The Planning of Ground Delay Programs Subject to Uncertain Capacity

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  – Decision Tradeoffs
  – Mathematical Approach:

• Initial application
  – Airborne Queue Size
  – Total Delay Cost
  – Unavoidable Delay
  – Delay Distribution

• Conclusions
Delays occur when arrival demand exceeds capacity

Demand Rate: 50 ac/hour

Arrival Rate: 60 ac/hour

Wind
GDPs create ground delays to avoid those in the air.

Demand Rate: 50 ac/hour

Arrival Rate: 60 ac/hour

Wind
GDP design balances two key tradeoffs

• How much ground delay should be assigned?
  – Too much causes additional, unnecessary delays
  – Too little and expensive airborne delays may occur

• When should the GDP be created?
  – Waiting means that flights depart and cannot be delayed
  – Additional, improved capacity information becomes available over time

GDPs are both stochastic and dynamic
A numerical example: arrival demand over time

ORD Arrival Demand

Source: ETMS, June 22nd, 14:45 Z, aggregated by author
A numerical example: arrival capacity scenario

Scenario of Airport Capacity Profiles by Time Period

Current/Scheduled
Forecast Revision

Period Start Time (hh:mm Z)

Arrivals/Period (Aircraft)
Full Odoni Richetta (1993) formulation

Minimize:
\[
\sum_{q=1}^{Q} p_q \left\{ \sum_{k=1}^{K} \sum_{s=1}^{Q} \sum_{i=t_s+1}^{T} \sum_{j=i+1}^{T+1} C_g (k, j - i) \times \chi_{qksij} + c_a \sum_{i=1}^{T} W_{qi} \right\}
\]

Subject to:
\[
\chi_{sksij} = \chi_{s+1ksij} = \ldots = \chi_{Qksij} \quad \forall \ s = 1 \ldots Q - 1; i = t_s + 1 \ldots T; i \leq j \leq T + 1; q = 1 \ldots Q; k = 1 \ldots K
\]
\[
\sum_{j=i}^{T+1} \chi_{qksij} = N_{ksi} \quad \forall \ k = 1 \ldots K; s = 1 \ldots Q; i = t_s + 1 \ldots T
\]
\[
\sum_{i=1}^{T+1} S_{qi} = \sum_{i=1}^{T} M_{qi}
\]
\[
W_{qi} - W_{qi-1} - \sum_{k=1}^{K} \sum_{s.t.s<i} \sum_{j=t_s+1}^{i} \chi_{qksji} - S_{qi} = -M_{qi} \quad \forall \ i = 1 \ldots T + 1
\]
\[
W_{q0} = W_{qT+1} = 0
\]
\[
\chi_{qksij}, W_{qi}, S_{qi} \geq 0
\]
Queue Size – without a GDP

Scenario Arrival Queues by Time

- FC 1
- FC 2
- FC 3
- FC 4
- FC 5

Period Start Time (hh:mm Z)

Aircraft

13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00
Queue Size – with the proposed GDP

Airborne Queue Size by Capacity Profile

Aircraft

Time (hh:mm Z)

FC 1
FC 2
FC 3
FC 4
FC 5
Cumulative Delay Cost

Total Delay Cost by Capacity Profile

Cost

Time (hh:mm Z)

FC1
FC2
FC3
FC4
FC5
Exp

0 1000 2000 3000 4000 5000 6000 7000

13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00
Unavoidable delay and critical decision times

Cumulative Unavoidable Delay for the Proposed GDP

Accumulated Delay (minutes)

Period Start Time (hh:mm Z)
The distribution of delay cost will vary by outcome
- FC 3 has a tight distribution
- FC 4 assigns heavy delay costs to some flights
- But… delay cost, as with demand and capacity, should vary
Flight delay by scheduled departure time

Delay Cost by Scheduled Departure Time for FC 1

Delay Cost by Scheduled Departure Time for FC 1

13:30 15:00 16:30 18:00 19:30

Time (Z)

Delay Cost

0 10 20 30 40 50 60
Flight delay by scheduled arrival time

Delay Cost by Scheduled Arrival Time for FC 1
Conclusions

• Optimization can be used to design GDPs
  – Offers an opportunity to improve the program

• Optimization techniques, however, are not the complete answer
  – Solutions do not consider important elements such as equity
  – Cannot guarantee many external constraints
  – May allow for the possibility of extreme outcomes

