FLIGHT TRANSPORTATION LABORATORY
REPORT R 91-4

PRESENTATIONS FROM THE
MIT/INDUSTRY COOPERATIVE RESEARCH
PROGRAM ANNUAL MEETING, 1991

Belobaba, Williamson, et al.

May 1991
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O-D / SEGMENT SEAT INVENTORY CONTROL:
Modeling and Implementation Issues

Professor Peter P. Belobaba
MIT Flight Transportation Laboratory

MIT/Industry Cooperative Research Program
Annual Meeting
May 23, 1991
PASSENGER ITINERARY CONTROL

- In contrast to the control of seat inventories by flight leg/booking class, passenger itinerary control requires methods that can distinguish among passenger itineraries vying for seats on the same flight leg, even within the same fare product "category".

- Passenger Itinerary Control concepts can be applied through:

  DUAL/OVERLAP FLIGHTS: Two or more flight numbers representing different itinerary "paths" assigned to a single flight leg.

  POINT OF SALE CONTROL: Seat availability is differentiated between points of sale due to currency or net revenue differences.

  SEGMENT CONTROL: Seat availability is managed by booking class and passenger itinerary on a multiple-leg flight with the same flight number.

  O-D CONTROL: Seat availability is managed by fare category and O-D itinerary, even across connecting flights.
PASSENGER ITINERARY CONTROL

DUAL / OVERLAP FLIGHTS:

DTW
NW1649

BOS
NW049

LGW

POINT OF SALE: KL 015

SEGMENT CONTROL: AC113

CONNECTING O-D CONTROL:
NETWORK OPTIMIZATION APPROACHES

- Traditional O.R. approach to dealing with itinerary control is to perform a joint optimization over the entire network of flight legs defined by the problem.

- Network formulations and/or mathematical programming approaches are used to find the optimal allocation of seats to each origin-destination itinerary and fare type (ODF) on each flight leg:
  -- requires demand forecasts and fare values for each ODF
  -- problem representation can be deterministic or probabilistic
  -- solution ensures balanced ODF allocations across flight legs
  -- ODF allocations are "optimal" given assumed mathematical formulation of problem
• Implementation of these "optimal" network ODF seat allocations as ODF booking limits, however, can have substantial negative revenue impacts.

  -- use of partitioned or discrete booking limits lowers expected revenue relative to nested limits

  -- negative revenue impact becomes larger with more ODF allocations

  -- dynamic simulations show that use of "optimal" partitioned segment/class limits on a 3-leg flight can result in revenue reductions of 1% to 2% relative to simple leg/booking class control

• The optimal solution to an assumed mathematical formulation does not maximize revenues when implemented this way.
NESTING OF NETWORK OPTIMAL SOLUTIONS

1. Nesting of ODF Allocations Within Each O-D/Segment

- Network ODF allocations for each O-D/segment are nested into a shared inventory of seats, in order of normal nested booking classes

  -- each ODF allocation is treated as a fare class "protection level" within the O-D/segment "nest"

  -- each flight leg still has a discrete allocation of seats for each segment/O-D itinerary

  -- simply summing discrete allocations gives sub-optimal nested booking limits within each O-D/segment nest
EXAMPLE: 2 segments on Leg A-B  
(Capacity = 100)

<table>
<thead>
<tr>
<th>ODF</th>
<th>Optimal Allocation</th>
<th>Segment Nesting</th>
</tr>
</thead>
<tbody>
<tr>
<td>YAB</td>
<td>8</td>
<td>42</td>
</tr>
<tr>
<td>BAB</td>
<td>12</td>
<td>34</td>
</tr>
<tr>
<td>MAB</td>
<td>06</td>
<td>22</td>
</tr>
<tr>
<td>QAB</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>YAC</td>
<td>18</td>
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<td>MAC</td>
<td>23</td>
<td>33</td>
</tr>
<tr>
<td>QAC</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
2. Joint Allocation and Nesting Within O-D/Segment

- Published by Curry in Transportation Science (1990)

-- approach jointly finds optimal allocation to each "O-D nest" and nested limits on each booking class within the nest

-- optimal solution to the formulated problem

-- still a discrete allocation of seats to each segment/O-D (i.e., "O-D nest")

- Both approaches above can have positive revenue impacts compared to leg/booking class control provided that number of discrete O-D nests does not become large

- Otherwise, negative revenue impacts can result when implemented as a control methodology
3. Nesting of ODF Allocations on Shadow Prices

- Described in Williamson's (1988) MIT Master's thesis

  -- optimal ODF allocations are ranked and nested in order of shadow price values derived from the optimization algorithms

  -- the shadow price of an ODF allocation is the amount by which total expected network revenue will increase (or decrease) if one additional seat is allocated to that ODF

  -- on each flight leg, ODFs with highest shadow prices values receive greatest availability -- ODF allocations are treated as "protection levels" for nesting purposes
EXAMPLE: 2 segments on Leg A-B
(Capacity = 100)

<table>
<thead>
<tr>
<th>ODF</th>
<th>Optimal Allocation</th>
<th>Shadow Price</th>
<th>Nested Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>YAB</td>
<td>8</td>
<td>225</td>
<td>100</td>
</tr>
<tr>
<td>BAB</td>
<td>12</td>
<td>200</td>
<td>92</td>
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<td>YAC</td>
<td>18</td>
<td>190</td>
<td>80</td>
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<td>BAC</td>
<td>7</td>
<td>165</td>
<td>62</td>
</tr>
<tr>
<td>MAB</td>
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<td>110</td>
<td>55</td>
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<tr>
<td>MAC</td>
<td>23</td>
<td>40</td>
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<td>QAC</td>
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<td>26</td>
</tr>
<tr>
<td>QAB</td>
<td>16</td>
<td>0</td>
<td>16</td>
</tr>
</tbody>
</table>

- Implementation into control structure possible through virtual inventory classes defined by shadow price ranges

- Nesting of optimal ODF allocations on current shadow prices results in theoretically sub-optimal booking limits for different ODFs

- Yet, a large number of dynamic booking simulations of this approach as a control methodology show consistent and substantial revenue improvement over leg/booking class control
4. Network "Bid-Price" Approaches

- Developed at MIT: Simpson (1989) and Williamson (1990)

-- network optimization can also produce shadow prices on the capacity constraint associated with each flight leg, or "bid prices"

-- Bid Price Control of seat inventories simply requires a comparison of the fare of the requested ODF itinerary and the sum of the bid prices involved in the itinerary.

-- Implementation requires frequent (real-time?) updating of network bid prices to overcome absence of booking limit controls

- Bid Price Approach is a sub-optimal control application of optimal network solution, which overcomes negative impacts of discrete ODF allocations through "implicit nesting" of availability through bid price evaluation decision.
SUMMARY -- NETWORK OPTIMIZATION APPROACHES

- Network optimization approaches produce optimal ODF seat allocations over a network of flights:
  -- require ODF demand forecasts and fares
  -- generate partitioned ODF allocations that must be "nested" in sub-optimal ways to have positive revenue impacts

- Truly optimal solution for control of ODF itineraries over a network requires an approach that
  -- accounts for nesting of ODFs explicitly
  -- allows "desirability" of ODFs to change as demand materializes
  -- recognizes dynamic nature of future booking process
  -- overcomes "small number" problems of forecasting ODF demands
CONCLUSIONS

- Network optimization methods produce an optimal solution to an assumed mathematical formulation of the O-D/segment control problem.

- Implementation of optimal solutions in actual reservations control structures can lead to negative revenue impacts if done incorrectly.

- Nesting of optimal network ODF allocations for control purposes is a sub-optimal solution, although some nesting approaches consistently produce better revenue impacts than others.

- No one has formulated, let alone "solved" the dynamic, nested ODF network seat inventory control problem.
APPLICATION OF NETWORK SOLUTIONS TO O-D SEAT INVENTORY CONTROL

Elizabeth L. Williamson
Flight Transportation Laboratory
Massachusetts Institute of Technology

Presented to
MIT/Industry Cooperative Research Program
May 23, 1991
Cambridge, MA
Introduction

Reviewing network seat inventory control techniques and applying them to three different multi-leg examples, using real airline data:

1) 2 Leg Flight
   - 4 Fare Classes
   - 3 OD Pairs
   - 12 ODF Combinations

2) 3 Leg Flight
   - 4 Fare Classes
   - 6 OD Pairs
   - 24 ODF Combinations

3) 4 Leg Flight
   - 4 Fare Classes
   - 10 OD Pairs
   - 40 ODF Combinations
Network Solutions
Nested on Shadow Prices

- Network formulation used to find seat allocations for each ODF over an entire network of flights.

- Distinct allocations are nested according to the shadow price of each ODF.

- Shadow Price: The amount the optimal system revenue value would change if one more seat was made available to the given ODF.
Nested Deterministic by Shadow Prices

3 Leg Example
Leg BC - Capacity=90

<table>
<thead>
<tr>
<th>ODF</th>
<th>Seats Allocated</th>
<th>Fare</th>
<th>Shadow Price</th>
<th>Booking Limit</th>
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<tr>
<td>ACY</td>
<td>2</td>
<td>519</td>
<td>322</td>
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<td>BCY</td>
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<tr>
<td>ADY</td>
<td>3</td>
<td>582</td>
<td>216</td>
<td>78</td>
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<td>ACB</td>
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<td>46</td>
</tr>
<tr>
<td>ACQ</td>
<td>14</td>
<td>231</td>
<td>34</td>
<td>42</td>
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<tr>
<td>BCB</td>
<td>12</td>
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<td>28</td>
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<tr>
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<td>379</td>
<td>13</td>
<td>16</td>
</tr>
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<td>15</td>
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<td>199</td>
<td>-167</td>
<td>0</td>
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</tbody>
</table>
NETWORK SOL'NS NESTED ON SHADOW PRICES

2 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

- NDSP
- NPSP
NETWORK SOL'NS NESTED ON SHADOW PRICES

3 Leg Flight

Load Factor

NDSP + NPSP

Percent Difference from Leg Based EMSR

NDSP + NPSP

0.76 0.8 0.84 0.88 0.92 0.96

0 0

0

0 0

-1 -2 -3
NETWORK SOL'NS NESTED ON SHADOW PRICES

4 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

- NDSP
- NPSP
EXAMPLE

Single Leg, 4 Fare Classes

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>STD</th>
<th>FARE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
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<td>7</td>
<td>500</td>
</tr>
<tr>
<td>M</td>
<td>15</td>
<td>5</td>
<td>350</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>Q</td>
<td>25</td>
<td>8</td>
<td>150</td>
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</table>

