Summary Lecture #1

• Airline schedules (Aircraft, crew, passengers) are optimized leading to:
  - Little slacks (idle time)
  - Schedule dependencies
  - Delay chain effects

• Causes of schedule disruptions
  - Shortages of airline resources
  - Shortages of airport resources

• Complex airline resource regulations
  - Aircraft maintenance
  - Pilots
Airline Schedules Recovery

- Schedule Recovery Model (SRM)
- Aircraft Recovery Model (ARM)
- Crew Recovery Model (CRM)
- Passenger Flow Model (PFM)
- Journey Management
- Passenger Re-accommodation
Summary Lecture #1 (Cont.)

- **Airline schedules recovery problems**
  - **Aircraft maintenance module:**
    - Objective: feasibility only
  - **Crew schedule recovery module**
    - Objective: to minimize disruptions, recover the disrupted with minimum flight schedule disruptions and control Flight Time Count
    - Complex rules
  - **Passenger schedule recovery module**
    - Objective: to minimize passenger delays, ill will, gap between expected and delivered service
    - Complexity:
      - Priority rules (booked over disrupted, priority among disrupted: network, user, FFP, fare class)
      - Seat availability uncertainty
Lecture #2 Outline

- Passengers are important to satisfy
- Tricks to prevent schedule disruptions and recover schedules
- Traditional ARM; Model shortcomings
- Interdependency of passengers and aircraft operations
- Our approach: Minimizing sum of disrupted passenger
- Flight copy generation and solution feasibility
- Minimizing sum of passenger delays
- Proxy of minimizing sum of passenger delays
- Simulation environment
- Conclusion
**Importance of delivering services as expected in airline industry**

- Very competitive industry
- Low profit margin (5% in 2000, best year)
- Dissatisfied customers might shop next to competitors, jeopardizing your profitability
- On time service is not prime factor to attract customers but it contributes to loyalty
- Passenger delay distribution is not continuous, few passengers suffer high delays
- Passenger dissatisfaction function with respect to delays is not linear
- Clear objective: minimize passenger ill will with same operations costs
Trade off: Passenger service reliability versus operating costs

- Admissible operating cost region
- Feasible operating space

Passenger dissatisfaction

Operating costs
Flight delays and flight cancellations
Passenger bookings for each scheduled itinerary

Disrupted?  
Yes  
Build the list of disrupted passengers, \( L \) 
Sort \( L \) according to service policy

No  
Assign all non-disrupted passengers to their planned itineraries

Remove seats from remaining inventory

Record passenger delay

Is \( L = \emptyset \)?

Yes  
END

No  
Take next disrupted passenger in \( L \)
Find best recovery itinerary and assign passenger

Remove seat from remaining inventory

Record passenger delay

Passenger Delay Statistics
Flight delays underestimate passenger delays

Key explanation lies in the disrupted passengers
Disrupted passengers versus non disrupted passengers

<table>
<thead>
<tr>
<th>August 2000</th>
<th>Av. Delay (minutes)</th>
<th>% Passengers</th>
<th>% Delays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disrupted passengers</td>
<td>320 minutes</td>
<td>3.2%</td>
<td>40%</td>
</tr>
<tr>
<td>Non disrupted passengers</td>
<td>16 minutes</td>
<td>96.8%</td>
<td>60%</td>
</tr>
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</table>

Disrupted passengers experience long delays in general because 20% of them are stranded overnight (delay propagation results in more disruptions later during the day).

Although a small percentage, disrupted passengers account for 40% of the total passenger delay and most of the severely delayed passengers (80% of passengers delayed by more than 4 hours).
Risk of being disrupted

- Although fewer planned connecting passengers, higher number are disrupted
- The risk of a passenger to be disrupted is 2.75 times greater for connecting (5.5%) than for local (2%)
- Does not bode well for hub-and-spoke with banks

<table>
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<tr>
<th>Passenger type</th>
<th>Connecting</th>
<th>Local</th>
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<tr>
<td>Scheduled passenger mix</td>
<td>35%</td>
<td>65%</td>
</tr>
<tr>
<td>Disrupted passenger mix</td>
<td>60%</td>
<td>40%</td>
</tr>
<tr>
<td>Caused by flight cancellations</td>
<td>52%</td>
<td>100%</td>
</tr>
<tr>
<td>Caused by missed connections</td>
<td>48%</td>
<td></td>
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</table>
Passenger disruption: important factors

- Disruption time & Route frequency

![Graph showing the relationship between disruption time and average delay of disrupted passengers. The graph includes a line with points indicating data points, and the r-squared value R² = 0.95 is shown.]
Passenger service reliability study: Conclusions

- Disrupted passengers are important: 80% of the passengers delayed by more than 4 hours are disrupted
- Minimizing the sum of disrupted passengers while recovering the schedule might be a good idea...
Resource Dependability: Ripple effects

PC: Pilot Crew; CC: Cabin Crew; A: Aircraft

Source: Sabre, 1998
## Disruption Impacts; Solutions and Constraints

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- **Hold flights**
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- **Aggregate flights**
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**Swap resources**
**Aircraft route swaps**

Swapping useful to:

- Spread the delays informally, converge toward bank integrity
- Postpone the shortage problem
- Recover from irregularities

Constraints: Crew compatibility and legalities
HYPOTHETICAL CASE: Flights not canceled (NC)
ACTUAL OPERATIONS: Flights canceled (C)
Flight cancellation benefits passengers when...

