Modeling Demand Uncertainties During Ground Delay Programs

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Ground Delay Programs (GDPs)

- To balance arrival demand and capacity at the afflicted airport
- Transfer costly airborne delay to less expensive ground delay

Input parameters - Airport Capacity and Arrival Demand
- Capacity and demand, both stochastic in nature
Demand Uncertainties

Three main sources of demand uncertainties

- Flight Drifts,
- Flight Cancellations, and
- Pop-up Flights

Combined Effects

- Under-Utilization of the airport resources (slots)
- Unpredictable arrival sequence
- Increased airborne holding
Flight Cancellations

- Flight Cancellations without notices in advance, cause “holes” in the arrival sequence.
- Timed Out (TO) Cancellations almost always result in slots being unused.
Pop-up Flights

Any flight that arrived during a GDP and that first appeared in the ADL after the GDP model time

Pop-ups add to the arrival demand and displace the actual arrival sequence
Flight Drifts

Flight Drifts are results of:

- CTD non-compliance, where ARTD > or < CTD
- CTA non-compliance, where AETE > or < OETE

Net Drift = Ground Drift + Enroute Drift

- ARTA - Actual Runway Time of Arrival
- ARTD - Actual Runway Time of Departure
- AETE - Actual Enroute Time
- CTA - Control Time of Arrival
- CTD - Control Time of Departure
- OETE - Original Estimated Enroute Time
Modeling Demand Uncertainties

- Stochastic Mixed Integer Optimization (SMIO) Model
  - Incorporates only flight cancellations and pop-ups
  - Generates **Optimal Planned Arrival Rates (PAARs)** for any GDP scenario

- Simulation Model
  - Incorporates flight cancellations, pop-ups and drifts
  - Validates the SMIO model by generating **Pareto Optimal PAARs** for a large set of scenarios
Details on SMIO Model

- **Objective Function**: Minimize the expected airborne queue

- **Variables**: \( X_{\text{ paar}}(k,t) = 1 \) if PAAR = k in time period t; else 0
  
  \( Y(k,j,t) \) : probability that at the end of time period “t” an airborne queue of size “j” exists and PAAR = k in time period “t”

- **Main Input Parameters**: AAR(t), \( P_{\text{ cnx}} \), \( P_{\text{ pop}} \), and Utilization Parameter “\( \varepsilon \)”

- **Main Constraints**
  
  - **Markovian Constraint**: \( \sum_k Y(k,j,t) = \sum_i q(k,i,j,t) Y(k,i,t-1) \),
    
    where \( q(k,i,j,t) = \Pr\{i + \text{number of arrivals in } t - \text{AAR(t)} = j / \text{PAAR} = k\} \)
  
  - **Utilization Constraint**: Expected Number of unutilized slots \( \leq \varepsilon \)

- **Outputs**: Optimal PAARs and Optimal Expected Queue Size
Formulation of SMIO Model

Minimize \[ \Sigma_t \Sigma_k \Sigma_j j \ Y(k,j,t) \]

Subject to:

1. \[ \Sigma_k \ X_{\text{paar}}(k,t) = 1 \quad \forall \ t = 1, 2, \ldots P \] \hspace{1cm} (1)

2. \[ \Sigma_j Y(k,j,t) \leq X_{\text{paar}}(k,t) \quad \forall \ j = 1, 2, \ldots \text{MaxQ} \] \hspace{1cm} (2)

3. \[ \Sigma_k^* Y(k^*,j,t) \leq \Sigma_k \Sigma_i q(k,i,j,t) Y(k,i,t-1) \quad \forall \ j, \forall \ t \] \hspace{1cm} (3)

4. \[ \Sigma_t \Sigma_k \Sigma_i Q_e(k,i,t) Y(k,i,t-1) \leq \varepsilon \] \hspace{1cm} (4)

\[ X_{\text{paar}}(k,t) \in \{0,1\} \]
Details on Simulation Model

- Single-Server Queuing Model

- Input Distributions
  - Geometric distribution for flight cancellations
  - Empirical distribution for drifts
  - Exponential distribution for pop-ups

- Performance Measures
  - Ground delay
  - Airborne delay
  - Utilization
Empirical Analysis of Drifts

Distribution of Ground Drifts (1999 SFO)

† Ground Drift = ARTD - CTD

† Mean is shifted to the right - more forward drifts
Empirical Analysis of Drifts (contd..)

- Enroute Drift = AETE - OETE
- Actual Enroute Time less than expected
- Enroute Drifts confined to a small window
Empirical Analysis of Cancellations

- Cancellations follow a geometric distribution during GDP
Empirical Analysis of Pop-up Flights

GDP Avg Popup per Hour
SFO

Number of GDPs

Mean = 1.70
Stdv = 1.93

Avg Popups per Hour

(Courtesy: Bob Hoffman)
Results for SMIO Model

- Capacity Scenario: (30,30,30,30,30,30,30) on 05/01/98 SFO
Results for SMIO Model (contd.)
Results for Simulation Model

- Capacity Scenario: (30,30,30,30,30,30)

- Tested the scenarios for all PAARs in the interval [28, 34]

- Used **Pareto Optimality** with Airborne Delay and Utilization as Objective functions

**Pareto Optimality**

A state $A$ (a set of parameters) is said to be Pareto optimal, if there is no other state $B$ dominating the state with respect to a set of objective functions.

A state $A$ dominates a state $B$, if $A$ is better than $B$ in at least one objective function and not worse with respect to all other objective functions.
Results for Simulation Model (contd.)

Pareto Optimal PAARs

<table>
<thead>
<tr>
<th>Utilization</th>
<th>Airborne Holding (Min) per Flight</th>
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<tr>
<td>0.84</td>
<td>0 - (29, 30, 30, 30, 30, 30)</td>
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<tr>
<td>0.86</td>
<td>5 - (32, 30, 30, 30, 30, 30)</td>
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<td>0.88</td>
<td>10 - (33, 30, 30, 30, 30, 28)</td>
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<td>0.90</td>
<td>15 - (33, 30, 30, 30, 30, 29)</td>
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<td>0.92</td>
<td>20 - (33, 30, 30, 30, 30, 28)</td>
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<tr>
<td>0.94</td>
<td>25 - (33, 30, 28, 30, 30, 29)</td>
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<tr>
<td>0.96</td>
<td>30 - (33, 30, 28, 30, 28, 30)</td>
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<tr>
<td>0.98</td>
<td>35 - (34, 30, 28, 30, 28, 29)</td>
</tr>
<tr>
<td>1.00</td>
<td>40 - (34, 30, 28, 29, 28, 29)</td>
</tr>
</tbody>
</table>
Summary

- Significant stochasticity in airport arrival demand
- Demand Uncertainties lead to under-utilization, and excessive airborne holding
- Two models - SMIO and Simulation Model - are developed
- Models recommend policy changes in setting of PAARs - substituting *staggered patterns* for *flat patterns*