SERVICE NETWORK DESIGN:
APPLICATIONS IN
TRANSPORTATION AND
LOGISTICS

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Outline

Service network design
  – Time-definite parcel delivery

Robust, Dynamic Scheduling
  – Airline schedule design
Service Network Design

Problem Definition

– Determine the cost minimizing or profit maximizing set of services and their schedules
  - Satisfy service requirements
  - Optimize the use of resources
Service Network Design
Problems

Examples:

1. Jointly determining the aircraft flights, ground vehicle and package routes and schedules for time-sensitive package delivery
2. Determining an airline’s flight network, its schedule and the assigned fleets
3. Determining the locations of warehouses and inventory in a service parts logistics operation
Challenges

Service network design problems in transportation and logistics are characterized by:

- Costly resources, tightly constrained
- Many highly interconnected decisions
- Large-scale networks involving time and space
- Integrality requirements
- Fixed costs
  - Associated with sets of design decisions, not a single design decision

Both models and algorithms are critical to tractability

- Large-scale mathematical programs
- Notoriously weak linear programming relaxations
Designing Service Networks for Time-Definite Parcel Delivery

- Problem Description and Background
- Designing the Air Network
  - Optimization-based approach
- Case Study

Research conducted jointly with Prof. Andrew Armacost, USAFA
Problem Overview

Gateway
Hub
Ground centers

1
Pickup Route

2

3
Delivery Route

H

pickup link
delivery link
feeder/ground link
UPS Air Network Overview

- **Aircraft**
  - 168 available for Next-Day Air operations
  - 727, 747, 757, 767, DC8, A300

- **101 domestic air “gateways”**

- **7 hubs** (Ontario, DFW, Rockford, Louisville, Columbia, Philadelphia, Hartford)

- **Over one million packages nightly**
Research Question

What aircraft routes and schedules provide on-time service for all packages while minimizing total costs?
UPS Air Network Overview

Delivery Routes

Pickup Routes
Problem Formulation

- Select the minimum cost routes, fleet assignments, and package flows

Subject to:
- Fleet size restrictions
- Landing restrictions
- Hub sort capacities
- Aircraft capacities
- Aircraft balance at all locations
- Pickup and delivery time requirements
The Size Challenge

- Conventional model
  - Number of variables exceeds one billion
  - Number of constraints exceeds 200,000
Column and Cut Generation

Constraint Matrix

Billions of variables

Variables in the optimal solution

Additional variables considered

Additional constraints added

Constraints not considered

Variables not considered

Hundreds of thousands of constraints

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ARM vs UPS Planners
Minimizing Operating Cost for UPS

- Improvement (reduction)
  - Operating cost: 6.96 %
  - Number of Aircraft: 10.74 %
  - Aircraft ownership cost: 29.24 %
  - Total Cost: 24.45 %

- Running time
  - Under 2 hours
ARM vs. Planners

Routes for One Fleet Type

Pickup Routes

Delivery Routes

Planners’ Solution

ARM Solution
ARM Solution
Non-intuitive double-leg routes

Model takes advantage of timing requirements, especially in case of A-3-1, which exploits time zone changes

Model takes advantage of ramp transfers at gateways 4 and 5
Robust, Dynamic Scheduling

An approach to improve airline schedule profitability
- Dynamic scheduling and passenger routing (revenue maximizing)
- Hub de-banking (cost minimizing)
- Robust (flexible) scheduling
Flight Scheduling and Demands

- Flight schedules and fleet assignments are developed based on deterministic, static passenger demand forecasts (made months or longer in advance)
  - Air travel demand is highly variable
  - Each daily demand is different

- Significant mismatch exists between supply and demand
  - Even with sophisticated revenue management systems

- Idea: Dynamically adjust airline networks in the booking process to match supply with demand
Dynamic Airline Scheduling

Adjust the schedule during the booking period to match capacity to demand for each individual date.

