Incorporating Stochastic Models and Stochastic Information Within Traffic Flow Management Systems

*Speaker:*

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Outline

• Introduction
• Background on stochastic models for Ground Delay Programs
  – Static vs. dynamic models
• Recent work on dynamic model for GDP planning
  – Capacity scenarios and scenario tree
  – Experimental results
  – Application under CDM
• Extension to enroute capacity problem ➔ DFW corner post problem
  – Graphically explain the decision making process
  – Experimental results
• Concluding remarks
  – Complexities associated with practical implementation
  – Future research
Sources of Uncertainty in Traffic Flow Management

- Demand (uncertain departure/arrival times)
- Capacity (forecast uncertainty)
- Control actions traffic managers may take
- Effects of coordination and timing of inter-related activities
Mitigating Uncertainty

• Reduce uncertainty by *improving information quality*.

• Create plans that “*hedge against*” *multiple possible future outcomes*.

• Create flexible systems that can *dynamically react to changing conditions*. 
NEXTOR Research on Uncertainty in ATM

- Uncertainty in airport capacity
  - Richetta and Odoni (1993, and 1994)
  - Ball et al. (1999, 2003)
  - Inniss and Ball (2001)
  - Mukherjee and Hansen (2003)
  - Liu et al. (2005)

- Demand uncertainty
  - Willemain (2002)

- Enroute airspace capacity
  - Mukherjee and Hansen (2004)
Research on Stochastic Ground Holding Problem

• Static Stochastic Optimization Models
  – Richetta and Odoni (1993)
  – Ball et al. (2003)
  – Considers multiple scenarios of airport capacity profile along with their probability of occurrence
  – Interesting properties of the IP formulation
  – Can be applied repeatedly ➔ “partially” dynamic
Research on Stochastic Ground Holding Problem

• (Partially) Dynamic Stochastic Optimization Model: Richetta and Odoni (1994)
  – Plans GDP in stages \(\Rightarrow\) utilizes updated information on capacity
  – Unable to revise ground delays once they are assigned, even if the flight hasn’t departed. However, this increases predictability of flight departure times.

  – Capacity scenarios and scenario tree
  – Utilizes updated information on capacity to revise ground delays of flights
  – Can incorporate non-linear measures of ground delay
Scenarios and Scenario Tree

Airport Capacity Scenarios

Scenarios Tree

P(Scenario 2) = 0.2

Scenario 1 (p=0.3)
Scenario 2 (p=0.2)
Scenario 3 (p=0.4)
Scenario 4 (p=0.1)
Scenario “Tree” Doesn’t Grow

- Can be constructed based on probabilistic weather forecasts
- Can be obtained by performing statistical modeling of historical data on actual airport capacity (Liu et al., 2005)
Illustration of the Decision Making Process

If the flight is delayed by 1 time period, then it can be released under scenario 1 at the flight's scheduled time to depart during its first time period and arrive by end of 2nd time period. It may need to be released under both scenarios 1 and 2, and hence face airborne delay of one time period if scenario 2 occurs.

In the Static Model, decisions are made during the 1st time periods, and not revised later.
Experimental Results

- Applied to Dallas Fort Worth Intl. Airport (DFW)
- 351 flights
- Six capacity scenarios
- Four cases of varied model parameters
- Results compared with that from existing stochastic models (Ball et al 2003, Richetta-Odoni, 1994)
Scenarios, Scenario Tree, and Cost Ratio

**Probability Mass Function**

\[ P\{\xi_1\} = 0.4; P\{\xi_2\} = 0.2; P\{\xi_3\} = 0.1; P\{\xi_4\} = 0.1; P\{\xi_5\} = 0.1; P\{\xi_6\} = 0.1 \]

**Cost Ratio** \( \lambda = 3 \)
Results

- Due to low cost ratio, airborne delays are faced in all models

- Dynamic Model
  - Less total expected cost
  - Ground delays more severe
  - Less airborne delays

- Delay reduction compared to Static Model
  - 10% in Dynamic Model
  - 2% in Richetta-Odoni
Application in CDM

