flight re-timing $k_f^- \leq x_f \leq k_f^+$
- The new slack on each arc $y_{f_1,f_2} \geq 0$
- Delay propagated from f_1 to f_2 when f_1 is delayed by m minutes $d_{f_1,f_2}^m \geq 0$

Our Research: Key Constraint

changes in departure times

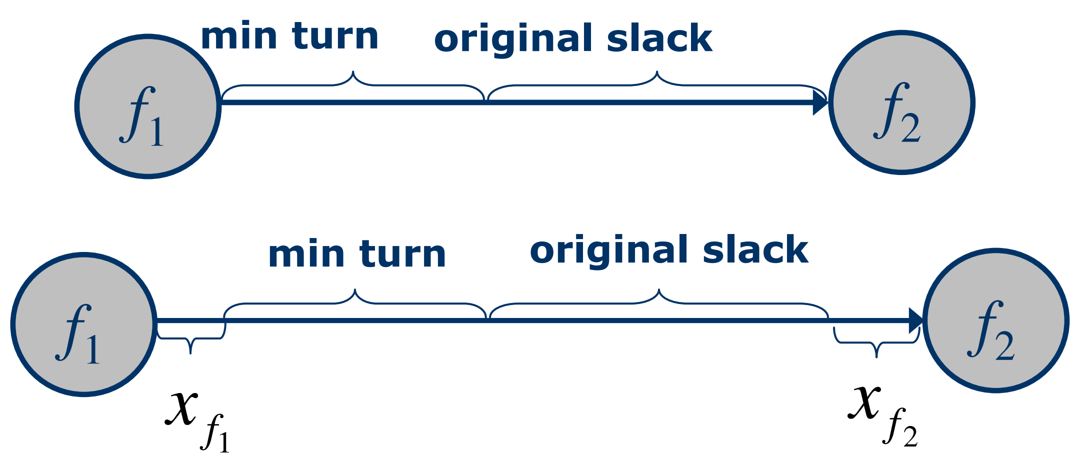
new slack

original slack

$$y_{f_1,f_2} = s_{f_1,f_2} - x_{f_1} + x_{f_2}$$

original schedule

modified schedule



Our Research: Single-Layer Model

$$\min \sum_{m \in \mathrm{M}} \sum_{(f_1,f_2) \in \mathrm{A}} p_{f_1}^m d_{f_1,f_2}^m$$

$$y_{f_1,f_2} = s_{f_1,f_2} - x_{f_1} + x_{f_2} \qquad \forall (f_1, f_2) \in \mathrm{A}$$

$$d_{f_1,f_2}^m \geq m - y_{f_1,f_2} \qquad \forall (f_1, f_2) \in \mathrm{A} \quad \forall m \in \mathrm{M}$$

$$d_{f_1,f_2}^m \geq 0 \qquad \forall (f_1, f_2) \in \mathrm{F} \quad \forall m \in \mathrm{M}$$

$$k_f^- \leq x_f \leq k_f^+ \qquad \forall f \in \mathrm{F}$$

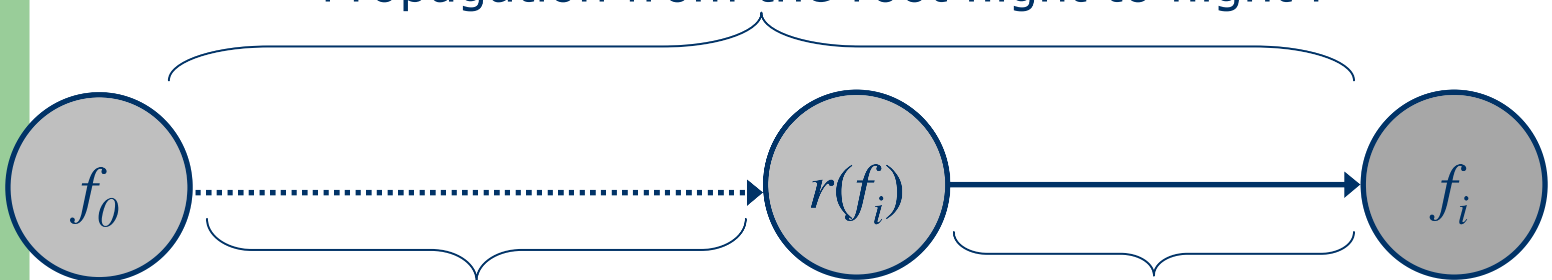
$$y_{f_1,f_2} \geq 0 \qquad \forall (f_1, f_2) \in \mathrm{A}$$

Our Research: Expanded Model

- How to consider all layers of propagation?

$$d^{m}_{f_0, f_i} \geq d^{m}_{f_0, r^{m}_{f0}(f_i)} - y_{r^{m}_{f0}(f_i), f_i}$$

Propagation from the root flight to flight i



Propagation from root flight to the parent flight of *i*

New slack between parent flight and flight *i*

Our Research: Implementation

- Implemented the model using CPLEX10.0/C++
- Used historical data in order to compute the probability of root departure delays
- Assumptions:
  - Equal time windows (+/- 15 minutes)
  - Flights that start a duty period can't move earlier
  - Flights that end a duty period can't move later
  - Relax this in later experiments…

Our Research: Size vs. Run Time

Data Set	Duty Restriction	Model	No. of Constraints	No. of Variables	No. of Nonzeros	Time (sec.)
1	15	SLM	2,701	3,217	5,867	4
1	15	MLM	6,108	6,636	16,080	8
2	15	SLM	2,444	2,923	5,289	2
2	15	MLM	5,376	5,865	14,081	6