- Low loads in canceled flights
- Strong down line
- Passenger disruptions
- Severe delay

But often crew disruptions...

Unless canceled flights belong to the same crew duty sequence
Airline Schedule Recovery Problem: Assumptions

- At a given time of the day, we assume that airline controllers know the state of the system:
  - Locations and availability of resources
    - Aircraft
    - Pilot and flight attendant crews
  - Passenger states (i.e., disrupted or not) and locations/destinations
Airline Recovery Model, ARM (G. Yu et al.)

\[
\min \left( \sum_{f \in F} \sum_{t \in T_f} d_t^f \times x_t^f + \sum_{f \in F} c_f \times z_f \right)

\text{Ops cost + Cancellation cost}
\]

\[\begin{align*}
\sum_{t \in T_f} x_t^f + z_f &= 1 && \text{Flight coverage} \\
\sum_{f \in F} x_t^f + y_t^- &= \sum_{f \in F} x_t^f + y_t^+ && \text{Aircraft balance} \\
\sum_{f \in F} x_t^0 + y_t^0 &= j_0 && \text{Initial resource at airports} \\
\sum_{f \in F} x_t^- + y_t^- &= j_- && \text{End of the day resource at airports}
\end{align*}\]

\[x_t^f \in \{0,1\}; \quad y_t^f \geq 0\]

- Objective is to minimize operating cost (flight delay and cancellation costs)
Aircraft route schedule
Aircraft actual operations: unexpected delay (e.g., aircraft technical problem)
Passenger actual itineraries Operations decision #3: don’t cancel & postpone aircraft B
Flight copy generations

- We have developed a technique to minimize the number of flight copies
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- Four types of flight copies are generated:
  - Aircraft ready times
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Flight copy generations

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- Four types of flight copies are generated:
  - Aircraft ready times
  - Copies to prevent passengers from missing connections
  - Consequence of type 2, aircraft postponement propagation
  - Schedule (for cancellations)
- Claim: We generate the minimum set of copies to capture one optimal solution.
- Had we generated copies every minute (as proposed in literature), we would typically have to generate between 5 and 10 times as many flight copies (10,000 to 20,000 per day of operations), which would greatly increase running time and may jeopardize solution feasibility because of running time.
Maintaining crew feasibility

- Respect planned duty period (constraints)
  - Given a sequence of flights assigned to a crew (duty), add feasibility constraints
  - Not always needed because either the flight terminates the crew duty assignment or some reserve crews can be used (typically at hubs); up to the user to define these constraints (shadow prices indicates the benefit for the passengers of relaxing the constraint)
$X_1 + X_2 \leq 1$
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- Satisfy regulatory constraints (Flight copies)
  - Maximum total flying time (not affected)
  - Maximum total elapsed time (MTET); iterative algorithm: if by adding a flight copy, the associated crew’s elapsed time exceeds MTET, don’t generate copy, otherwise do
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- Model solutions do not result in any additional crew disruptions due to postponement decisions; keep control on overhead operating costs

- Several models to minimize the crew disruption impact and minimize the cost of crew disruptions, but these models assume the flight operations are given. They can be used as complement to our models (Desrosier et al. (optimal); Yu et al. (heuristic))
Minimizing Sum of Disrupted Passengers

Minimize \( \sum_{p \in P} n_p \times \rho_p \)

st: \( \sum_{t \in T_f} x_f^t + z_f = 1 \)

\[ \sum_{(f,t) \in \text{In}(j)} x_f^t + y_f^- = \sum_{(f,t) \in \text{Out}(j)} x_f^t + y_f^+ \]

\( \sum x_f^* + y_f^* = \text{Res}(a,f,t,* \mathcal{C}) \)

\( \rho_p \geq z_f \)

\( x_f^t + \sum_{g \in \mathcal{C}(u) \mid d(g) < a(f)} x_g - \rho_p \leq 1 \)

\( \rho_p \in [0;1] \); \( x_{f,a} \in \{0,1\} \); \( y_f^t \geq 0 \)

- Objective: Minimize sum of disrupted passengers
- Flight coverage constraints
- Aircraft balance for each sub fleet type
- Initial and end of the day aircraft resource constraints
- Passenger cancellation constraints
- Missed connected passengers constraints
- Only flight copy variables, \( x \), have to be binary
Minimizing passenger delay

- Need to consider all potential recovery itineraries for each passenger
- Large scale problem: 500,000 integer variables; 12 hours CPU using B&B deep first search methodology