ALLOCATIONS

<table>
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<tr>
<th></th>
<th>DETER</th>
<th>PROB</th>
<th>EMSR</th>
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<tbody>
<tr>
<td>Y</td>
<td>20</td>
<td>27</td>
<td>17</td>
</tr>
<tr>
<td>M</td>
<td>15</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>31</td>
<td>27</td>
</tr>
<tr>
<td>Q</td>
<td>25</td>
<td>23</td>
<td>36</td>
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BOOKING LIMITS

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<tr>
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<th>NDSP</th>
<th>NPSP</th>
<th>EMSR</th>
<th>OPTIMAL</th>
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<tr>
<td>Y</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
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<tr>
<td>M</td>
<td>80</td>
<td>73</td>
<td>83</td>
<td>83</td>
</tr>
<tr>
<td>B</td>
<td>65</td>
<td>54</td>
<td>63</td>
<td>62</td>
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<tr>
<td>Q</td>
<td>35</td>
<td>23</td>
<td>36</td>
<td>33</td>
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</table>
Initial Allocations

3 Leg Example
AB Leg - Capacity=75

<table>
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<tr>
<th>Distinct Deterministic</th>
<th>Distinct Probabilistic</th>
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<tbody>
<tr>
<td>Y M B Q</td>
<td>Y M B Q</td>
</tr>
<tr>
<td>AB 25 3 7 26</td>
<td>AB 28 5 10 26</td>
</tr>
<tr>
<td>AC 2 1 4 4</td>
<td>AC 3 0 1 0</td>
</tr>
<tr>
<td>AD 3 0 0 0</td>
<td>AD 2 0 0 0</td>
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</table>
Difference in Allocations  
(Prob - Deter)

<table>
<thead>
<tr>
<th></th>
<th>Y</th>
<th>M</th>
<th>B</th>
<th>Q</th>
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<tr>
<td>AB</td>
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<td>AC</td>
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<td>-1</td>
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<tr>
<td>AD</td>
<td>-1</td>
<td>0</td>
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</table>
Comparison of Allocations
Over 15 Revisions

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<th>Mean</th>
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<th>Prob Alloc</th>
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<tr>
<td>AB Y</td>
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<td>25</td>
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<tr>
<td>25.1</td>
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<td>5.9</td>
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<td>15</td>
</tr>
<tr>
<td>2.6</td>
<td>3</td>
<td>11</td>
</tr>
</tbody>
</table>
Partially Nested versus Fully Nested

Partially Nested (Curry):

- Determine discrete allocations for each OD, based on expected revenue from nested fare classes.

- Determine fare class booking limits within each OD allocation.
Expected Revenue per Seat

O-D Pair BC

Expected Revenue ($)

Number of Seats
## Fully Nested versus Partially Nested

### 3 Leg Example

Leg BC - Capacity=75

<table>
<thead>
<tr>
<th>ODF</th>
<th>NDSP Allocations</th>
<th>NDSP BL</th>
<th>DOD-NFC BL</th>
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</thead>
<tbody>
<tr>
<td>ACY</td>
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<td>75</td>
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<tr>
<td>ACM</td>
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<td>38</td>
<td>3</td>
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<tr>
<td>BDQ</td>
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</tr>
</tbody>
</table>
FULLY NESTED VS. PARTIALLY NESTED

2 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

☐ NDSP  +  DOD-NFC
FULLY NESTED VS. PARTIALLY NESTED
3 Leg Flight

Load Factor
- NDSP + DOD-NFC
FULLY NESTED VS. PARTIALLY NESTED
4 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

NDSP + DOD-NFC
Bid Price

- Bid Price is a Shadow Price for the capacity constraints.

- Obtained from the same network formulations.

- The marginal value of the last seat of a given flight leg.

- Bid Prices establish a "cutoff" value for each flight leg, on which decisions can be made whether to accept or reject a given O-D/fare class request.

- For a single leg itinerary, a fare class is open for bookings if the corresponding fare is greater than the bid price, or shadow price, for the leg.

- For a multi-leg itinerary, fares must be greater than the sum of the bid prices from the respective flight legs.
3 Leg Example
Capacity=75

A-B  34
B-C  197
C-D  169

BC:  197  AC:  231  AD:  400

Y  440  Y  519  Y  582
M  315  M  344  M  379
B  223  B  262  B  302
Q  197  Q  231  Q  269
DETERMINISTIC NETWORK METHODS
2 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

NDSP + BID
DETERMINISTIC NETWORK SOLUTIONS

3 Leg Flight

Load Factor

NDSP + BID
DETERMINISTIC NETWORK METHODS

4 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

□ NDSP  +  BID
Revenue Impacts vs. Revisions
3 Leg Example - 98% Load Factor

Percent Difference from Leg Based EMSR

Number of Revisions

□ NDSP + BID
PROBABILISTIC NETWORK METHODS

2 Leg Flight

Load Factor

NPSP + PBID
PROBABILISTIC NETWORK SOLUTIONS

3 Leg Flight

Load Factor

NPSP + PBID
PROBABILISTIC NETWORK METHODS

4 Leg Flight

Percent Difference from Leg Based EMGR

Load Factor

NPSP + PBID
## UPPER BOUND

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>STD DEVI</th>
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<tbody>
<tr>
<td>ABY</td>
<td>36.12</td>
<td>14.91</td>
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<td>ABQ</td>
<td>34.06</td>
<td>25.96</td>
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</table>

## ACTUAL DEMAND

<p>| | | | |</p>
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<thead>
<tr>
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<th></th>
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</tr>
</thead>
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<tr>
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<td>14</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>ABM</td>
<td>18</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>ABQ</td>
<td>39</td>
<td>32</td>
<td>34</td>
</tr>
</tbody>
</table>
UPPER BOUND COMPARISON

2 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

- NDSP
- BID
- UPPER
UPPER BOUND COMPARISON

3 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

□ NDSP  + BID  ○ UPPER
UPPER BOUND COMPARISON
4 Leg Flight

Percent Difference from Leg Based EMSR

Load Factor

- NDSP
- BID
- UPPER
Summary

- Nested Deterministic on Shadow Prices outperforms Nested Probabilistic on Shadow Prices.

- Given full ODF forecasts, better to use a fully nested method, such as NDSP, rather than a partially nested method.

- Deterministic Bid Price approach performs well and uses a very simple control methodology, however it is important to be able to make frequent revisions using such an approach.

- Using Upper Bound, the true potential from better control of seat inventories over current leg based approaches can be determined.
Planning and Scheduling of Tasks in a Dynamic Environment

Lyman R. Hazelton

23 May 1991
The Strategic Control of systems requiring *planning* and *scheduling* of activities is called *Operations Management*.

- Reasoning about the future in a dynamic environment.
- Determination of the time that a state or process should be maintained.
- Situation dependent objectives.
- No final system state.
- Often involve non-quantifiable parameters.
A decision was made to attempt to solve the problem with an "Expert Systems" approach. However, existing AI planning methods

- Were based on a back-chained, goal seeking technology.
- Have been shown to be NP-hard or even Non-terminating for conjunctive goals.
- Assumed a single actor, non-stochastic universe.
- Had no logic or even representation for time, dependent activities.

In summary, the automatic reasoning technology necessary to attack the problem did not exist.
At the time the research was initiated:

- There were NO programs or even algorithms for temporal database management
- There were NO data representations for concurrent temporally bounded information
- Automatic plan generation was restricted to
  - Single Actor Domains
  - Determinate Domains
  - Instantaneous Actions
Operations Management Model

- Learn
- Observe
- State
- Models
- Simulate
- Projection
- Goals
- Analyze
- Plan
- Actions
- Execute
RULESYS

Observations

Temporal System Analyzer
(Logical Inference Engine)

Advice

Assertions

Requests

Schedules

Time Map Manager
(Temporal Database Manager)

TIMEBOX

Scheduler

SCHEDULE
Plan: PAINT LADDER

Procedure:
GET PAINT
GET LADDER
APPLY-PAINT LADDER

Results:
PAINTED LADDER

Plan: PAINT CEILING

Procedure:
GET PAINT
Goal: NEAR CEILING
APPLY-PAINT CEILING

Results:
PAINTED CEILING

Goal:
PAINTED CEILING
and
PAINTED LADDER
Goal: PAINTED CEILING

Plan: PAINT CEILING
Procedure:
  GET PAINT
  Goal: NEAR CEILING
  APPLY-PAINT CEILING
Results:
  PAINTED CEILING

Goal: PAINTED LADDER

Plan: PAINT LADDER
Procedure:
  GET PAINT
  GET LADDER
  APPLY-PAINT LADDER
Results:
  PAINTED LADDER
Truth Maintenance
A first attempt to extend logic into a dynamic environment.

\[ R: p \cdot q \rightarrow r \cdot \{R \ p \ q\} \top \ r \]

\[ \sim p \mid \sim q \Rightarrow r \]

\[ \begin{array}{ccc}
R & p & q \\
\downarrow & \downarrow & \rightarrow \\
& r \\
\end{array} \]

"
● Inferred evolution

\[ R: p \cdot q \rightarrow r \cdot \neg p \cdot \]
\[ \{R p q\} \vdash r \]
\[ \neg p \mid \neg q \supset r \quad (TM) \]
Introduce EXPLICITLY the TIME INTERVAL during which a proposition (was, is, will be) true:

\[ p(\tau) \]

where \( \tau \) is a time interval having a starting time and an ending time.
- Persistence:

\[ R: \ p \rightarrow q \]

\[ \sim p \sim q \quad \text{(NO TM)} \]

If it is raining \((p)\), the roads will be wet \((q)\).

But if it stops raining \((\sim p)\), the roads do not instantly become dry. Wet roads persist.
Temporal Logic (continued)

Rules of Inference

Modus Ponens:

\[ p \rightarrow q \]

\[ p(\tau) \]

\[ \therefore q(\tau) \text{ Non-persistent} \]

\[ \therefore q(\text{start(}\tau), \infty) \text{ Persistent} \]
Inferred evolution revisited

\[ R: p(\tau_1) \cdot q(\tau_2) \rightarrow r(\tau_1 \cap \tau_2) \cdot \neg p(\tau_1 \cap \tau_2) \]

\[ \{ R p(\tau_1) q(\tau_2) \} \vdash r(\tau_1 \cap \tau_2) \]

\[ \{ R p(\tau_1) q(\tau_2) \} \vdash \neg p(\tau_1 \cap \tau_2) \]

\[ \neg p(\tau) \vdash \neg q(\tau) \supset r(\tau) \]

\[ R p(\tau_1) \quad q(\tau_2) \]

\[ \downarrow \quad \downarrow \quad \downarrow \]

\[ r(\tau_1 \cap \tau_2) \cdot \neg p(\tau_1 \cap \tau_2) \]
The problem stems from the fact that the reasoner's BELIEF (i.e., knowledge) changes during the reasoning process.