Consider:
- The set of flight legs scheduled for day $d$
- The associated current booking data on day $d - t$ for each of these flight legs, say with $t = 21$ days prior to day $d$
- The forecasted demand for each of these flight legs, updated on $d-21$

(Extend earlier research to integrate both re-timing and re-fleeting decisions (Berge and Hopperstad (1993), Bish (2004), Sherali et al. (2005)))
Dynamic Airline Scheduling

Dynamic scheduling idea

- Adjust the capacity (supply) in various markets so as to satisfy more exactly emerging demand by:
  - Retiming flights
    - Creating new itineraries and eliminating itineraries only if no bookings to date
  - “Swapping” aircraft
    - Re-assigning aircraft within the same fleet family
      - Maintaining crew feasibility
      - Maintaining conservation of flow (or balance) by fleet type
      - Maintaining satisfaction of maintenance constraints
“Matching Capacity and Demand”

- Assign new aircraft with different numbers of seats to the flight legs
- Re-time flight legs and create a new itinerary
  - Potentially many opportunities in a de-peaked hub-and-spoke network
De-banked (or De-peaked) Hubs

American de-peaked

Continental de-peaked
EWR


Delta de-peaked ATL (2005)

Lufthansa de-peaked
FRA (2004)
Hub-and-Spoke Networks

1. Improve aircraft and crew productivity
   • Shorter turn times

2. Reduce maximum demand for gates, ground personnel and equipment, runway capacity, etc.

3. Improve schedule reliability

4. Eliminate passenger connections
   • Extend/ reduce duration of passenger connections
Opportunity in a De-Banked Schedule

Flight re-timing creates new itineraries, adjusts market supply
De-Peaking Hub Operations

Find flight schedule and associated fleet assignment that maximizes profitability and limits the number of departures + arrivals to 5 in any 10-minute interval.

Maximize Profit

Flight Cover Constraints

Serve Passenger Demand

Capacity Constraints

Aircraft Balance Constraints

Aircraft Count Constraints

Departure/Arrival Activities Constraints

(For De-peaking)

Separate Mainline & Express Network

Depature/arrival activities

Time

Depature/arrival activities

Time

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25
De-Banking Results

- Load factor and schedule profitability essentially unchanged
- Set of flight legs unchanged
- Flight schedule execution requires one fewer aircraft (A320)
- Average passenger connection times increase by 8 minutes after de-peak (from 73 minutes to 81 minutes)
The Dynamic Case

New schedule guarantees:
- All connecting itineraries sold in Period 1 remain feasible
- # of aircraft for each fleet overnighted at each station is the same as originally planned

21 days prior to departure

3/21/2007 Barnhart - Service Network Design 27
Re-optimization Formulation

\[
\sum_{m \in M} \sum_{r \in R(m)} x_{mr} f_{are_m}^F - \sum_{l \in L} \sum_{k \in C(l)} \sum_{\pi \in \Pi} c_{lk\pi} f_{lk\pi} - \sum_{\pi \in \Pi} z_{\pi} c_{\pi}
\]

The set of constraints are:

\[
\sum_{k \in C(l)} \sum_{\pi \in \Pi} f_{lk\pi} = 1, \ \forall l \in L
\]

\[
\sum_{r \in R(m)} x_{mr} \leq D^F_m, \ \forall m \in M
\]

\[
\sum_{m \in M} \sum_{r \in R(m)} \delta_{mr} x_{mr} \leq \sum_{\pi \in \Pi} f_{lk\pi} (CAP_{\pi} - BKD_l), \ \forall l \in L, k \in C(l)
\]

\[
\sum_{l \in L} \sum_{k \in C(l)} f_{lk\pi} \alpha^i_{lk} + \sum_{g \in G} y_{g\pi} \alpha^i_g = 0, \ \forall i \in N^\pi, \ \pi \in \Pi
\]

\[
\sum_{l \in L} \sum_{k \in C(l)} f_{lk\pi} \beta^i_{lk} + \sum_{g \in G} y_{g\pi} \beta^i_g = z_{\pi}, \ \forall \pi \in \Pi
\]