Our Research: Results

Data Set	Duty Restrictions	Single-Layer Model	Multi-Layer Model
1	0	6.3%	7.2%
1	5	23.0%	27.4%
1	10	33.6%	40.9%
1	15	41.5%	51.0%
2	0	5.3%	5.8%
2	5	23.5%	27.3%
2	10	34.4%	41.5%
2	15	43.1%	52.2%

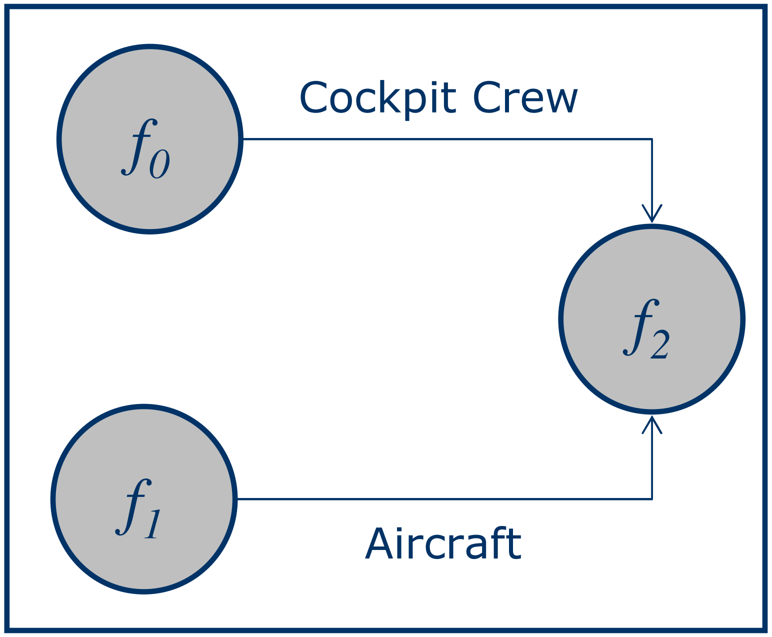
Our Research: Observations

- Can relax integrality of decision variables
  - The coefficient matrix is totally unimodular
- The optimal solution is not too sensitive to the objective function coefficients
  - Small errors in estimating the delay probabilities don’t dramatically affect the solution quality

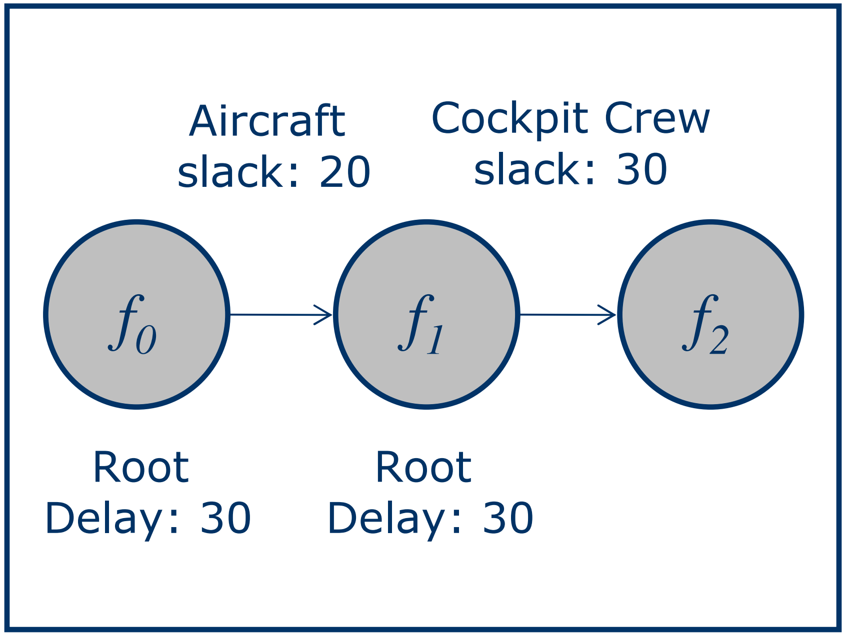
Our Research: Limitations

- Objective function ignores recovery intervention
- Model considers each root delay independently

Our Research: Over-Counting



Our Research: Under-Counting



Our Research: Validation

Data Set	Duty Restrictions	Single-Layer Model	Multi-Layer Model
1	**0**	**(3.2%, 5.4%)**	**(4.4%, 6.6%)**
1	5	(21.8%, 23.9%)	(23.4%, 25.5%)
1	10	(35.6%, 37.5%)	(37.5%, 39.2%)
1	15	(46.0%, 47.6%)	(47.8%, 49.3%)
2	**0**	**(2.6%, 5.0%)**	**(3.5%, 5.9%)**
2	5	(22.7%, 24.8%)	(24.3%, 26.3%)
2	10	(37.0%, 38.8%)	(38.9%, 40.6%)
2	15	(47.9%, 49.5%)	(50.1%, 51.7%)

Future Challenges, Opportunities

- Challenges:
  - Fuel issues
  - Mergers
  - Congestion

Future Challenges, Opportunities

- Opportunities
  – Computers are getting faster
  – Algorithms are getting better
  – New integrated planning tools
  – Silos are coming down
  – Academics, industry are working together