There are TWO time intervals involved in temporal reasoning.
- The **ACTIVITY** interval, during which the proposition *(was, is, will be)* true

- The **BELIEF** interval, during which the reasoner believes a proposition about some activity interval to be true
Types of consequents

Bounded

Persistent

Decayed

Probabilistic
Figure 3.2: Temporal Relations
FACT:
thing
attribute

Past

History Cell

Future

$\mathbf{t}_1 \quad \mathbf{t}_2$
CONTRIBUTIONS

• Extension to Non-monotonic Temporal Logic by introducing Belief Intervals

• Introduced Persistence as rule specific knowledge

• Designed structures to represent time dependent knowledge

• Implemented an efficient temporal database management program
CONTRIBUTIONS
(continued)

• Implemented a Temporal System Analyzer employing Extended Temporal Logic and Persistence

• Created a Scheduler Program, thereby extending Domain Independent Planning to include Parallel, Time Bounded, Non-Instantaneous Actions
Novel ideas and methods developed for this system include

- A highly compact representation for the description of discrete time dependent processes.
- An efficient time based logical inference system.
- Deeper understanding of human cognitive and communication processes involved in Command and Control Systems.
- A replacement of "Truth Maintenance" by "History Maintenance", and a better understanding of default versus dynamic logic.
Concentration in U.S. Air Transportation: An Analysis of Origin-Destination Markets since Deregulation

Jan Van Acker

Flight Transportation Laboratory
May 23, 1991
Agenda

I. Thesis Objective and Methodology

II. Analysis of Top 100 Markets

III. Analysis of Dominated City Markets

IV. Conclusions
I. Thesis Objective

- Study effects of deregulation on concentration
- Focus on Origin-Destination City-Pair Markets
Focus on Concentration in O-D City-Pairs

- Other studies found:
  - Fares are positively related to concentration
  - Concentration levels have decreased on average

- Our study looked at:
  - Top 100 domestic O-D markets
  - Markets out of dominated cities
Measurement of Concentration

- Concentration indices used:
  - Hirschman-Herfindahl Index (HHI)
  - 2-Firm Concentration Ratio (C2)
  - Number of Competitors with >5% Market Share (Number of Effective Competitors)

- Market share is measured in terms of local passengers transported in market
II. Changes in Concentration in Top 100 Markets

- Markets ranked 1-100 in terms of local passengers transported in 1989

- Cumulative number of passengers was 31% of U.S. domestic total in 1989


- With focus on 1979, 1985, 1989
Average Number of Effective Competitors was One more in 1989 than in 1979

<table>
<thead>
<tr>
<th>Year</th>
<th>Average Number of Effective Competitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>2.7</td>
</tr>
<tr>
<td>1981</td>
<td>3.3</td>
</tr>
<tr>
<td>1983</td>
<td>3.5</td>
</tr>
<tr>
<td>1985</td>
<td>3.8</td>
</tr>
<tr>
<td>1987</td>
<td>3.6</td>
</tr>
<tr>
<td>1989</td>
<td>3.7</td>
</tr>
</tbody>
</table>

![Graph showing the number of carriers with >5\% MS over years 1979 to 1989]
56 Markets Were Served by Four or More Effective Competitors in '89, as Compared to only 16 in '79

<table>
<thead>
<tr>
<th># Carriers With &gt;5% MS</th>
<th>1979</th>
<th>1985</th>
<th>1989</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>24</td>
<td>29</td>
</tr>
<tr>
<td>5 to 6</td>
<td>5</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>7 to 8</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

# of Carriers with >5% Market Share
62% of the Passengers Flew in Markets Served by 4 or More Effective Competitors in ‘89 -- only 18% in ‘79

<table>
<thead>
<tr>
<th># Carriers With &gt;5% MS</th>
<th>1979</th>
<th>1985</th>
<th>1989</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.5%</td>
<td>0.0%</td>
<td>0.7%</td>
</tr>
<tr>
<td>2</td>
<td>30.9%</td>
<td>12.6%</td>
<td>16.5%</td>
</tr>
<tr>
<td>3</td>
<td>45.8%</td>
<td>29.1%</td>
<td>20.5%</td>
</tr>
<tr>
<td>4</td>
<td>11.3%</td>
<td>26.3%</td>
<td>28.9%</td>
</tr>
<tr>
<td>5 to 6</td>
<td>6.5%</td>
<td>30.7%</td>
<td>30.2%</td>
</tr>
<tr>
<td>7 to 8</td>
<td>0.0%</td>
<td>1.2%</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

![Graph showing passenger frequency in % for different years and number of carriers with >5% market share.](image-url)
Average HHI Was Lower in 1989 than in 1979

<table>
<thead>
<tr>
<th>Year</th>
<th>Average HHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>4917</td>
</tr>
<tr>
<td>1981</td>
<td>4077</td>
</tr>
<tr>
<td>1983</td>
<td>3913</td>
</tr>
<tr>
<td>1985</td>
<td>3361</td>
</tr>
<tr>
<td>1987</td>
<td>3705</td>
</tr>
<tr>
<td>1989</td>
<td>3586</td>
</tr>
</tbody>
</table>

![Graph showing the trend of Average HHI from 1979 to 1989](image-url)
The Majority of the Markets Experienced a Decrease in HHI from 1979 to 1989

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-8000 to -6000</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-6000 to -4000</td>
<td>9</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>-4000 to -2000</td>
<td>19</td>
<td>29</td>
<td>4</td>
</tr>
<tr>
<td>-2000 to 0</td>
<td>47</td>
<td>49</td>
<td>37</td>
</tr>
<tr>
<td>0 to 2000</td>
<td>20</td>
<td>13</td>
<td>54</td>
</tr>
<tr>
<td>2000 to 4000</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>4000 to 6000</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total Decreased</td>
<td>76</td>
<td>85</td>
<td>41</td>
</tr>
<tr>
<td>Total Increased</td>
<td>24</td>
<td>15</td>
<td>59</td>
</tr>
<tr>
<td>Average Change</td>
<td>-1330</td>
<td>-1555</td>
<td>225</td>
</tr>
</tbody>
</table>

![Histogram of Change in HHI from 1979 to 1989](image)
The Non-Hub Markets Were Served on Average by a Greater Number of Effective Competitors in '89 than the Hub Markets

<table>
<thead>
<tr>
<th>Year</th>
<th>Hub Markets</th>
<th>Non-Hub Markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>1981</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>1983</td>
<td>3.7</td>
<td>3.4</td>
</tr>
<tr>
<td>1985</td>
<td>3.9</td>
<td>3.7</td>
</tr>
<tr>
<td>1987</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>1989</td>
<td>3.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Concentration Decreased from '79 to '89 in All but One of the Non-Hub Markets

<table>
<thead>
<tr>
<th>Change in # Carriers With &gt;5% MS</th>
<th>'79-'89</th>
<th>'79-'85</th>
<th>'85-'89</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4 to -3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-2 to -1</td>
<td>1</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>0</td>
<td>8</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>1 to 2</td>
<td>33</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>3 to 4</td>
<td>7</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>5 to 6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Decreased</td>
<td>1</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Total Increased</td>
<td>40</td>
<td>33</td>
<td>19</td>
</tr>
<tr>
<td>Average Change</td>
<td>1.10</td>
<td>0.33</td>
<td>1.43</td>
</tr>
</tbody>
</table>
But Was Higher in ‘89 than in ‘79 in 30% of the Hub Markets

<table>
<thead>
<tr>
<th>Change in # Carriers With &gt;5% MS</th>
<th>’79-’89</th>
<th>’79-’85</th>
<th>’85-’89</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4 to -3</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>-2 to -1</td>
<td>11</td>
<td>7</td>
<td>26</td>
</tr>
<tr>
<td>0</td>
<td>9</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>1 to 2</td>
<td>25</td>
<td>28</td>
<td>8</td>
</tr>
<tr>
<td>3 to 4</td>
<td>4</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>5 to 6</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Decreased</td>
<td>12</td>
<td>7</td>
<td>27</td>
</tr>
<tr>
<td>Total Increased</td>
<td>30</td>
<td>36</td>
<td>8</td>
</tr>
<tr>
<td>Average Change</td>
<td>1.12</td>
<td>-0.41</td>
<td>0.71</td>
</tr>
</tbody>
</table>
The Top 10 Markets Were on Average Less Concentrated than the Top 50 and Top 100 Markets

<table>
<thead>
<tr>
<th>Year</th>
<th>Top 100 Markets</th>
<th>Top 10 Markets</th>
<th>Top 50 Markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>86.6%</td>
<td>79.5%</td>
<td>83.9%</td>
</tr>
<tr>
<td>1981</td>
<td>79.2%</td>
<td>74.8%</td>
<td>77.7%</td>
</tr>
<tr>
<td>1983</td>
<td>78.4%</td>
<td>75.0%</td>
<td>77.0%</td>
</tr>
<tr>
<td>1985</td>
<td>73.3%</td>
<td>70.6%</td>
<td>71.8%</td>
</tr>
<tr>
<td>1987</td>
<td>74.7%</td>
<td>72.2%</td>
<td>74.3%</td>
</tr>
<tr>
<td>1989</td>
<td>73.6%</td>
<td>66.2%</td>
<td>73.3%</td>
</tr>
</tbody>
</table>
Conclusions of Top 100 Markets Analysis

- Average concentration was lower in '89 than in '79

- Concentration was lower in 70% of the markets

- Non-hub markets were better off on average in 1989 than hub markets

- Top ten markets were less concentrated on average than top 100 markets
III. Changes in Concentration in Top Ten Markets out of Dominated Cities

- Cities at which 60% of total passenger enplanements in 1985 were carried by one airline, or 85% by two:
  
  Atlanta  Detroit  Pittsburgh  
  Charlotte  Greensboro  Raleigh/Durham  
  Cincinnati  Memphis  St. Louis  
  Dayton  Minneapolis  Salt Lake City  
  Denver  Nashville  Syracuse  

- Markets ranked 1-10 in terms of local passengers transported in 1989 out of each of the cities
Changes in Concentration in Top Ten Markets out of Dominated Cities


- With focus on 1979, 1985, 1989
Average Number of Effective Competitors in 150 Markets Peaked in '85, but Was Still Higher in '89 than in '79

<table>
<thead>
<tr>
<th>Year</th>
<th>Dominated Airport Markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>2.2</td>
</tr>
<tr>
<td>1981</td>
<td>2.8</td>
</tr>
<tr>
<td>1983</td>
<td>2.8</td>
</tr>
<tr>
<td>1985</td>
<td>3.1</td>
</tr>
<tr>
<td>1987</td>
<td>2.9</td>
</tr>
<tr>
<td>1989</td>
<td>2.5</td>
</tr>
</tbody>
</table>

![Graph showing the average number of effective competitors over the years from 1979 to 1989.](image-url)
Average Number of Effective Competitors for each of the Dominated Cities

Top 10 Atlanta Markets

Top 10 Charlotte Markets

Top 10 Cincinnati Markets

Top 10 Dayton Markets
Average Number of Effective Competitors for each of the Dominated Cities

- **Top 10 Denver Markets**
  
  - # of Carriers with >5% MS
  - Graph shows a trend from 2.5 to 5.0 over the years.