• It is important to have additional information
  – Other decision support tools can evaluate the proposed GDP
  – Optimization can be used as part of a larger process
Further research

• Improve decision-making process
  – Design LPs to address system loads
  – Design decision support tools and a process to incorporate them

• Define GDP design objectives
  – Cost functions should allow non-linear / aggregate delay costs
  – Equity should be defined within the GDP context

• Improve system modeling
  – Account for stochastic, dynamic demand
  – Model operator behavior for popups and cancellations
  – Further information from capacity profiles?
Methodology

- The design of a GDP must be approached from both a social and a technical perspective

- Improve understanding of the system
  - How decisions are made
    - Interview traffic managers at the FAA
  - How stakeholders are affected
    - Interview operation managers at different airlines

- Reformulate a model to capture new elements
- Define the role that optimization/models have in the overall GDP design process
Sources

- Avijit Mukherjee and Mark Hansen, “Dynamic Stochastic Model For Single Airport Ground Holding Problem”, 2004
- Michael Hanowsky, “A Tool to Support the Planning of Ground Delay Programs Subject to Uncertain Arrival Capacities”, Masters Thesis at the Massachusetts Institute of Technology, 2006
- “SFO Marine Stratus Forecast System Documentation,” MIT Lincoln Laboratory, November 29, 2004
- US Department of Transportation, Federal Aviation Administration website: http://www.faa.gov, October 14, 2005
- Michael Ball, Robert Hoffman, “Analysis of Demand Uncertainty Effects in Ground Delay Programs,” 2001
- Michael Ball and Guglielmo Lulli, “Ground Delay Programs: Optimizing Over the Included Flight Set Based on Distance”
Appendix Table

- Key assumptions
- Stages/scenario clarification
- 1993 Odoni-Richetta formulation
- 2005 Mukherjee formulation
- Processing LP output into revised departure times
- Data calculation in the Hanowsky tool
- Different ATFM techniques
- Map of ARTCC boundaries
- Time and information tradeoff
- Categorization of sources of delay
- Relative ground/air cost functions
- Actual ground/air cost functions
- Relevant flight times
Ground Delay Programs require more advance planning than other ATFM tools.
Calculation and data flows in the Excel tool

- Sources of Flight Data
  - ETMS
  - Other
  - Exemptions
  - Order of Flights
  - Proposed Departure Times by Flight
  - Proposed Cumulative Arrival Slots
  - Proposed Demand Times by Flight
  - Cumulative Arrival Demand

- Apply to Possible Outcomes
- Forecasted Flight Arrival Times
- Proposed Departure Times by Flight
- Create GDP
- FAARs
- PAARs
- Forecasted Cumulative Arrival Slots

Steps:
1. Sources of Flight Data
2. Create GDP
3. Proposed Demand Times by Flight
4. Forecasted Flight Arrival Times
5. Proposed Departure Times by Flight

Michael Hanowsky -- October 26, 2006
Map of the US with standard ARTCC boundaries

Source: Traffic Situation Display software (FAA), edited by the author using Adobe Photoshop
The relationship between time and information
Flight times relevant to ETMS arrival demand forecasts
Categorization of delay sources

- Capacity
- Scope
- NAS Users
- FAA

- Delay Costs
- Action
- NAS
- Reaction

- Weather
- Drift
- ATC Response
- Airline Response

- Schedule Changes
- Demand
- Pilot Response
Recent Literature: There is an opportunity

- Uncertain forecast arrival capacities can be quantified
  - MIT Lincoln Laboratory (2004): use airport-specific meteorological data
  - Hansen and Liu (2006): use historical AARs

- Linear programming techniques can model GDPs with uncertain arrival capacities
  - Odoni and Richetta (1993): stochastic and dynamic conditions
  - Mukherjee and Hansen (2004): aircraft based model

- GDPs with uncertain arrival capacities can be analyzed
  - Hanowsky (2006): Analysis of GDPs with uncertain capacity

Existing literature does not discuss the application of optimization models
The system is dynamic

- Flight arrival demand changes
- Information on arrival capacity improves
  - Limited by the “two-stage” decision model

![Diagram showing stages 1 and 2 with forecast profiles FC1 to FC5 at 1300 Z and 1500 Z.]
Odoni-Richetta (1993): 2 stages and 1 aircraft class

