Equitable Allocation of Enroute Airspace Resources

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General Problem Addressed:
Congestion in the Enroute Airspace

Demand predicted to exceed capacity in portion of enroute airspace:
- demand surge
- capacity reduction (due to weather)

Earlier approach: reduce demand using ground delay programs (GDP’s) into major airports that serve as destination for most affected flights.
Limitations of Using Ground Delay Programs for Solving Enroute Problems

Many flights through the impacted region are not controlled because they are not going to the GDP airports.

Affected flights not controlled

Many uninvolved flights are unnecessarily delayed because they are going to GDP airports.

Delay flights that are not part of problem
Flow Constrained Area is a general function within the Traffic Situation Display to flexible identify demand in the enroute airspace.

Demand may be filtered by destination, airways, altitude etc.

AFP uses GDP-like tools (ration-by-schedule, substitutions, etc.) to reduce demand into FCA while provide flight operator flexibility.

**New Initiative:** System Enhancements for Versatile Electronic Negotiation (SEVEN) seeks to ration access to airspace while providing users the ability to flexibly specify preferences. *Also application target for our research.*
Airport demand rationing vs airspace demand rationing

Airport arrival demand has a fixed schedule, which can be used as basis for rationing (ration-by-schedule) – given a flight plan, a “scheduled” arrival time at an airspace boundary could be computed – however, flight plans can be varied day-to-day and sometimes are changed multiple times during a day.

Airlines cannot replace flight to airport A with flight to airport B ➔ FAA must accommodate all airport demand – however, airlines can reroute around FCA. Airport arrival capacity can be well-approximated with list of slots of fixed time width – airspace capacity is more complex.
Problem Studied

Many flights
Fewer Slots??

FCA

Slots

AFP’s slots = Arrival slots at FCA boundary

Who gets the slots?
Which slots do they get?
Take into account user preferences.
Overview of Procedure

Inputs:

- List of flights with “scheduled” arrival times at FCA boundary
- Flight operator preference information

Step 1: determine “claim” for each flight operator.

Step 2: allocate slots to flight operators in manner consistent with claims while taking into account preference information.
Claim (fair share)
Generation Philosophy

Earliest arrival slot

X101 \rightarrow s1
Y201, X102 \rightarrow s2
Y202, X103 \rightarrow s3
Z301 \rightarrow s4

Compromise between two principles:
i) Priority based on scheduled arrival time
ii) Proportional allocation

Earlier flight generates larger claim than later flight.
More flights \rightarrow greater claim

Problem: number flights > number slots
• Some operators might have one flight \rightarrow such an operator will have claim \leq 1
\rightarrow on some days that operator will receive 1 slot and on other days 0 slots

How to balance day-to-day?
• Credit system \rightarrow carry over credits from one day to next
• Randomization \rightarrow expected number of slots equals fair share on average.
Calculating Claims:
Proportional Random Assignment

**Earliest arrival slot**

- X101 → s1
- Y201, X102 → s2
- Y202, X103 → s3
- Z301 → s4

**PRA Philosophy:** each flight has equal right to all slots it might use in an assignment to uses all available slots.

**PRA Algorithm:** starting from the earliest slot, randomly assign with equal likelihood an eligible flight that has not yet received a slot.

PRA claim for flight $f_i = \text{Prob}[\text{PRA assigns } f_i \text{ a slot}]

Flight Operator A Claim: sum over claims of flights it owns.
Choose randomly among flights eligible for $s_1$

- $X_{101} \rightarrow s_1$
- $Y_{201}, X_{102} \rightarrow s_2$
- $Y_{202}, X_{103} \rightarrow s_3$
- $Z_{301} \rightarrow s_4$
Sample Execution of PRA