- **Top 10 Detroit Markets**
  
  - # of Carriers with >5% MS
  - Graph shows a trend from 1.0 to 5.0 over the years.

- **Top 10 Greensboro Markets**
  
  - # of Carriers with >5% MS
  - Graph shows a trend from 1.0 to 5.0 over the years.

- **Top 10 Memphis Markets**
  
  - # of Carriers with >5% MS
  - Graph shows a trend from 1.0 to 5.0 over the years.
Average Number of Effective Competitors for each of the Dominated Cities

Top 10 Minneapolis Markets

Top 10 Nashville Markets

Top 10 Pittsburgh Markets

Top 10 Raleigh-Durham Markets
Average Number of Effective Competitors for each of the Dominated Cities

Top 10 Salt Lake City Markets

Year

Top 10 St. Louis Markets

Year

Top 10 Syracuse Markets

Year
## Changes in Concentration in the Top Ten Atlanta Markets

<table>
<thead>
<tr>
<th>O-D City-Pair Markets</th>
<th>HHI</th>
<th>'79-'89</th>
<th>'79-'85</th>
<th>'85-'89</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1989</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlanta Boston</td>
<td>5446</td>
<td>455</td>
<td>-547</td>
<td>1002</td>
</tr>
<tr>
<td>Atlanta Chicago</td>
<td>2949</td>
<td>-2538</td>
<td>-2031</td>
<td>-508</td>
</tr>
<tr>
<td>Atlanta Dallas/Fort Worth</td>
<td>5932</td>
<td>-350</td>
<td>-1968</td>
<td>1618</td>
</tr>
<tr>
<td>Atlanta Los Angeles</td>
<td>5089</td>
<td>-219</td>
<td>-656</td>
<td>437</td>
</tr>
<tr>
<td>Atlanta Miami</td>
<td>3737</td>
<td>-1004</td>
<td>-885</td>
<td>-119</td>
</tr>
<tr>
<td>Atlanta New York</td>
<td>3913</td>
<td>-935</td>
<td>-1294</td>
<td>359</td>
</tr>
<tr>
<td>Atlanta Orlando</td>
<td>5608</td>
<td>482</td>
<td>-880</td>
<td>1362</td>
</tr>
<tr>
<td>Atlanta Philadelphia</td>
<td>4097</td>
<td>-995</td>
<td>-410</td>
<td>-585</td>
</tr>
<tr>
<td>Atlanta Tampa</td>
<td>6002</td>
<td>955</td>
<td>-637</td>
<td>1593</td>
</tr>
<tr>
<td>Atlanta Washington</td>
<td>4701</td>
<td>-193</td>
<td>-721</td>
<td>528</td>
</tr>
<tr>
<td><strong>Total Decreased</strong></td>
<td>7</td>
<td>10</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>Total Increased</strong></td>
<td>3</td>
<td>0</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>4747</td>
<td>-434</td>
<td>-1003</td>
<td>569</td>
</tr>
</tbody>
</table>
Concentration Levels Decreased Substantially in Most of the Top Ten Syracuse Markets

<table>
<thead>
<tr>
<th>O-D City-Pair Markets</th>
<th>HHI</th>
<th>Change in HHI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1989</td>
<td>'79-'89</td>
</tr>
<tr>
<td>Syracuse Atlanta</td>
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<td>4</td>
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<tr>
<td>Average</td>
<td>5770</td>
<td>-2397</td>
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Concentration Increased in all Top Ten St. Louis Markets after the TWA-Ozark Merger

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<th>O-D City-Pair Markets</th>
<th>HHI</th>
<th>Change in HHI</th>
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<tr>
<td>St. Louis Phoenix</td>
<td>4780</td>
<td>-320</td>
</tr>
<tr>
<td>St. Louis San Francisco</td>
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<td>155</td>
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<tr>
<td>St. Louis Washington</td>
<td>8252</td>
<td>302</td>
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</table>

| Total Decreased                | 7    | 10     | 0      |
| Total Increased                | 3    | 10     |
| Average                        | 5336 | -326   | -1893  | 1567   |
Conclusions of Dominated City Markets Analysis

- Single trend of hub development led to decreased concentration through '85 at most of the cities, but to increases from '85 on

- Two-hub markets were less concentrated than one-hub markets in 1989

- Average concentration across the 150 markets was slightly lower in '89 than in '79
IV. Conclusions

- Concentration was lower in top 100 markets, both on average and in most of the markets.

- Concentration in non-hub markets decreased throughout period '79-'89 because of development of hub-and-spoke networks.

- These networks led to increases in concentration in most hub markets after 1985.
Conclusions

- Single trend of hub development led to decreases in concentration through '85 at most of the dominated cities, but to increases from '85 on

- Concentration was on average slightly lower in the 150 markets out of dominated cities in 1979 than in 1989, and was lower in half of the markets
Pricing in the Airline Industry
Current Practice and
Future Research

Theodore C. Botimer
MIT Flight Transportation Laboratory
Presentation to Cooperative Research Program
May 23, 1991
Presentation Outline

Overview

- Nature of Airline Competition
- Fare Product Differentiation
- Seat Inventory Management
- Pricing Strategies
- Role of the Pricing Analyst
- “The Ultimate Pricing Model”
- Theoretical Issues for Investigation

Case Study Analysis

- Case Study Overview
- Case Study Objectives
- O/D Market Choice
- ATL - BOS Market
- ATL - STL Market
- Conclusions
Nature of Airline Competition

- Hub and spoke route structures prevail in the industry allowing almost every major carrier to serve any O/D market

- Most competition on non-price level

- Dollar value of nonstop service is unclear

- Must consider strength of competitive position in each O/D market separately

- Characterize competition in all markets:
  • major players
  • level of service offered
  • number of flights per day offered
  • nonstop vs. nonstop competition

- Anticipate response to price changes:
  • who are the competitors?
  • do the competitors offer comparable service in the market?
  • how have competitors reacted to fare changes in the past?
  • what response will be given to hostile reactions by competitors?
Fare Product Differentiation

- Airlines seek to segment demand by offering differentiated fare products in different fare classes

- Delta offers tickets in 10 fare classes:
  1) F - full fare first class
  2) Y - full fare coach class
  3) B - reserved for military/convention/negotiated fares
  4) M - highest discount coach fare
  5) H - discount coach class fare
  6) Q - discount coach class fare
  7) K - reserved for competitive filings
  8) L - reserved for competitive filings
  9) A - first class free tickets
  10) W - coach class free tickets

- Differentiation occurs within fare classes
  - peak vs. off-peak fares
  - weekday vs. weekend fares
Fare Product Differentiation (con’t)

- Fare restrictions or “fences” used to control which type of consumer is able to purchase which type of ticket

- Common fare restrictions include:
  - advanced purchase requirements
  - Saturday night stayover
  - blackout periods
  - flight validity restrictions (good for travel between...)
  - ticket purchase restrictions (purchase tickets by...)
  - availability limits for discount fares
  - military discount fares
  - senior citizen discount fares
Seat Inventory Management (IM)

- Pricing sets O/D prices and restrictions

- IM decisions made with fixed prices and restrictions

- IM seeks to maximize revenue given fixed prices and restrictions

- IM controls price/seat quantity decisions
  - protect full fare seats
  - limit discount fares
  - strictly limit deep discount fare seat availability

- Matching stances require booking limits
  - strictly limited availability on competitive fare filings
Pricing Strategies and Their Effects

- Matching a fare
  • retain market share
  • possible drop in yield
  • remain listed on Page 1 of CRS
  • often done to remain competitive
  • viewed as price taker in the market

- Not matching a fare
  • possible loss of market share
  • maintain yield
  • may lose competitiveness
  • loss of goodwill

- Partially matching a fare
  • attempt to retain market share
  • reduce non-matching yield loss
  • market factors influence strategy
  • will be non-competitive at peak
  • accept that competitor offers low fare on all flights
Role of the Pricing Analyst

- Analysts do not look at operating costs

- Consider strength of competitive position in each O/D market

- Add routing restrictions to discount fares

- Pricing analysts should be familiar with own market and relevant hub:
  • traffic flows
  • flight load factors

- Be aware of fare differential effects
  • high differentials not seen on CRS
  • business travelers susceptible to higher differentials
  • not all fares registered in ATP listings are available in reality

- Must monitor the number of bookings to determine the effect on yield of changes
Ultimate Pricing Model

- Inputs:
  - published daily fare changes
  - system-wide flight schedule
  - price level (by O/D market & flight)

- Outputs:
  - Suggested strategy
    -- matching
    -- partial matching
    -- not matching
  - Projected impact on market share
  - Projected impact on revenue
  - Management reports telling:
    -- suggested matching decision
    -- implemented matching decision
    -- reasons for matching decision
  - Ability to run simulations
  - Ability to do what-if scenarios
Theoretical Issues for Investigation

- Joint seat/price optimization problem
- Optimal differential pricing strategies
- Model development for pricing strategies
  - matching
  - not matching
  - other pricing strategies
- Impacts of price changes
- Measurements of price elasticity
- Explore impacts of pricing strategies on:
  - profitability
  - load factor
  - yield
  - customer satisfaction
Case Study Overview

- Close look at 10 O/D markets

- Representative cross section of markets flown by Delta Airlines

- Quarterly analysis

- Examine quarterly data 1986:1 - 1990:2

- Give consideration to:
  • published fares
  • competitive responses
  • major price level changes

- Use information from several data bases:
  • PIPPS (Historical ATP data)
  • DOT O/D traffic stats (10% sample)
  • Official Airline Guide

- Preliminary analysis on two markets:
  • ATL - BOS
  • ATL - STL
Case Study Objectives

- Initial look at revenue management from pricing perspective

- Develop market by market case studies
  - Present a market overview
  - Characterize pricing practices
  - Analyze competitive environment
  - Uncover competitive characteristics
  - Highlight major market events

- Analyze the quality and level of detail of the available data sources

- Relate market strength to fare level
  - between carriers
  - over time

- Develop a measure of the sensitivity of travelers to changes in fare level

- Determine selling fares during the period

- Use available data to determine the effects of pricing decisions

- Discuss future directions for research
O/D Market Choice

Length of Haul

- Short Haul (<1000 miles)
- Medium Haul (1000-2000 miles)
- Long Haul (>2000 miles)