\[
z_{\pi} \leq n^\pi, \ \forall \pi \in \Pi
\]
Re-optimization Formulation

\[
\sum_{l \in L} \sum_{k \in C(l)} \sum_{\pi \in \Pi} \gamma_{l k \pi} f_{l k \pi} \leq MAX ACT^{ai}, \forall t \in T
\]

\[
\sum_{l \in L} \sum_{k \in C(l)} \sum_{\pi \in \Pi} \gamma_{l k \pi} f_{l k \pi} \leq MAX ACT^{di}, \forall t \in T
\]

\[
f_{l k \pi} = 0, \forall l \in L, k \in C(l), \pi' \neq FML(\pi_i^0)
\]

\[
\sum_{g \in G} y_{g \pi} \xi_g^i \leq y_{g \pi}^0, \forall i \in S, \forall \pi \in \Pi
\]

\[
\sum_{\pi \in \Pi} f_{l_1 k_1 \pi} + \sum_{\pi \in \Pi} f_{l_2 k_2 \pi} \leq 1, \forall (l_1, l_2) \in P, (k_1, k_2) \notin C(l_1, l_2)
\]

\[
f_{l k \pi} \in \{0, 1\}, \forall l \in L, k \in C(l), \pi \in \Pi
\]

\[
x_{mr} \geq 0, \forall m \in M, r \in R(m)
\]

\[
y_{g \pi} \geq 0, \forall g \in G^\pi, \pi \in \Pi
\]

\[
z_{\pi} \geq 0, \forall \pi \in \Pi
\]
Case Study

Major US Airline
- 832 flights daily
- 7 aircraft types
- 50,000 passengers
- 302 inbound and 302 outbound flights at hub daily
  - Banked hub operations- must de-bank

Re-time
- +/- 15 minutes

Re-fleet
- A320 & A319
- CRJ & CR9

One week in August, with daily total demand:
- higher than average (Aug 1)
- average (Aug 2)
- lower than average (Aug 3)

Protect all connecting itineraries sold in Period up to $d-t$
- $t =$21 or 28 days

Two scenarios concerning forecast demand
- Perfect information
- Historical average demand
Improvement In Profitability

- Consistent improvement in profitability
  - Forecast A
    - 4-8% improvement in profit
    - 60-140k daily
  - Forecast B
    - 2-4% improvement in profit
    - 30-80k daily
    - Benefits remain significant when using Forecast B - a lower bound
- not including benefit from aircraft savings, reduced gates and personnel ...

![Graph showing improvement in profitability over 7 days for Forecast A and B](image)
The two mechanisms are synergistic
- $P^A_{\text{Dynamic scheduling}} > P^A_{\text{re-fleeting}} + P^A_{\text{re-timing}}$
- $P^B_{\text{Dynamic scheduling}} > P^B_{\text{re-fleeting}} + P^B_{\text{re-timing}}$

Re-timing is less affected by deterioration of forecast quality
- Larger $P^B/P^A$ ratios

Re-timing contributes more than flight re-fleeting
- $P^A_{\text{re-fleeting}} < P^A_{\text{re-timing}}$
- $P^B_{\text{re-fleeting}} < P^B_{\text{re-timing}}$

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### Comparison: Re-Time & Re-Fleet

#### Average daily profitability results ($$)

<table>
<thead>
<tr>
<th></th>
<th>Forecast A</th>
<th>Forecast B</th>
<th>$P^B/P^A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Scheduling</td>
<td>99,541</td>
<td>49,991</td>
<td>50.22%</td>
</tr>
<tr>
<td>Re-fleeting Only</td>
<td>28,031</td>
<td>7,542</td>
<td>26.91%</td>
</tr>
<tr>
<td>Re-timing Only</td>
<td>44,297</td>
<td>37,800</td>
<td>85.33%</td>
</tr>
</tbody>
</table>
Other Statistics

- System load factors went up 0.5-1%

- Aircraft savings

<table>
<thead>
<tr>
<th>Date</th>
<th>Perfect + retime + swap</th>
<th>Average + retime + swap</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Aug</td>
<td>1 A320</td>
<td>1 A320</td>
</tr>
<tr>
<td>2-Aug</td>
<td>1 A320 1 CR9</td>
<td>1 A320 1 CR9</td>
</tr>
<tr>
<td>3-Aug</td>
<td>1 A320 2 CR9</td>
<td>1 A320</td>
</tr>
</tbody>
</table>

- Schedule changes
  - About 100 fleet changes
  - 85-90% flights are retimed
    - Average retiming of 8 minutes
Flexible Planning

- Re-optimization decisions constrained by original schedule
  - Can we design our original schedule to facilitate dynamic scheduling?