Choose randomly among flights eligible for s1

X101 must be chosen

A101 → s1

B201, A102 → s2

B202, A103 → s3

C301 → s4
Sample Execution of PRA

Choose randomly among the remaining flights eligible for s2

X101 → s1

Y201, X102 → s2

Y202, X103 → s3

Z301 → s4

X101
Sample Execution of PRA

Choose randomly among the remaining flights eligible for s2

2 flights have $\frac{1}{2}$ chance; say Y201 chosen

X101 \[\rightarrow\] s1

Y201, X102 \[\rightarrow\] s2

Y202, X103 \[\rightarrow\] s3

Z301 \[\rightarrow\] s4
Sample Execution of PRA

Choose randomly among the remaining flights eligible for s3

X101 \rightarrow s1 \quad X101

Y201, X102 \rightarrow s2 \quad Y201

Y202, X102, X103 \rightarrow s3

Z301 \rightarrow s4
Sample Execution of PRA

Choose randomly among the remaining flights eligible for s3

3 flights have 1/3 chance; say X102 chosen

X101

Y201, X102

Y201

Y202, X102, X103

X102

Z301

s4
Choose randomly among the remaining flights eligible for s4

X101 \rightarrow s1 \rightarrow X101

Y201, X102 \rightarrow s2 \rightarrow Y201

Y202, X102, X103 \rightarrow s3 \rightarrow X102

Y202, X103, Z301 \rightarrow s4
Sample Execution of PRA

Choose randomly among the remaining flights eligible for s4

X101 → s1

Y201, AX102 → s2

Y202, X102, Y103 → s3

Y202, X103, Z301 → s4

3 flights have 1/3 chance; say Y202 chosen

X101

Y201

X102

Y202
Result from PRA

Note: the PRA allocation is not used; rather the structure of the algorithm is used to calculate the claims.

In this example:

FS_X = 2 1/3
FS_Y = 1 1/3
FS_Z = 1/3

The RBS allocation would be:

FS_X = 3, FS_Y = 1,
FS_Z = 0.
Overall Procedure

Inputs:
- List of flights with “scheduled” arrival times at FCA boundary
- Flight operator preference information

Step 1: determine “claim” for each flight operator.
Step 2: allocate slots to flight operators in manner consistent with claims while taking into account preference information.
# Flight Operator Preference Information

Most General Form:

ordered list of flight/slot pairs

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>A01, s1</td>
</tr>
<tr>
<td>2</td>
<td>A01, s2</td>
</tr>
<tr>
<td>3</td>
<td>A02, s4</td>
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<tr>
<td>4</td>
<td>A01, s3</td>
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<tr>
<td>5</td>
<td>A01, s4</td>
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<tr>
<td>6</td>
<td>A01, s5</td>
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<tr>
<td>7</td>
<td>A02, s5</td>
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<tr>
<td>8</td>
<td>A01, s6</td>
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<tr>
<td>9</td>
<td>A02, s6</td>
</tr>
<tr>
<td>10</td>
<td>A03, s6</td>
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</tbody>
</table>
**Flight Operator Preference Information**

**More compact form:** ordered list of flight/slot intervals

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>A01, s1:s2</td>
</tr>
<tr>
<td>2</td>
<td>A02, s4:s4</td>
</tr>
<tr>
<td>3</td>
<td>A01, s3:s5</td>
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<tr>
<td>4</td>
<td>A02, s5:s5</td>
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<tr>
<td>5</td>
<td>A01, s6:s6</td>
</tr>
<tr>
<td>6</td>
<td>A02, s6:s6</td>
</tr>
<tr>
<td>7</td>
<td>A03, s6:s6</td>
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</tbody>
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Overview of Procedure

Inputs:
• List of flights with “scheduled” arrival times at FCA boundary
• Flight operator preference information

Step 1: determine “claim” for each flight operator.

Step 2: allocate slots to flight operators in manner consistent with claims while taking into account preference information.
Desirable Properties for Slot Allocation Procedure

1. The number of slots allocated to carrier A should *approximately equal* its fair share, $F_{S_A}$
   - $\lfloor F_{S_A} \rfloor \leq \text{number slots} \leq \lceil F_{S_A} \rceil$
   - expected number of slots $= F_{S_A}$

2. Each flight operator should be motivated to submit a “truthful” preference list, i.e. no “gaming”

3. The allocation process should be consistent with the flight operator priorities.
Overview of Allocation Procedure

Preference-Based Proportional Random Assignment (PBPRA):

Divide the claim $F_A$ for each airline $A$ into a fractional part $FFS_A$ and integer part $IFS_A$ (note small carriers will only have a fractional part). Compute a corresponding total allocation for fractional parts, $FTOT$, and integer parts, $ITOT$.