Nature of Competition

- Delta offers non-stop service
- Only competitors offer non-stop service
- No one offers non-stop service

Markets Chosen

1) ATL-BOS
2) ATL-SEA
3) ATL-STL
4) BOS-PHX
5) CLT-MSP
6) DFW-PHL
7) JAN-SDF
8) MSP-SAN
9) MSY-PWM
10) SAV-SAN
ATL - BOS Market Characteristics
1986:1 - 1990:2

- Two non-stop carriers during the period
  -- Delta
  -- Eastern

- Non-stop carriers flew 93% of all pax

- Frequency of approximately 12 daily non-stops each way

- Total traffic level of 925 passengers per day in both directions

- Carriers with ATL hub
  -- Delta
  -- Eastern

- Eastern Airlines strike in 1989:2
ATL–BOS Passengers
1986:1 – 1990:2

Passengers Thousands

Year:Quarter

ATL-BOS Market Share

1986:1 - 1990:2

Year:Quarter

- Delta
- Eastern
ATL--BOS Average Fare

1986:1 - 1990:2

Average Fare (dollars)

Year:Quarter

Delta
Eastern
### ATL - BOS
#### Summary Table

<table>
<thead>
<tr>
<th></th>
<th>Passengers</th>
<th>Revenues</th>
<th>Average Fare</th>
<th>Coupon Mileage</th>
<th>Passengers Per Day</th>
<th>Market Share</th>
<th>Revenue Share</th>
<th>Yield Per CPM</th>
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<td>0.00</td>
<td>9.68</td>
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</table>
ATL - STL Market Characteristics
1986:1 - 1990:2

- Four non-stop carriers during the period
  -- Delta
  -- Eastern
  -- Ozark
  -- TWA

- Non-stop carriers flew over 90% of all pax

- Frequency of approximately 15 daily non-stops each way

- Total traffic level of under 450 passengers per day in both directions

- Carriers with ATL hub
  -- Delta
  -- Eastern

- Carriers with STL hub
  -- Ozark
  -- TWA

- Eastern Airlines strike in 1989:2

- Ozark - TWA merger in 1987
ATL – STL Passengers
1986:1 – 1990:2

Year:Quarter

Passengers

ATL – STL Passengers
1986:1 – 1990:2

Year:Quarter

Passengers
ATL – STL Average Fare
1986:1 – 1990:2
ATL - STL Market Share

Year:Quarter

1986:1 - 1990:2

Market Share (%)
ATL - STL Average Fare

1986:1 - 1990:2

Year:Quarter

80 86:1  86:2  86:3  86:4  87:1  87:2  87:3  87:4  88:1  88:2  88:3  88:4  89:1  89:2  89:3  89:4  90:1  90:2

100 110 120 130 140 150 160 170 180

Average Fare ($)
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<th>Average Fare</th>
<th>Coupon Mileage</th>
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<td>-12.26</td>
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<td>0.00</td>
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</table>
Conclusions

- Carrier strength varies by O/D market

- Delta holds a stronger position in ATL - BOS than in ATL - STL

- Delta fare levels may have been too high in ATL - STL during the strike given its competitive position
Future Directions

- Quantify consumer price sensitivity and market share changes

- Determine relationships between market strength and fare levels

- Develop a model to characterize competitive structure of markets
CHANGES IN O-D PASSENGER TRAFFIC FLOWS

NEWARK AIRPORT

Chung Y. Mak
and
Professor Peter P. Belobaba
MIT Flight Transportation Laboratory

MIT / Industry Cooperative Research Program
Annual Meeting
May 24, 1991
BACKGROUND : PREVIOUS ANALYSIS

- Removal of Peop!Express from the New York (EWR) market has had the most significant impact on traffic flows.
- Domestic connecting passengers have dropped in both absolute and percentage terms at all three airports, suggesting a shift by carriers away from New York airports as domestic hubs.

Newark Airport (EWR)

- Stable departure levels since PE withdrawal, but fewer seats and reduced aircraft sizes.
- Major drop in on-board passengers after 1986-3; downward trend continues through 1989-3 for virtually all carriers.
- Local originating passengers cut by half when PE failed; levels have barely returned to pre-1984 levels.
- Domestic connecting passengers were similarly affected by PE withdrawal from EWR.
Total Seats Departed for Majors

All New York City Area Airports

Figure 1.2
Total Seats Departed for Majors (T9)

Figure 1.8
Total Seats Departing

Newark International

Figure 1.9
Total Onboard Pax for Majors

Newark International

Figure 2.3
Total Onboard Pax

Newark International

Onboard Pax (Million)

Figure 2.6
Total Connecting Pax (EWR)

(Ten Percent Sample)

Figure 3.5
Total Connecting Pax (EWR)

(Ten Percent Sample)

Figure 3.8
NEWARK AIRPORT

TRAFFIC FLOW ANALYSIS (Phase 2)

OBJECTIVE

- Identify and evaluate changes in O-D passenger traffic flow patterns through Newark (EWR) and alternative hub routings.
- Determine shifts in connecting traffic away from EWR in O-D markets previously served by PeoplExpress.

HISTORICAL DATA

- Ten percent ticket coupon sample provides passenger itinerary information by quarter from 1985 to 1989.
- Database Products Inc. “OD Plus” database used to extract data.
- Official Airline Guide (OAG), schedule data for each of the periods.
PASSENGER TRAFFIC FLOW ANALYSIS

DEMAND AND SUPPLY MEASURES

- Ten percent O-D passengers travelled between each selected city pair by carrier.
- Scheduled service in each city pair by carrier.

AIR CARRIERS

- "Major" U.S. carriers offering service to domestic destinations, defined to include smaller airlines with large market presences (e.g. Midway).
ANALYSIS METHODOLOGY

- Obtained top 500 US Domestic O-D markets in terms of passenger traffic for 1989.

- Selected markets served by PeoplExpress in 1986.

- Discarded all city pairs with New York as an Origin/Destination, leaving 50 sample markets.

- Used O-D Plus to obtain passenger traffic data for 3rd quarter 1986 for all major carriers serving these city pairs.

- Selected O-D pairs based on market share and passenger information for detailed analysis:
  
  - markets with greater than 5% market share by PeoplExpress in 1986 or;
  
  - markets with more than 20 passengers carried by PeoplExpress per day.

- A total of 20 markets were chosen based on these criteria.

- Used O-D Plus again to obtain detailed passenger traffic information by individual market and carrier from 1985-3 to 1989-3.
### 20 SELECTED O-D MARKETS

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<tr>
<th>Market</th>
<th>1986-3 PE Share</th>
<th>1986-3 Pax/Quarter</th>
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<td>ORL-CMH</td>
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</tr>
<tr>
<td>PIT-HOU</td>
<td>4.95%</td>
<td>3240</td>
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<td>PIT-LAX</td>
<td>4.91%</td>
<td>1810</td>
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<tr>
<td>WAS-MIA</td>
<td>5.74%</td>
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<td>WAS-BUF</td>
<td>9.36%</td>
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<tr>
<td>WAS-DEN</td>
<td>8.73%</td>
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<td>WAS-PVD</td>
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</tr>
<tr>
<td>BOS-LAX</td>
<td>1.14%</td>
<td>1920</td>
</tr>
<tr>
<td>BOS-ORL</td>
<td>1.80%</td>
<td>2110</td>
</tr>
<tr>
<td>BOS-PIT</td>
<td>16.45%</td>
<td>9490</td>
</tr>
<tr>
<td>BOS-SFO</td>
<td>1.86%</td>
<td>2530</td>
</tr>
<tr>
<td>BOS-WAS</td>
<td>3.44%</td>
<td>9220</td>
</tr>
<tr>
<td>BOS-DEN</td>
<td>12.10%</td>
<td>9320</td>
</tr>
<tr>
<td>BWI-DEN</td>
<td>6.45%</td>
<td>1930</td>
</tr>
</tbody>
</table>
FINDINGS

Aggregate : 20 O-D Markets

- Total traffic in selected O-D pairs decreased slightly since withdrawal of PeoplExpress in 1986-3.
  - Aggregate traffic decreased by 5.94% from 1986-3 to 1989-3.
- However, proportion of this traffic connecting through EWR dropped from 4.84% to 0.71% during the same period.
- In 1985, PeoplExpress carried 8% of total traffic in these markets.
- By 1989, Continental carried a total of 10% of traffic in these markets.
- However, only 1% was carried by CO via EWR.
Total Passengers for 20 Selected Market
10% Sample

Year

Passengers
Thousands
0 50 100 150 200

---

Total EWR

---
Total Market Share
20 Selected Markets

Year

Percent of Passengers
0% 5% 10% 15%

- CO - EWR
- CO - OTHER
- PE
- TOTAL - EWR
Disaggregate Market Analysis

Examples of market share changes 1985 to 1989 follow, showing PE, CO and the two competing carriers with the greatest increase in market share:

- "CO - Other" refers to Continental traffic routed primarily through other CO hubs.
Market Share Comparison
BOS – PIT

BOS-PIT:

- PE had 28% market share in 1985, virtually all of which was taken over by USAir (non-stop service).

- CO never recaptured significant market share.
Market Share Comparison
BOS – FMY

BOS-FMY:

- PE had peak market share of 45% in 1985, of which CO now carries only 9% via EWR.
- AA market share grew from 0 to 24% (CNX via RDU).
- DL also took over market share (via ATL and CVG).
BOS-DEN:

- CO has captured most of PE's 12% market share, but on non-stop service. UA also shows market share growth (non-stop service).
**BOS-WAS:**

- PE had 10% market share in 1985. CO did not capture any of this traffic (via EWR), except in 1987 when CO offered non-stop service to IAD.

- Greatest MS growth by US and UA (both non-stop services).
CHI - BDL:

- PE's 9% market share in 1985 was captured by CO via EWR until 1988, when UA increased non-stop service.
Market Share Comparison
PIT – LAX

PIT-LAX:

- PE carried up to 5% of market share in 1986 via EWR.
- CO increased its MS from 0 to 16% in 1987, but not via EWR (i.e. via IAH, DEN, CLE).
Market Share Comparison
WAS – BUF

WAS-BUF:

- PE carried 37% of market share in 1985, only 7% of which was captured by CO via EWR in 1987.
- Biggest market share gains went to UA (non-stop to IAD) and US (non-stop to BWI/DCA).
SUMMARY OF FINDINGS

- O-D routings with PeoplExpress in 1986 were almost exclusively through EWR, and PE had an average of 8% MS in 20 selected markets.

- After withdrawal of PeoplExpress from EWR:
  - CO became an effective competitor in many of these markets, but traffic was split between EWR, CLE, DEN, and IAH hubs.
  - Growth of alternative and new hubs operated by other carriers further reduced attractiveness of EWR connections.
O-D Routings
After PeopIExpress 1989
(via Continental Airlines)
O-D Routings
After PeoplExpress 1989
(Other Carriers)
CONCLUSIONS

- Withdrawal of PeoplExpress has had significant negative impact on connecting traffic levels at Newark.