Minimize:
\[
\sum_{q=1}^{Q} p_q \left\{ \sum_{s=1}^{2} \sum_{i=t_s+1}^{T} \sum_{j=i+1}^{T+1} C_g (j-i) \times \chi_{qsi} + C_a \sum_{i=1}^{T} W_{qi} \right\}
\]

Minimize Cost

Subject to:
\[
\chi_{1ij} = \chi_{2ij} = \ldots = \chi_{Qij} \quad \forall \; i = t_s + 1 \ldots T; \; i \leq j \leq T + 1
\]

Solve each decision

\[
\sum_{j=i}^{T+1} \chi_{qsi} = N_{si} \quad \forall \; s = 1 \ldots 2; \; i = t_s + 1 \ldots T; \; q = 1 \ldots Q
\]

Conserve Flow

\[
\sum_{i=1}^{T+1} S_{qi} = \sum_{i=1}^{T} M_{qi} \quad \forall \; q = 1 \ldots Q
\]

\[
M_{qj} + W_{qj} = W_{qj-1} + \sum_{s,t_s < j = t_s + 1}^{j} \chi_{qsj} + S_{qj} \quad \forall \; j = 1 \ldots T + 1; \; q = 1 \ldots Q
\]

\[
W_{q0} = W_{QT+1} = 0
\]

\[
\chi_{qsi}, W_{qi}, S_{qi} \geq 0
\]
The formulation is an adapted network flow model.
LP Results: Wait for more information

- Only limited delays are assigned to flights that depart before 1500 Z
  - 23 flights
  - 2 hours cumulative delay
    - Delays shown in h:mm
    - Aircraft operator codes have been masked
- Delay assigned to flights that depart after 1500 Z depends on the capacity of stage 2

- Objective function value
  - Two-Stage: 3,820 a/c-delay min
  - One-Stage at 1500 Z: 3,845 a/c-delay min
  - No GDP: 7,356 a/c delay min

<table>
<thead>
<tr>
<th>Flight</th>
<th>1500 Z Delay</th>
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<tbody>
<tr>
<td>10A321</td>
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<td>01A1840</td>
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<td>53A534</td>
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<td>53A132</td>
<td>0:14</td>
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<td>48A46</td>
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<td>40A8083</td>
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<td>0:02</td>
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<td>53A8124</td>
<td>0:03</td>
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<tr>
<td>54A1825</td>
<td>0:06</td>
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<td>01A2325</td>
<td>0:01</td>
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<td>48A128</td>
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<td>46A908</td>
<td>0:01</td>
</tr>
<tr>
<td>Total</td>
<td>2:06</td>
</tr>
</tbody>
</table>
System Load

• Objective
  – FAA defines specific system load standards to ensure safety
    • Strict limits on the number of aircraft
      – in a sector
      – under the responsibility of one controller

• …and Subjective
  – Not always easy to predict whether a future time/location will meet this standard
    • Flight location, speed uncertain
    • The FAA can apply other techniques to reduce demand
Efficiency

- Efficiency
  - Maximization of use of system, minimize “cost”

- Scarce resources:
  - Fuel
  - Time
  - Airspace

- LPs can maximize an objective function
  …but can an appropriate objective function be identified?
Equity

• Very subjective

• Define equity by how the FAA views the system
  – All aircraft are treated independently and identically
  – Aircraft size, economy, passenger load… *not* considered

Do GDPs assign delays to some flights more than others?
Do GDPs assign more delays to some carriers than others?

• There are many other ways to define equity
  – Passengers, system efficiency
Key Assumptions

• En route times are deterministic and constant
  – Drift, en route congestion, other ATFM strategies

• Demand is constant
  – Popups, cancellations

• Flight arrival order is processed as a single FCFS D/D/1 queuing system
  – Multiple runway system, tactical ATFM

• Air carriers will adhere to assigned departure times
  – NavCanada
Subjective Criteria

• GDPs are designed by traffic managers at the FAA
  – A framework is used to guide decisions
  – No optimization tools are used

• “Safe and efficient”

• Equitable
  – Idea: Are programs sustainable?
  – Do users receive more benefits than costs?
Example of stages/scenarios
Full Odoni Richetta (1993) formulation