- Dynamic substitution model that can be used by individual airlines to perform scenario-contingent substitutions
  - Airlines cannot exceed the number of slots (during any hour) assigned to them in the initial stage (by the GH model)
  - While making substitutions, airlines must not violate the coupling constraints that account for limited information on airport capacity in future time periods

- Dynamic compression model that can be used by the FAA
  - An optimization model that works like the Compression Algorithm currently used by the FAA
  - Vacant slots (due to cancellations) are utilized by making substitutions, and priority is given to canceling airline
  - No flight is assigned a later slot than it currently owns ➔ Everyone is better off
Intra-Airline Substitution Benefits

Percentage Reduction of Delay Cost

- AAL
- ANW
- CAA
- CHQ
- CCA
- DAL
- EGF
- SKW

carrier
Benefits from Compression

![Graph showing benefits from compression with data points for different airlines.](image-url)
Enroute Airspace Capacity Problem
Model Formulation

• Input:
  – Scheduled demand
  – Capacity scenarios and scenario tree
  – Set of enroute fixes where rerouting can occur and the available routes

• Main Decision Variables
  – Planned arrivals at enroute fixes where flights may be rerouted
  – Cumulative count of flights inbound via available routes
Delay Calculations

Total number of flights that passes fix \( m \) under scenario \( \xi \):

\[
R_m + 1 \sum_{r=1}^{\xi} D_{m,r} (m, t)
\]

Scheduled Arrivals \( SD_m(t) \)

Planned Arrivals \( X_m(t) \)

Ground Delay

Airborne Holding under Scenario \( \xi \)
Capacity Scenarios

Airport: DFW

Arrival Fixes: BYP, CQY

\[ t_1 \text{ and } t_2 \in \{8:00, 8:30, 9:00, 9:30, 10:00\} \]

\[ 5 \times 5 (=25) \text{ scenarios} \]
Experimental Case

- All scenarios equally likely
- Cost ratio 1:3

Results
- Rerouting results in additional flight time
- Overall delay cost in dynamic model 9% less than static model
- Ground delay in Dynamic RR model 30% less than Static model
- *Loss due to imperfect information:*
  - 13% less in dynamic model
Summary

• Mitigating uncertainty
  – Improve the quality of information
  – Hedge against possible outcomes

• Need to incorporate decision support models that address uncertainty in ATM
  – Compatibility with Collaborative Decision Making is a necessary criteria
  – Models/algorithms needs to be simple and transparent in order to be implemented in practice

• Dynamically adjusting plans in response to changing conditions and updated information is key to making the system more efficient
Work in Progress

• Develop realistic scenarios and scenario trees from past data
  – Cluster analysis of airport capacity profiles
  – Challenges in practical implementation: Identifying branching

• How to incorporate weather forecasts providing new capacities and probability of occurrence?
  – Compare the performance of dynamic model with static model applied repeatedly
Questions?
Backup Slides
**Decision Variables**

\[
X_{f,t}^q = \begin{cases} 
1 & \text{if flight } f \text{ is planned to arrive by the end of time period } t \text{ under scenario } q; \\
0 & \text{otherwise}
\end{cases}
\]

\[q \in \Theta, f \in \Phi, t \in \{Arr_f..T+1\}\]

\[
Y_{f,t}^q = \begin{cases} 
1 & \text{if flight } f \text{ is released for departure by the end of time period } t \text{ under scenario } q; \\
0 & \text{otherwise}
\end{cases}
\]

\[q \in \Theta, f \in \Phi, t \in \{Dep_f..T+1\}\]

\[
Y_{f,t}^q = \begin{cases} 
X_{f,t}^q + Arr_f - Dep_f & \text{if } t + Arr_f - Dep_f \leq T \\
1 & \text{otherwise}
\end{cases}
\]

\[q \in \Theta, f \in \Phi, t \in \{Arr_f..T+1\}\]

\[W_q^q = \text{number of aircraft subject to airborne queuing delay at time } t \text{ for one or more time periods, under scenario } q\]
**Objective Function**

\[
\text{Min } \sum_{q \in \{1..Q\}} P_q \times \left\{ \sum_{f \in \{1..F\}} \sum_{t=\text{Arr}_f}^{T+1} (t - \text{Arr}_f) \times (X_{f,t}^q - X_{f,t-1}^q) \right\} + \lambda \times \sum_{t=1}^{T} W_t^q \right\}
\]