**Phase I** randomly chooses carriers in proportion to $FFS_A$ and gives them their most preferred slot until $FTOT$ slots are assigned.

**Phase II** proceeds from the earliest to latest unassigned slot, randomly chooses an eligible flight operator in proportion to $IFS_A$ and assigns that slot to the flight most preferred by that flight operator.
Sample Execution PBPRA

X101 → s1
Y201, X102 → s2
Y202, X103 → s3
Z301 → s4

FS_X = 2 1/3
FS_Y = 1 1/3
FS_Z = 1/3

FFS_X = 1/3
FFS_Y = 1/3
FFS_Z = 1/3
IFS_X = 2
IFS_Y = 1
IFS_Z = 0
Sample Execution PBPRA

Phase I: One of X, Y or Z is chosen randomly with 1/3 prob;

Say Z is chosen it would (by necessity) choose slot s4.

| X101 | → | s1 |
| Y201, X102 | → | s2 |
| Y202, X103 | → | s3 |
| Z301 | → | s4 |

FFS_x = 1/3
FFS_y = 1/3
FFS_z = 1/3
IFS_x = 2
IFS_y = 1
IFS_z = 0
Phase II, step 1: slot s1 allocated to an eligible flight operator in proportion to $IFS_A$.

*Only one eligible (X) so slot is allocated to X101. $IFS_X$ is decremented by 1.*
Sample Execution PBPRA

Phase II, step 2: slot s2 allocated to an eligible flight operator in proportion to $IFS_A$, i.e. choose between X and Y with equal likelihood.

*Say Y is chosen so s2 allocated to Y201; $IFS_Y$ is decremented by 1.*
Sample Execution PBPRA

Phase II, step 2: slot s2 allocated to an eligible flight operator in proportion to $IFSA$, i.e. choose between X and Y with equal likelihood.

Say Y is chosen so s2 allocated to Y201; $IFS_Y$ is decremented by 1.
Sample Execution PBPRA

Phase II, step 3: slot s3 allocated to an eligible flight operator in proportion to $IFS_A$.

*Only X has positive $IFS_A$ value $\Rightarrow$ allocated to X, say flight X102.*
Final Result: PBPRA

FS_X = 2 1/3
FS_Y = 1 1/3
FS_Z = 1/3

Slots
Received
X: 2
Y: 1
Z: 1
Experimental Setup

Considered rationing problem associated with historical FCA (time period: 18:00 – 21:00)

Simulated airline cost function:
  – $64 per minute air delay; $32 per min ground delay; $.60 per minute passenger delay (0 → 15 min free);
  – Tot cost = airline direct cost + 1/6 total passenger cost.

Considered multiple FCA capacity reductions: 40% → 80%

Calculated appropriate reroute option for each flight

Preferences defined so as to minimize cost function

Compared PBPRRA allocation with RBS allocation
  – To evaluate average performance, experiment run 2,000 times

Two performance criteria considered:
  – Impact on internal airline cost functions
  – Ability to get close to claims on the average
Results of Experiment:
Impact on Total Airline Costs

Total Cost RBS vs. PBPRA

Cost

$250,000

$500,000

$750,000

(% Capacity Reduction)

40  50  60  70  80
Result of Experiment: Ability to get close to claims (fair share) on average

Number of Slots assigned in 50% capacity reduction (RBS vs. PBPRA)

Airline | Number of Slots | RBS | Claim (fair share) | PBPRA
--- | --- | --- | --- | ---
A | 10 | Blue | Red | Yellow
B | 15 | Blue | Red | Yellow
C | 20 | Blue | Red | Yellow
D | 25 | Blue | Red | Yellow
E | 30 | Blue | Red | Yellow
F | 35 | Blue | Red | Yellow

Result of Experiment: Ability to get close to claims (fair share) on average
Result of Experiment: Ability to get close to claims (fair share) on average

Plotted: Sum of Squared Errors (average deviation from Fair Share)
Final Thoughts

New resource allocation methods designed specifically for enroute problem:

- Use of airline preferences
- Use of randomization
- New fair allocation/equity principles

Improves ability of flight operators to minimize internal cost functions

Future research:

- Specific modeling of airspace capacity
- New fair allocation “standards”