Minimize:  
$$ \sum_{q=1}^{Q} \sum_{k=1}^{K} \sum_{s=1}^{Q} \sum_{i=t_s+1}^{T} \sum_{j=i+1}^{T+1} C_g(k, j-i) \times \chi_{qksij} + c_a \sum_{i=1}^{T} W_{qi} $$

Subject to:  
$$ \chi_{sksij} = \chi_{s+k-1sij} = \ldots = \chi_{Qksij} \quad \forall s = 1 \ldots Q-1; i = t_s + 1 \ldots T; i \leq j \leq T + 1; q = 1 \ldots Q; k = 1 \ldots K $$

$$ \sum_{j=i}^{T+1} \chi_{qksij} = N_{ksi} \quad \forall k = 1 \ldots K; s = 1 \ldots Q; i = t_s + 1 \ldots T $$

$$ \sum_{i=1}^{T+1} S_{qi} = \sum_{i=1}^{T} M_{qi} $$

$$ W_{qi} - W_{qi-1} - \sum_{k=1}^{K} \sum_{s.t_s<i} \sum_{j=t_s+1}^{i} \chi_{qksji} - S_{qi} = -M_{qi} \quad \forall i = 1 \ldots T + 1 $$

$$ W_{q0} = W_{qT+1} = 0 $$

$$ \chi_{qksij}, W_{qi}, S_{qi} \geq 0 $$

Minimize: \[ \sum_{q \in \Theta} P(q) \times \left\{ \sum_{f \in \Phi} \sum_{t=Arr_f}^{T+1} (t - Arr_f) \times (\chi_{f,t}^q - \chi_{f,t-1}^q) + \lambda \times \sum_{t=1}^{T} w_t^q \right\} \]

Subject To:

\[ \chi_{f,t}^q - \chi_{f,t-1}^q \geq 0 \]
\[ w_{t-1}^q - w_t^q + \sum_{f \in \Phi} (\chi_{f,t}^q - \chi_{f,t-1}^q) \leq M_t^q \]
\[ w_0^q = w_{T+1}^q = 0 \]
\[ \chi_{f,T+1}^q = 1 \]
\[ Y_{f,t}^{S_i} = Y_{f,t}^{S_k} = Y_{f,t}^{S_{N_i}} \quad \forall \ f \in \Phi; \ t \in \{1...T\}; \ S_i \in \Omega_i : N_i \geq 2, \sigma_i \leq t \leq \mu_i \]
Delay assignment (based on the Odoni-Richetta formulation)

- Ground delays are assigned based upon underlying FAA methodology: FCFS by aircraft
  - Consider five flights in stage 1 (13:00 to 15:00) with arrivals between 15:00 Z and 15:04 Z.
  - LP output: $\chi_{25,25} = 3$ and $\chi_{25,27} = 2$

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<tr>
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<th>Arr Time</th>
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<td>15:00 Z</td>
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<td>A3</td>
<td>13:00 Z</td>
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<td>A4</td>
<td>13:45 Z</td>
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</tr>
<tr>
<td>A5</td>
<td>13:00 Z</td>
<td>15:04 Z</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flight</th>
<th>Rev Arr</th>
<th>Rev Dep</th>
<th>Gnd Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>15:00 Z</td>
<td>14:00 Z</td>
<td>0:00</td>
</tr>
<tr>
<td>A2</td>
<td>15:01 Z</td>
<td>14:22 Z</td>
<td>0:00</td>
</tr>
<tr>
<td>A3</td>
<td>15:02 Z</td>
<td>13:00 Z</td>
<td>0:00</td>
</tr>
<tr>
<td>A4</td>
<td>15:10 Z</td>
<td>13:52 Z</td>
<td>0:07</td>
</tr>
<tr>
<td>A5</td>
<td>15:10 Z</td>
<td>13:06 Z</td>
<td>0:06</td>
</tr>
</tbody>
</table>

- Arrival times are assigned FCFS
- For delayed flights, the revised arrival times are at the beginning of the new arrival period
- En route time is assumed to be constant
One possible set of ground and air cost functions

![Graph showing cumulative delay cost by duration of delay (Units). The graph includes two lines representing air delay and ground delay. The x-axis represents duration of delay in minutes, ranging from 0 to 140, and the y-axis represents cost in units, ranging from 0 to 250.]
Air, ground, and total cost functions

Cumulative Flight Delay Cost by Duration of Delay

- General
- Ground
- Air