- Continental took over from PeoplExpress, and Newark (EWR) became one of the 4 hubs operated by Continental with CLE, DEN, IAH.

- CO now serves many O-D pairs through it alternative hubs, providing a bigger choice of departures and more direct routings.

- CO did not replace PE as a competitor, its replaced PE as the hub operator of EWR.

- Development of existing and new hubs by other carriers captured additional EWR market share.
Airline Seat Inventory Control

For Group Passenger Demand

Presented by

Peter Belobaba
Tom Svrcek

May 1991
Individual Passenger Seat Inventory Control

Assumes Demand For Each Individual Fare Class Is Independent And Normally Distributed.

Definition

Expected Marginal Revenue (EMR) Of An Additional Seat Allocated To A Particular Fare Class Is

\[ EMR(i) = \text{Fare Class Revenue} \times \text{Probability of Selling Seat } i. \]

P( \( X > 0 \) ) = .999
EMR(1) = $500

P( \( X > 25 \) ) = .05
EMR(26) = $25
### Individual Passenger Seat Inventory Control

**Example: Setup**

<table>
<thead>
<tr>
<th>Total Fare Classes</th>
<th>4</th>
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<tbody>
<tr>
<td>Aircraft Capacity</td>
<td>100</td>
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</table>

<table>
<thead>
<tr>
<th>Fare Class</th>
<th>Demand Mean</th>
<th>Demand Stdev</th>
<th>Average Revenue</th>
</tr>
</thead>
<tbody>
<tr>
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<td>14</td>
<td>5</td>
<td>380</td>
</tr>
<tr>
<td>B</td>
<td>12</td>
<td>6</td>
<td>320</td>
</tr>
<tr>
<td>M</td>
<td>35</td>
<td>10</td>
<td>270</td>
</tr>
<tr>
<td>Q</td>
<td>42</td>
<td>12</td>
<td>220</td>
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## Individual Passenger Seat Inventory Control

### Results

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<tr>
<th>Seat No.</th>
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<td>118.19</td>
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<td>217.83</td>
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<td>16</td>
<td>159.93</td>
<td>98.66</td>
<td>263.91</td>
<td>217.32</td>
<td>290.79</td>
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</table>

### Fare Class Allocations

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<td>B</td>
<td>13</td>
</tr>
<tr>
<td>M</td>
<td>34</td>
</tr>
<tr>
<td>Q</td>
<td>37</td>
</tr>
</tbody>
</table>
Group Passenger Demand

Why Is Group Demand Different From Individual Passenger Demand?

- Group Demand Is Realized Many Months In Advance
  Examples: Rose Bowl, Mardi Gras ...

- Groups Negotiate For A Lower Fare
  (Bulk Pricing)

- Unused Bookings Are Absent From Seat Inventory For Months,
  Potentially Displacing Individual Passengers

- Cancellation Penalties Often Difficult To Enforce
  Due To Competitive Environment
Problem Statement

Given we receive a request for a group request of size S for a specific origin/destination and date.

What is the minimum group fare an airline should charge given that we may potentially displace S individual passengers?

"Answer:"

\[
\text{Min. Group Fare} = \frac{\text{Total Expected Revenue Of Displaced Individual Pax}}{\text{Size Of Group Request}}
\]

\[
\text{Example: } \frac{2,200}{20} = 110 \text{ Per Group Pax}
\]
Group Passenger Seat Inventory Control

Two Solution Methodologies

Case 1:
Assume Group Is Indivisible. Find The Itinerary With The Smallest Displacement Cost Of Individual Passengers.

Case 2:
Relax Indivisibility Constraint. Find Optimal Split Over N Possible Alternatives For Each Group Request.
Group Passenger Seat Inventory Control

Large Hub and Spoke Networks Operated by Today’s Major Carriers Allow for Several Different Routings (with Similar Departure and Arrival Times) For Many Origin – Destination Pairs.

For Example, Delta Air Lines Service Between:

New York (EWR/LGA/JFK) and Seattle (SEA)

<table>
<thead>
<tr>
<th>Dept</th>
<th>Arr</th>
<th>Flts</th>
<th>Stps/Via</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:20aE</td>
<td>11:35a</td>
<td>377/835</td>
<td>ATL</td>
</tr>
<tr>
<td>7:05aJ</td>
<td>12:30p</td>
<td>1429/1655</td>
<td>SLC</td>
</tr>
<tr>
<td>8:15aL</td>
<td>1:45p</td>
<td>467/233</td>
<td>DFW</td>
</tr>
<tr>
<td>8:20aE</td>
<td>1:45p</td>
<td>281/233</td>
<td>DFW</td>
</tr>
<tr>
<td>9:30aL</td>
<td>2:45p</td>
<td>937/623</td>
<td>CVG</td>
</tr>
<tr>
<td>9:50aE</td>
<td>2:45p</td>
<td>583/623</td>
<td>CVG</td>
</tr>
<tr>
<td>11:00aJ</td>
<td>8:23p</td>
<td>1601/301</td>
<td>MCO</td>
</tr>
<tr>
<td>11:29aL</td>
<td>5:10p</td>
<td>983/833</td>
<td>DFW</td>
</tr>
<tr>
<td>11:55aE</td>
<td>5:10p</td>
<td>887/833</td>
<td>DFW</td>
</tr>
<tr>
<td>3:29pL</td>
<td>8:25p</td>
<td>1187/367</td>
<td>CVG</td>
</tr>
<tr>
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<td>10:40p</td>
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<td>2</td>
</tr>
<tr>
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<td>8:25p</td>
<td>1038/367</td>
<td>CVG</td>
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<tr>
<td>5:10pE</td>
<td>12:25a</td>
<td>237/300</td>
<td>LAX</td>
</tr>
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<td>5:20pJ</td>
<td>10:40p</td>
<td>1425/1187</td>
<td>SLC</td>
</tr>
<tr>
<td>6:45pL</td>
<td>1:33a</td>
<td>729/625</td>
<td>ATL</td>
</tr>
<tr>
<td>6:50pE</td>
<td>1:33a</td>
<td>1421/625</td>
<td>SLC</td>
</tr>
</tbody>
</table>
Group Passenger Seat Inventory Control

Numerical Example: Setup

Dept Date: 12 JUL 91
Group Size: 15

Possible Outbound Itineraries

1)  
| DL 583 | EWR | 950A | CVG | 1142A | 72S |
| DL 623 | 108P | SEA | 245P | 72S |

2)  
| DL 99  | EWR | 340P | ATL | 640P | 757 |
| DL 197 | 652P | SEA | 910P | 757 |

3)  
| DL 887 | EWR | 1155A | DFW | 226P | 72S |
| DL 833 | 312P | SEA | 510P | 72S |

4)  
| DL 281 | EWR | 820A | DFW | 1055A | 72S |
| DL 233 | 1152A | SEA | 145P | 72S |

Published Fares for EWR/SEA on 12 JUL 91

<table>
<thead>
<tr>
<th>Class</th>
<th>Fare</th>
<th>Basis</th>
</tr>
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<tbody>
<tr>
<td>Y</td>
<td>$642.00</td>
<td>O/W</td>
</tr>
<tr>
<td>B</td>
<td>$425.00</td>
<td>O/W</td>
</tr>
<tr>
<td>M</td>
<td>$325.50</td>
<td>O/W</td>
</tr>
<tr>
<td>Q</td>
<td>$277.00</td>
<td>O/W</td>
</tr>
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</table>
Group Passenger Seat Inventory Control

Numerical Example: Results

Itinerary #1

<table>
<thead>
<tr>
<th>Seat</th>
<th>Flt 583</th>
<th>Flt 623</th>
<th>Itin #1</th>
</tr>
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<tbody>
<tr>
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<td>24.40</td>
<td>97.20</td>
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<td>135</td>
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<td>137</td>
<td>21.59</td>
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<td>114.58</td>
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<td>138</td>
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<td>109.71</td>
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<td>19.53</td>
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<td>17.72</td>
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</tr>
<tr>
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<td>16.21</td>
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<td>94.12</td>
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<td>144</td>
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<td>66.82</td>
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</tr>
<tr>
<td>150</td>
<td>10.23</td>
<td>65.29</td>
<td>75.52</td>
</tr>
</tbody>
</table>

Leg 1     Leg 2     Total
Min. Group Fare Calculation => \( \frac{1426.75}{15} = 95.12 \)
Group Passenger Seat Inventory Control

Group Booking Model Output

<table>
<thead>
<tr>
<th>Rank</th>
<th>Itin Out</th>
<th>Outbound</th>
<th>Min. Group Fare</th>
<th>Request for 15 Pax</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Leg 1</td>
<td>Leg 2</td>
<td></td>
</tr>
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<td>1</td>
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<td>$236.51</td>
</tr>
</tbody>
</table>

Lowest Published Fare for EWR/SEA on 12JUL91: $277.00

Minimum Group Fare: $87.80

Negotiation Does The Rest!
Group Passenger Seat Inventory Control

What Is The Optimal Reduced Fare?

For The Carrier:

$277.00

For The Group:

$87.80

Competitive Advantage

Carrier Implementing Displacement Cost Strategy Has

$277.00 - $87.80 = $189.20

Of "Competitive Leverage".
Group Passenger Seat Inventory Control

Case 2: Relaxation Of Indivisible Group Constraint

<table>
<thead>
<tr>
<th>Group Seat</th>
<th>Itin 1</th>
<th>Itin 2</th>
<th>Itin 3</th>
<th>Itin 4</th>
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<td>246.32</td>
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<td>88.85</td>
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Model Output

<table>
<thead>
<tr>
<th>Optimal Split Over All Itineraries</th>
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<tbody>
<tr>
<td>Itinerary 1 5 Pax</td>
</tr>
<tr>
<td>Itinerary 4 10 Pax</td>
</tr>
</tbody>
</table>

Minimum Group Fare (Divided) $81.79
Minimum Group Fare (Undivided) $87.80
Group Passenger Seat Inventory Control

Question:

Why Are Groups Different From Traditional Bulk Pricing?

Answer:

In Bulk Pricing, Marginal Cost Of Each Additional Item Is Non-Increasing.

Example:

- 6 Bagels at $ 0.40 / item
- 24 Bagels at $ 0.30 / item

But:

- 6 group pax at $ 175.00 / pax
- 24 group pax at $ 189.00 / pax

Each Additional Passenger We Displace Has A Higher Expected Marginal Revenue Than The Previous One.