Investigators approximate approaches that meet the time constraint requirements

\[
\begin{align*}
\text{Min} & \quad \sum_{p \in P} \sum_{i \in I_p} b^i_p q^i_p \\
\sum_{t \in T_f} x^t_f + z^t_f &= 1 \quad \forall f \in F \\
\sum_{(f,t) \in \text{In}(j)} x^t_f + y^{-t_t}_f &= \sum_{(f,t) \in \text{Out}(j)} x^t_f + y^{+t_t}_f \\
\sum_{f} x^0_f + y^{0+}_f &= j^* \\
\sum_{i \in I_p} q^i_p &= n_p \\
\sum_{p \in P} \sum_{i \in I_p} \delta^t_{fi} q^i_p &\leq C^t_f \times x^t_f \\
q^i_p &\geq 0; x^t_f \in \{0,1\}; y^{+t_t}_f \geq 0
\end{align*}
\]
Minimize \( \sum_{p \in P} n_p \times \rho_p \)

st : \( \sum_{t \in T_f} \sum_{a \in A_f} x_{f,a}^t + z_f = 1 \)

\( \sum_{f \in F_{dj}} x_{f,a}^t + y_{f}^t = \sum_{f \in F_{oj}} x_{f,a}^t + y_{f}^{t+} \)

\( \sum_{f \in F_{oj}} x_{f,a}^0 + y_{f}^{0+} = j_{0,a} \)

\( \rho_p \geq z_f \)

\( x_f^t + \sum_{g \in C(u) | d(g) < a(f)} x_g^u - \rho_p \leq 1 \)

\( \rho_p \in [0;1] ; x_{f,a}^t \in \{0,1\} ; y_f^t \geq 0 \)

Total delay = \( \sum D(DP) \times N(DP) + \sum D(NDP) \times N(NDP) \)

NDP = TP − DP

Minimize(\( \sum \tilde{D}(DP) \times N(DP) + \sum D(TP − DP) \times N(TP − DP) \))

Estimate delay of disrupted passenger using PDC
Objective function

- Objective function:
  - Fine grained to Passenger Name Record
  - Estimate each passenger dissatisfaction: assign a cost (expected future revenue loss of delay d for PNR p)
  - Let the model chose flight decisions

- Enforcing feasibility:
  - Minimizing crew disruptions
  - Preventing maintenance routing infeasibility
Airline system state:
Aircraft: position, maintenance, operational
Crews: position, disruption status, duty time, flight time, etc.
Passengers: position, destination, PAT, disruption status

Crew operations recovery, Repair pairings
→ Operations forecasts
→ Flight copy generation algorithm
→ optimizer
→ Flight departure times, X* and flight cancellations Z*
→ Aircraft routing based on (X*,Z*)

∃ Feasible route R?
Yes
→ Prevent infeasible aircraft route swaps
Modify flight departure solution
Obtain feasible aircraft route R' and associated optimal solution (X*'*,Z*'*)
→ Optimal disrupted passenger re-routing
Considering seat availability uncertainty

Recovery priority policies
→ Optimal disrupted passenger re-routing
Routing passengers

Several optimizations models that route passengers to their destinations are used depending on the service priority rules.

<table>
<thead>
<tr>
<th>Passenger service priority rule</th>
<th>Routing algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority given to booked passengers over disrupted</td>
<td>Recovery priority among disrupted passengers</td>
</tr>
<tr>
<td>Yes</td>
<td>FDFS for disrupted; local first when same disruption time</td>
</tr>
<tr>
<td>No</td>
<td>Optimal passenger recovery</td>
</tr>
<tr>
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Routing algorithm:
- The Passenger Delay Calculator (PDC)
- The Passenger Mix model (PMIX)
- Combination of PDC+PMIX
- Stochastic PDC; Don’t know exact seat capacity before boarding ends due to potential no shows
Passenger routing algorithm performance

- PMIX provides the optimal passenger routings; We found that PDC is close to optimality (PMIX) to route the passengers.
- When passengers are disrupted at the hub (flight cancellation or missed connection), PDC provides the optimal recovery most of the time because only one route typically goes from the hub to destination airport (hub and spoke topology); Only when passengers are disrupted at the origin spoke (first flight canceled), does PDC might provide sub-optimal solution.
Conclusion and future research

- Propose new airline operations recovery models that reduce passenger disruptions and:
  - Does not disrupt additional crew duties
  - Recover aircraft plan
  - Maintain overhead costs
  - Found 10% to 20% reduction in passenger disruptions for bad days of operations, using a sophisticated simulation environment
  - Run fast and meet real time AOCC needs
- Airline long term profitability: higher service reliability improves customer retention and long term revenues
- Future research:
  - Estimate the impact of different disrupted passenger’s priority strategies (e.g. *Passenger routing*: recovery priority given to business passengers over leisure passengers; *Optimization*: minimize the revenue of disrupted passengers) on overall passenger population