Goal

- Maximize the number of connections that can be created to accommodate unexpected demands
  - Objective function value within 0.0% of original schedule
A Flexible Formulation (1)

Maximize

\[
\sum_{p \in PC} h_p w_p
\]  
(2.14)

subject to

\[
\sum_{k \in C(l)} \sum_{\pi \in \Pi} f_{lk\pi} = 1, \forall l \in L
\]  
(2.15)

\[
\sum_{l \in L} \sum_{k \in C(l)} f_{lk\pi} \alpha_{lk} + \sum_{g \in G^\pi} y_g \delta_{lg} = 0, \forall i \in N^\pi, \pi \in \Pi
\]  
(2.16)

\[
\sum_{l \in L} \sum_{k \in C(l)} f_{lk\pi} \beta_{lk} + \sum_{g \in G^\pi} y_g \gamma_{lg} = z_{\pi}, \forall \pi \in \Pi
\]  
(2.17)

\[
z_{\pi} \leq n_{\pi}, \forall \pi \in \Pi
\]  
(2.18)

\[
\sum_{l \in L} \sum_{k \in C(l)} \sum_{\pi \in \Pi} \gamma_{lk\pi}^a v_{lk\pi} \leq MAX_{ACT}^a, \forall i \in T
\]  
(2.19)

\[
\sum_{l \in L} \sum_{k \in C(l)} \sum_{\pi \in \Pi} \gamma_{lk\pi}^d v_{lk\pi} \leq MAX_{ACT}^d, \forall i \in T
\]  
(2.20)

\[
\sum_{r \in R(m)} x_{mr} \leq D_m, \forall m \in M
\]  
(2.21)

\[
\sum_{m \in M} \sum_{r \in R(m)} \delta_{mr} x_{mr} \leq \sum_{\pi \in \Pi} f_{lk\pi} C_{AP} \pi, \forall l \in L, k \in C(l)
\]  
(2.22)

Fleet assignment, Passenger flows de-peaked operations
A Flexible Formulation (2)

\[ \sum_{m \in M} \sum_{r \in R(m)} x_{mr} f_{ar} e_{mr} - \sum_{l \in L} \sum_{k \in C(l)} \sum_{\pi \in \Pi} c_{lk\pi} f_{lk\pi} - \sum_{\pi \in \Pi} z_{\pi} c_{\pi} \geq p^* \quad (2.23) \]

[Constraints that relate \( w_p \) to \( f_{lk\pi} \)]

\[ f_{lk\pi} \in \{0, 1\}, \forall l \in L, k \in C(l), \pi \in \Pi \quad (2.24) \]

\[ y_{g\pi} \geq 0, \forall g \in G, \pi \in \Pi \quad (2.25) \]

\[ x_{mr} \geq 0, \forall m \in M, r \in R(m) \quad (2.26) \]

\[ x_{mr} \geq 0, \forall m \in M, r \in R(m) \quad (2.27) \]

\[ z_{\pi} \geq 0, \forall \pi \in \Pi \quad (2.28) \]

\[ w_p \in \{0, 1\}, \forall p \in PC \quad (2.29) \]
Preliminary Results

Under Forecast A, improvement is not significant
- When forecast is perfect, dynamic scheduling can always make good decisions to respond

Under Forecast B, improvements obtainable
- When forecast is imperfect, an improved schedule can be constructed by accounting for dynamic scheduling opportunities
Summary and Contributions

- Solving large-scale service network design problems
  - Blend art and science
  - Model selection key to achieving
    - Tractability
    - Extendibility
- Dynamic and robust scheduling form core of next-generation optimization approaches