The Larger The Group, The Higher The Average Fare
Group Passenger Seat Inventory Control

**User Optimal Strategy**

- Be Flexible In Times / Dates
- Be Willing To Split Up
- Book Only As Many Seats As You Need

**Carrier Optimal Strategy**

- Find "Minimum Displacement" Seats For Each Requested Itinerary
- Try To "Split" Groups When Possible
- Book Only "Genuine" Seats
Conclusions

- Minimum Group Fare Based On Displacement Of Individual Passengers

- No Distribution Assumptions Necessary For Group Passenger Demand

- Given N Outbound Itineraries And R Return Itineraries, We Can Find The Best Of N * R Possible Combinations

- Optimal Mix Of Divisible Group is No More "Difficult". All Necessary Information Exists!

- Better Utilization Of Excess Capacity Means Greater Revenue Potential For Airlines
Airline Crew Scheduling Re-visited

Presentation at the
MIT/FTL -Industry Cooperative Research Program Review
May 23/24, 1991

Professor Robert W. Simpson
Problem Statement

GIVEN:

1. A fixed schedule of flights $F$ for one type of aircraft
   - a flight is one or more flight legs
   - arrival / departure times are fixed
   - schedule is cyclic over a day or week, $C$
   - schedule remains in effect over planning horizon, $H$

2. A set of crew bases $B$ where a number of crews $N_B$ are domiciled to fly this type of aircraft

FIND:

the cheapest set of work schedules, or "bidlines" $b$ for these crews during $H$ which does not violate work rules imposed by regulations or airline/union agreements;

- a crew trip $t$ consists of a series of flights to be flown starting from base and returning within one or more days

- a work schedule $b$ is a set of trips away from base on various days of the planning horizon, $H$
Typical Crew Work Rules - 1

1. Regulatory Rules
   (imposed by civil aviation authorities for safety)

   - Maximum Daily Flight Hours
   - Maximum Weekly (or 7 day period) Flight Hours
   - Maximum Monthly Flight Hours
   - Maximum Duty Hours (duty time is time without rest)
   - Minimum Off-Duty Interval

Note- Crew trips and bidlines which conform to these rules will be called legal or feasible.

These rules limit crew utilization to be substantially less than that expected by airlines from their aircraft, and mean that crews and aircraft cannot remain together during trips away from base. It is desirable to estimate the minimum number of crews required to cover one cycle of a given schedule as it would give a lower bound on the number of crew trips which must be generated. It is easy to compute the maximum number of airborne crews, but due to these constraints it is less than the minimum required crews.

Due to the aircraft flying perhaps 18 hours per day, and a daily duty limit of 12 or 14 hours, some crews must start their duty in the middle of the day to cover late night flights. Due to the minimum off-duty interval of 8-10 hours, crews on late night flights cannot start flying on the earliest flights the next morning.
Basis for Crew Costs

There are two kinds of crews: cockpit and cabin.

The cockpit crew flies together for one month, paired differently each month. Each aircraft requires a fixed crew.

The cabin crew complement has a minimum, but higher loads causes more members on certain legs. Changing reservation information can change work schedules dynamically.

There are three components which determine the monthly pay of crew members at a US Airline:

1. Monthly Base Pay - independent of hours flown
   - depends on grade and longevity

2. Hourly Flight Pay - $ per flight hour
   - depends on aircraft type

3. Trip Credit Pay - $ per trip away from base
   - depends on details of trip itinerary
   - may be zero

4. Overnight Costs - costs of meals, food, and transport to overnight crew away from base
Typical Crew Work Rules - 2

2. Airline/Union Trip Agreements

- Daily Flight Guarantee (eg. min. hours if called to duty)
- Flight/Duty Ratio Guarantee (eg. flight/duty time > 0.5)
- Flight/ Trip Ratio Guarantee (eg. flight/trip time > 0.25)
- Maximum No. of Daily Landings
- Deadhead Time is Flight Time

Note- These rules may cause a "penalty" to the airline in the form of extra pay and hourly credit to be assigned to a particular crew trip if it violates them. The total flight hours paid in a crew schedule may exceed the number of hours flown in the aircraft schedule.

Deadheading is flying the crew as passengers to/from base to other stations where their flying begins or ends.
Typical Crew Work Rules - 3

3. Airline/Union Bidline Agreements

- Max. Monthly Flight Hours
- Min. Monthly Flight Hours
- Min. Days Off per month
- Min. Weekends Off per Month
- Max. Duty Hours per Week
- Min. Off Duty Time at Base
- Max. Percentage for Reserve Crew Bidlines

These rules affect the monthly pattern of work for crews but generally do not cause extra costs. Whereas an aircraft may fly 300 hours per month, crews are limited to less than 100, so there are 3-5 times as many crews as aircraft.

Note- Due to schedule deviations caused by weather, crew sickness, or aircraft equipment failures, reserve crews are given bidlines which mainly consist of periods when they are "On-Call" and must be able to report for duty within 1 or 2 hours. There may be a few flights actually scheduled into a reserve bidline, caused perhaps by holidays or schedule changes.
The Current Airline Crew Scheduling Process

Stage 1. - Generation of Feasible Crew Trips from Bases
Stage 2. - Selection of "Optimal" Trips from Bases
Stage 3. - Construction of Crew Bidlines for Bases
Stage 4. - Construction of Reserve Crew Bidlines for Bases
Stage 5. - Execution of Crew Bidding Process

Note: 1. It is a sequential, heuristic Process and is not optimal, even if some of the stages are done optimally.

2. There should be some feedback of crew scheduling problems into the aircraft scheduling and airline market service planning. At present, this feedback does not exist since crew scheduling is done by airline flight operations personnel late in the airline schedule planning process. There is a need for some early assessment of crew scheduling problems in airline schedule development.

3. The availability and continual use of reserve crews affects the desirability of detailed optimal planning of fixed monthly bidlines.

4. A related process is crew re-scheduling by flight operations personnel when deviations from schedule plan are occurring. There is a need for good methods of solving real time, operational crew scheduling problems to minimize additional costs from disruptions.
Stage 1 - Generate Feasible Crew Trips

STEP 1 - Establish "Flights", F

For various reasons, it may be desirable to have an unbroken sequence of flights or flight legs; i.e., there may be some arbitrary specification of where crew connections can be made. Even though their flight number may change for marketing reasons, here these sequences will be called flights, f, belonging to a set F. Every crew trip t will now consist of a sequence of these flights.

STEP 2 - Generate feasible (or legal) Crew "Trips", T

Since there are a number of necessary and desirable attributes for a crew trip, it is necessary to generate each trip individually. It is not possible to create a crew "circulation flow". The number of feasible crew trips may be of the order of a million for a typical US domestic fleet of 100 aircraft, and in the next step, (the selection of the best trips to "cover" the schedule), the solution may only involve a set of trips of the order of twice the number of aircraft in the fleet, i.e., we are looking for the best 200 crew trips. Furthermore, there may not be much difference between the top 1000 solutions. It is desirable to find some "efficient" way to generate only the "best trips" as top candidates for a "cover" or solution.

Thus, it is vital to find some new way to generate trips which:

1) have zero trip penalty costs and good crew utilization
2) start from a given crew base after a specified start time
3) involve a specified flight or combination of flights
4) overnight at a specified location
Stage 2 - Select a Set of Crew Trips for each Base

1. All flights in the aircraft schedule must be covered by the selected set of crew trips.

2. Since each trip starts at a given crew base, the flying assigned to that crew base by selecting a set of trips must be proportional to the number of crews domiciled at that base.

3. The Selection Problem takes two mathematical forms:
   a) The Set Covering Version;

\[
\text{Minimize } [C.T] \text{ given constraints } \begin{bmatrix} \text{E.T } \geq 1 \\ \text{H.T } \geq B \end{bmatrix}
\]

where \( E \) is a zero-one matrix where columns \( j \) correspond to possible trips, and have a one in rows if the trip uses the flight corresponding to that row.

where \( H \) is a matrix of flight hours per trip, and \( B \) is the total number of flight hours desired to be assigned to a crew base corresponding to that row.

where \( T \) is a zero-one row variable to select trip \( j \) such as to minimize costs.

Since the constraints allow the row sum to be greater than unity, deadheading is allowed and the costs include all components.

   b) The Set Partitioning Version;

In this form, no deadheading is allowed and the constraints are equalities. The costs may be reduced to only the penalty costs associated with the guarantees.
Example of Trip Selection

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Cost = $c_2 + c_3 + c_5 + c_6$

Cheapest solution to this Set Partitioning Problem is the set of trips $(2, 3, 5, 6)$

With a large number of rows and columns, this problem is very difficult to solve exactly. With a few hundred rows and columns, there are a number of interesting ways to get solutions. If the lowest cost columns can be produced easily, and the lowest cost column which provides needed cover could be generated, good solutions may be found quite quickly.

The trip characteristics which are desirable depend on the bidline constraints and the number of crew available. It might seem important to generate trips which do as much flying as legally possible in a duty period, but this would just mean more days off per month for each crew. It is always important to avoid incurring penalties from the guarantees.
The Crew Tree -
A New Method for Constructing Crew Trips

It is possible to create methods which generate any crew trip from a given base and evaluate it for feasibility and cost. Such methods may be controllable by the analyst in creating new trips with particular characteristics which can be added to the cover matrix as desired to obtain better solutions.

An efficient method of finding "best" crew trips from a base is to create a labelling method which constructs a "crew tree" on the Schedule Map for the aircraft. This tree is rooted in the departures from that base, and finds the best crew routing for any flight in the schedule if it were to be flown by a crew from that base. The definition of "best" can be varied but maximizing the flight time achieved is a good basis.

The tree stops whenever the daily limits of flight and duty time are reached, so that it describes the "scope" of feasible crew routings from that base in one duty period. The labels indicate the routing used to reach any flight and the starting departure from base.

Whenever a crew routing returns to its base on some arrival flight a "best" crew trip has been found. The crew can go off-duty at that time. The analyst knows that for that pair of departure-arrival flights at this crew base a crew trip has been found which maximizes the amount of flying achieved. It is possible to extend the tree construction to find the second best and third best trips at the same time.

Crew Trees can be constructed for each base. Best trips can be extracted and the next tree constructed to generate more trips. It seems possible to generate a Crew circulation for one base at a time if needed.
Handling Overnight Trips

For discussion purposes, assume that there is a daily cycle in the aircraft schedule. Since there is usually a small number of crew bases and the aircraft schedule requires flights into secondary cities later in the evening with an early departure the next morning, there are identifiable "overnight" visits for aircraft and crew. Since these overnight visits cause out of pocket cost, they require special handling. There may be more than one crew overnighting at certain cities.

The crew tree will show the "best" way to route a crew from any base into the overnight arrival flights (if it is possible). Since there will be crew duties starting the next day at these bases, a crew tree is constructed from these overnight bases showing the best way to route crews back to base. By examination, it is easy to find the best two day trip for overnight crews. The search can be extended to three day trips if it is allowable or desirable.

