Evaluation of Collaborative Rationing of En Route Resources

Josh Marron, Antonio Abad
Bill Hall, Francis Carr, Steve Kolitz
25 Sept 2003
Outline

- The need for collaborative en route rationing
- Proposed routing schemes
- Evaluation methodology
  - Model for forecast/planning-execution
  - Metrics for comparison
- Scenarios
  - Mapping weather forecast to capacity forecast
  - Scenario selection
- Preliminary results
- Pending and future work
Background: Collaborative En-Route Rationing

- Collaborative
  - Operational decisions concerning the Air Transportation System are made by many stakeholders
    - Numerous Airlines
    - Air Traffic Management and Air Traffic Control
    - General Aviation
    - Airport Authorities

- Rationing
  - At times demand exceeds capacity
  - Rationing ensures safe operation

- En-Route
  - Has had relatively little attention
  - Large potential improvement
**Background: Definitions**

- **Capacity**: The rate at which aircraft can be processed through airspace (given very high demand)
  - Numerous operational constraints determine capacity
  - Under normal conditions, controller workload and frequency congestion limit capacity
  - Occasionally, bad weather shuts down parts of airspace
- **Resource**: A high level En Route sector $s$ at time $t$ with capacity $c$
Proposed routing schemes

- First-Filed, First-Served
- Equalize Accrued Delay
- Randomized Rerouting
- Global Optimization
First-Filed, First-Served

- Priority for en route resources assigned when the flight plan is first filed
- Advantage:
  - Encourages (earlier) proactive planning of airspace usage.
- Disadvantages:
  - Unexpected spillover from other Flight Control Areas.
  - Lack of built-in alternative plans.
  - Potential for “gaming”.

**File Times**

<table>
<thead>
<tr>
<th></th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAL213</td>
<td>1700</td>
</tr>
<tr>
<td>AAL2103</td>
<td>1720</td>
</tr>
<tr>
<td>UAL872</td>
<td>1732</td>
</tr>
</tbody>
</table>

**Resulting Flight Plans**

<table>
<thead>
<tr>
<th></th>
<th>Flight Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAL213</td>
<td>ZFW4901M...</td>
</tr>
<tr>
<td>AAL2103</td>
<td>ZFW4901M...</td>
</tr>
<tr>
<td>UAL872</td>
<td>ZFW4901M...</td>
</tr>
</tbody>
</table>
Equalize Accrued Delay

- Allocate resources to uniformly distribute delay
  - Analogous to RBS-based slot assignment in GDP-E.

- Advantage:
  - No user is unduly delayed.

- Disadvantage:
  - Disregards nature of delay. Can be mechanical, crew-related, etc.

Sector Capacity at Time t: 2 Flights

Delay Incurred by time T
- DAL213: 30 min
- AAL2103: 21 min
- UAL872: 15 min

Resulting Flight Plans
- DAL213 → ZFW4901M...
- AAL2103 → ZFW4901M...
- UAL872 → ZFW4901M...
Randomized Rerouting

- For each over-scheduled resource, re-route (randomly) selected subset of flights.

  Advantage:
  - "Pure" equitable allocation.

  Disadvantage:
  - *Maximum* capacities are respected, but sector loads remain unbalanced (favors most popular routes).
  - No *global* optimality guarantees.

Resulting Flight Plans

<table>
<thead>
<tr>
<th>Flight</th>
<th>Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAL213</td>
<td>ZFW4901M...</td>
</tr>
<tr>
<td>AAL2103</td>
<td>ZFW4901M...</td>
</tr>
<tr>
<td>UAL872</td>
<td>ZFW4901M...</td>
</tr>
</tbody>
</table>

Sector Capacity at Time t: 2 Flights
Global (ATC-side) Optimization

- Resources allocated by a central (FAA) authority via extended Bertsimas/Stock MIP formulation.

- Advantage:
  - Global optimality guarantee.

- Disadvantage:
  - Imperfect knowledge of stakeholder objectives and NAS state degrades user optimality.
Evaluation Method: Central Questions

- Identify performance trade-off between planning horizon and forecast accuracy
  - Short horizon rerouting benefits from more reliable forecasting
  - Long horizon rerouting benefits from a greater number of system degrees of freedom

- Examine dynamic stability/flexibility of plans
  - How much of the current situation and previous planning should be deemed "frozen?"