**Constraints**

Decision variables are non-decreasing

\[
X_{f,t}^q - X_{f,t-1}^q \geq 0; \quad \forall f \in \Phi, q \in \Theta, t \in \{\text{Arr}_f..T+1\}
\]

Number of flights that land during any time period, under different scenarios, must be less than or equal to the scenario specific airport arrival capacity during that time

\[
W_{t-1}^q - W_t^q + \sum_{f \in \Phi} \left( X_{f,t}^q - X_{f,t-1}^q \right) \leq M_q^q; \quad t \in \{1..T+1\}, q \in \Theta
\]
Feasibility Conditions

\[ W_0^q = W_{T+1}^q = 0 \]

\[ X_{f,T+1}^q = 1 \quad \forall f \in \Phi, q \in \Theta \]

Coupling constraints impose the condition that as long as two or more scenarios are possible, the decisions on flight release time must be same under all those scenarios.

\[ Y_{f,t}^1 = \ldots = Y_{f,t}^k = \ldots = Y_{f,t}^{N_i} ; \quad f \in \Phi, t \in \{1, T\}; S_{i}^k \in \Omega_i : N_i \geq 2 \text{ and } \sigma_i \leq t \leq \mu_i \]
Dynamic Substitution Model

Airline-specific objective function:

\[ z = \sum_{f \in F_a} \sum_{\xi \in \Theta} P\{\xi\} \times \sum_{t = \text{Arr}_f}^{T+1} c(f, t - \text{Arr}_f) \times (X_{f,t}^\xi - X_{f,t-1}^\xi) \]

Key Constraints:

The number of planned arrivals of an airline cannot exceed the number of slots assigned to the airline from the initial assignment (dynamic GH model)

\[ \sum_{f \in F_a} (X_{f,t}^\xi - X_{f,t-1}^\xi) \leq v_{a,t}^\xi; \quad \forall t \in \Gamma, \xi \in \Theta \]

Coupling (or non-anticipativity) constraints:

\[ Y_{f,t}^{S_1} = ... = Y_{f,t}^{S_k} = ... = Y_{f,t}^{N_i}; \quad \forall f \in F_a, t \in \Gamma, S_k \in \Omega_i : N_i \geq 2 \text{ and } o_i \leq t \leq \mu_i \]
Dynamic Compression Model

Objective Function

$$\min z = \sum_{\xi \in \Theta} P\{\xi\} \times \left( \sum_{a \in A} (1 + can_a) \times \sum_{f \in F_a} \sum_{t = Arr_f}^{T+1} (t - Arr_f) \left( X_{f,t}^{\xi} - X_{f,t-1}^{\xi} \right) \right)$$

Key Constraints

No flight can be assigned a later arrival slot under any scenario, than what it owns after airline substitutions

$$\sum_{t = Arr_f}^{T+1} t \times (X_{f,t}^{\xi} - X_{f,t-1}^{\xi}) \leq \rho_f^{\xi}; \quad \forall f \in G, \xi \in \Theta$$
Constraints Continued

Scenario-specific airport capacity constraints

$$\sum_{f \in G} (X_{f,t}^{\xi} - X_{f,t-1}^{\xi}) + W_{t-1}^{\xi} - W_{t}^{\xi} \leq M_{t}^{\xi}; \quad \forall t \in \Gamma, \xi \in \Theta$$

Amount of scenario-specific airborne holding during any time period must not exceed the corresponding values from initial assignment

$$W_{t}^{\xi} \leq \hat{W}_{t}^{\xi}; \quad \forall t \in \Gamma, \xi \in \Theta$$

Coupling constraints

$$Y_{f,t}^{S_{1}^{i}} = ... = Y_{f,t}^{S_{k}^{i}} = ... = Y_{f,t}^{S_{N_{i}}^{i}}; \quad \forall f \in G, t \in \Gamma, S_{k}^{i} \in \Omega_{i} : N_{i} \geq 2 \text{ and } o_{i} \leq t \leq \mu_{i}$$