The selection of low cost, efficient overnight trips can be made first. Once they are fixed, then all other trips must start and end at their crew bases within one day. The departure and arrival flights used for overnighting are then removed from the Schedule Map before constructing the one day trips.

The crew tree method is a new way to generate candidate trips for the second step of selection using some search methods of solving the set covering or partitioning problem. It is designed to only put forward the best candidates and keep the selection matrix very small. The process is not optimal, and it is intended that the analyst should be able to participate interactively in these searches, and return to this stage after the monthly bidlines have been initially constructed.
Stage 2 - Constructing the Bidlines

Given the trips that are to be used for constructing the bidlines, there are a variety of techniques to generate potential bidlines which obey all or most of the bidline rules. These rules may be soft in the sense that crew schedulers may know where and how often they can be bent.

There are research problems in beginning and ending the monthly bidlines, or "transitioning" between months. For domestic schedules, there are also problems arising from weekend deviations in the daily schedule. These problems may be handled by Reserve Crews, but if good methods of constructing bidlines can be automated, there are likely to be efficiencies in the number of reserve bidlines used (and therefore the crews required to support the fleet).

One method used to generate bidlines is to create an efficient "pattern" of trips over 7 days, and to involve 7 crews in flying exactly the same bidline for the month. This reduces the size of the selection matrix. A much smaller matrix of trips versus patterns is used to select the "best" set of patterns to be used. The focus then changes to finding good candidate patterns for the bidlines. The patterns can be "mixed" to provide some variety in the crews' monthly work if desired.

The solution of the bidline selection process once again requires a good heuristic search methods of quickly "solving" set covering and set partitioning problems.
Conclusions

1. There are some new approaches to creating interactive methods to support the crew scheduler in finding good low cost schedules for the crews.

2. There is a need to create methods for re-scheduling crews when deviations occur in executing the schedule. This should affect the current use of reserve crews.

3. There seems to be a need to create similar methods for the cabin crews which are responsive to their differences in scheduling rules.

4. There is a need to provide some "early warning" methods for market and aircraft schedulers to cause a feedback of expensive crew scheduling problems before the aircraft schedule is finalized.
COMPUTER AIDS FOR EXECUTION RESCHEDULING

1. Execution Rescheduling
2. The Influence of Rapid Advances in Computer Technology
3. The "Airline Scheduling Workstation" (ASW)
4. A 2-Stage Development Approach for An ASW
5. STAGE 1: A Manual, Interactive Graphics Scheduling System
6. STAGE 2: Automated Decision Support
7. Conclusions

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1. EXECUTION RESCHEDULING

GOAL:
- execute the operational schedule at least extra "cost" due to schedule aberrations

INPUTS:
- Operational schedule
- Operational deviations
  - Weather, breakdowns
  - Late arrivals
- Expected traffic loads and revenues
- Short term operating costs

OUTPUTS:
- Modified execution schedule
- Cancellations
- Delays
II. The Influence of Rapid Advances in Computer Technology

**Old Approach**
- "Techniques in search of an Application"
- use mainframe: large, fast supercomputer
- construct fixed code for technique
- user submits data, receives solution
- user reviews solution to comprehend it
- causality: user cannot ask for explanation of solution
- user may interface with OR analyst

**New Approach**
- "Customize techniques to the Application"
- smaller, interactive graphic workstations on common network
- create various fast heuristics to solve subproblems
- create links to solve large scale problems on mainframe
- user is master, computer is servant, direct interface
- processes are custom built to meet application needs
- systems to match existing procedures and organization
III. THE AIRLINE SCHEDULING WORKSTATION (ASW)

A COMPUTER TOOL FOR AIRLINE SCHEDULERS BASED ON THREE NEW TECHNOLOGIES:

1. Table top Engineering Workstations with a speed of 1-4 mips and disk storage of 100-1000 MB working together on a local area network, interfaced with existing airline mainframe systems.

2. Large (19 inch), high-quality color displays with interactive, instantaneous, manipulation of schedule graphics information using a "mouse".

3. Object-oriented programming to provide modular code, easily extendable to handle time-varying scheduling constraints, policies, etc., and to reduce programming support.

We shall call this tool the ASW (Airline Scheduling Workstation)
IV. DEVELOPMENT APPROACH FOR AN ASW

GENERAL DEVELOPMENT STRATEGIES

- Involve schedulers at all development stages—(there will be cultural and organizational shock)

- Provide familiar systems and reports first to ensure that the new system will not preclude doing certain schedule subprocesses by old methods.

- Expect changes in organization and procedures as workstation capabilities are perceived.

- Establish a local area network of workstations in scheduling area, capable of interfacing with the airline's existing mainframe system. (e.g., 3 workstations at $15,000 each). (Establish a "Schedule Generation" workroom).

- Develop modern, transportable, modular, object-oriented software, for automation of subprocesses in scheduling
  - easily extendable
  - easily supported
  - C, PASCAL, LISP language
  - good data structures

- A Two-Stage development process
  - STAGE 1: introduction of manual, interactive graphics scheduling system
  - STAGE 2: introduction of automated decision support
V. STAGE 1 - A MANUAL, INTERACTIVE GRAPHICS SCHEDULING SYSTEM

A) Provide computer graphic displays of schedule information
   - instantaneously modifiable by mouse
   - global data base modification
   - selectable screen data -- by fleet, station
   - save alternate solutions
   - audit trail
   - memo pad for scheduler
   - keyed to input data, and assumptions used
   - automated search routines, etc. to minimize keyboard
     and mouse work

B) Provide instantaneous error flagging (even if error occurs
   off-screen)
   - e.g., insufficient gates, flow imbalance, double crew
     layover, violation of turnaround or transit times, insufficient
     aircraft.

C) Integrate crew, gate, maintenance schedule with aircraft
   schedule

D) Provide familiar printed reports and graphics for distribution
   around airline

E) Provide interface to mainframe data system to maintain
   current scheduling processes.
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- ADD
- COPY
- DELETE
- COPY
- DELETE
- MOVE
- MOVE ALL
- INTERCHANGE
- MODIFY
- SWAP
- UNDELETE
- ZOOM

**Other Commands:**
- ARCH
- FILES
- WINDOW
- WEEKDAY
- QUIT
- ALGORITHM
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**ATL TIME ZONE:** -05
**DATE:** 881001  **Saturday**

**LOCAL**

**ALGORITHM 1**

**EDIT**

**ADD**

**COPY**

**DELETE**

**DELETE ALL**

**INTERCHANGE**

**MOVE**

**MOVE ALL**

**MODIFY**

**SWAP**

**UNDELETE**

**ZOOM**

**GMT**
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**Window Selection**

- **Saturday**
  - Window: 081001
  - Time Zone: -05
VI. STAGE 2 - AUTOMATED DECISION SUPPORT

INTRODUCTION OF AUTOMATED ALGORITHMS, EXPERT SYSTEMS

- to assist human schedulers with certain sub-problems
- to eliminate manual effort at certain steps of process
- to broaden search for optimal or good solutions to scheduling sub-problems
- may introduce mainframe, large scale optimization algorithms

EXAMPLES OF EXISTING AUTOMATED DECISION SUPPORT ALGORITHMS

a) Best cancellation of flights given breakdowns and spares
b) Least revenue loss when reducing available fleet
c) Optimal switching of flights between types of aircraft
d) Automatic switching for transition to new schedule plan
e) Automatic weekend schedule cancellations
f) Automatic holiday period rescheduling
g) Minimum fleet size for given services with time windows
h) Automatic gate assignment at all stations
i) Automatic aircraft rotation generation (with maintenance constraints)
VI. AUTOMATED DECISION SUPPORT

a) Best cancellation of flights given breakdowns and spares
b) Least revenue loss when reducing available fleet

Fleet Routing Models
- use network flow algorithms

OBJECTIVE:
Maximize Operating Income

GIVEN:
- Set of potential services to be flown with fixed operating times and known net operating income
- Daily ownership costs of aircraft
- Desired overnights
- Fixed number of available aircraft

OUTPUT:
- “Best” services to be flown
- Marginal value for services not flown
- Marginal value of adding an aircraft to fleet

WEAKNESS:
- Fixed service times
- Fixed net income for services i.e. no spill if not flown
- Single type of aircraft-solved sequentially
Cycle or Overnight Arc, C

$C_{i,j} = 0$

$u_{i,j} = \infty$

$c_{i,j} = \text{daily rental cost of aircraft}$

Service Arc, S

$C_{i,j} = 0$

$u_{i,j} = 1$

$c_{i,j} = \text{value of service}$

Ground arc, G

$I_{i,j} = 0$

$u_{i,j} = \infty$

$c_{i,j} = 0$

AO559

AO600

STATION A

STATION B

STATION C

CO559

CO600

Time
VII. SUMMARY - STATE OF THE ART IN COMPUTERIZED SCHEDULING

Conclusions

1. We cannot create analytical models which are adequate to describe mathematically the complete airline scheduling problem.

2. For existing models which promise utility, we generally do not have the correct data inputs, and it is difficult to conceive of creating the necessary models for passenger behavior in today's competitive markets. The existence of large scale solution techniques is not sufficient to justify their use at present.

3. We can provide quick, accurate answers to many sub-problems which occur in the complete scheduling process, but we need an environment which allows these techniques to be available to human schedulers. This environment is now available in the form of a network of computer workstations.

4. It is attractive to consider a single, integrated system to be used by various airline personnel as the scheduling process moves from initial planning to final execution.

5. People will remain an important part of the airline scheduling process. They are responsible for generating good schedules, and need "decision support" in their activities. There never will be a "push-button" scheduling system.

6. The desired approach is an incremental introduction of computerized assistance via graphic workstations. The strategy should be to create evolutionary stages:

Stage 1 - Introduce the Scheduling Workstations
Stage 2 - Introduce Automated Decision Support
Stage 3 - Extend to real time Execution Rescheduling
VI. SUMMARY - STATE OF THE ART IN COMPUTERIZED SCHEDULING (con't)

7. The scheduling process is not permanent
   - as time goes by, the problems change (perhaps temporarily), and the markets evolve, and there will be emphasis on different aspects. It will not be possible to create a completely automated decision maker which keeps up with changes.

8. As these tools are developed, they have their impact on the Scheduling Process
   - it will change in its flow of information, the sequence of processing will change, and eventually the airline's organizational structures will change. The introduction of computer automation must be adaptive to allow these changes to occur.

9. Every airline will have to develop its own automated scheduling system and manage the evolutionary impact on its operations. There is no single, turnkey solution to be provided by outsiders. A conceptual, long term plan is needed to direct the evolutionary effort and prevent building an incoherent set of sub-systems.