- Quantify the benefit of increased user collaboration
  - Multiple Flight Plan Submission
  - Voluntary Rerouting
Evaluation Methodology: Planning/Information Model

Demand Forecast:
Sector $x$

Weather Forecast:
Sector $x$

Source of Simulated Demand Forecast:
ETMS Data

Source of Simulated Weather Forecasting:
RTVS verified CCFP Data

Source of “Current” System State:
NEXRAD Data

1. Forecast
2. Plan
3. Execute

Receding Horizon Control Problem
Evaluation Methodology: Metrics

- Total Benefit (Cumulative Delay Reduction)
- Delay Distribution
  - Overall
  - User-Specific (e.g. distribution for each airline)
- Sector Density
  - Safety Metric
  - Compare resulting number of “hot spots” with what actually occurred and Monitor Alert
- Per flight costs
  - Account for missed connections using DB1 database of connecting flight information
Scenarios:

Wx Forecast ⇒ Capacity Forecast

- Model RTVS of CCFP.
- Given an $n \times m$ grid of cells (10nm squares), each with probability $\rho$ of convection, how many available paths?
- Percolation theory + max-flow optim.

![Diagram of a grid with 'X' representing cells and arrows indicating directions of traffic flow.](attachment:image.png)
Capacity Forecasts

- Uniform increase in mean paths as front length increases.

- Uniform decrease in mean paths as front width increases.
Capacity Forecasts

- CCFPs are issued every 4 hours
  - 2, 4, & 6 hour lead time forecasts
- In real-time, weather is dynamic, continuous and observable
- Must approximate this real-time ability via interpolation using hourly NEXRAD images
  - Zero Order Hold or Linear Interpolation

![Diagram showing zero order hold and linear interpolation between t₀ and t₀ + 1 hr]
Test Scenarios

- Scenario description
  - Strongly Convective Fronts (October 28, 2000)
  - Inaccurate Forecast (October 16, 2000)
  - Rapidly Developing Convection (October 15, 2000)
  - Weak and Dispersed Fronts (October 21, 2000)
Scenario 1: Strong Convective Front

- Strong front sweeps N. Texas and Oklahoma.
- Benchmark: Best-accuracy forecast... Best-case performance?
Scenario 2: Inaccurate Forecast

- Very little activity in the forecast area
- Benchmark: Robustness and performance degradation under inaccurate forecast
Scenario 3: Rapidly-Developing Convective Activity

- Quick-developing storm activity through N. TX, OK.
  - Radar Loop: 10/15/00, 1300Z – 0200Z (8 AM – 9 PM CST)
- Benchmark: Flexibility/adaptability of routing solutions; dependence on forecast horizon.
Scenario 4: Weak Storm Activity

- Weak “popcorn” storms over NM, TX, OK.
- Benchmark: Sensitivity to noise (weather is low-impact but unpredictable)
Preliminary Results

Qualitative

- Flights departing from FCA unduly held
  - Not as many DOFs as over-flight traffic
  - Segregate traffic into different classes

- Need to provide adequate “buffer” of nominally-constrained sectors around FCA
  - Inability to route around FCAs results in an extreme amount of incurred delay
Preliminary Results
Quantitative

- **Scenario 1**

<table>
<thead>
<tr>
<th>Rationing Scheme</th>
<th>Cumulative Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>sec.</td>
</tr>
<tr>
<td>First-Filed, First Served</td>
<td>11830</td>
</tr>
<tr>
<td>Equalize Accrued Delay</td>
<td>12140</td>
</tr>
<tr>
<td>Global Optimization</td>
<td>5450</td>
</tr>
</tbody>
</table>

**Delay Distribution for Scenario 1**

The chart shows the distribution of delays for different rationing schemes. The x-axis represents delay in minutes, while the y-axis shows the number of flights. The bars indicate the number of flights within each delay range for First Filed, First Served and Equalize Accrued Delay schemes.
Preliminary Results
Quantitative

- Scenario 1

**Maximum Relative Sector Usage**

![Graph showing maximum relative sector usage across sectors.](Image)

**Relative Sector Usage vs. Time**

1. **Equalize Accrued Delay**
   - Time (min): 800 900 1000 1100 1200 1300 1400 1500
   - max(Usage/Capacity): 0 0.2 0.4 0.6 0.8 1

2. **First Filed, First Served**
   - Time (min): 800 900 1000 1100 1200 1300 1400 1500 1600
   - max(Usage/Capacity): 0 0.2 0.4 0.6 0.8 1
Pending and Future Work

- Analyze remaining scenarios.

- Baseline sector capacities: observed (ETMS) and planned (MAP).

- Per-user costs (database-join against DB-1)
  - Passenger holding delay and delayed connections.

- Examine planning-horizon effects. Fully implement MP-RHC simulation (possible FACET integration).
Pending and Future Work

- Methods for increasing collaboration: Multiple (Filed/Preferred) Routings.

- Investigate user-acceptance issues:
  - “Fairness” via Completely Biased heuristic.
  - Site-visits to ZBW.
  - Dynamic stability of plans.

- Incorporate state-of-the-art Nowcasting ability
  - Growth & Decay Storm Tracker
  - Advection Interpolation and Extrapolation