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)
  - Wilson (2002)
  - Inniss and Ball (2001)
  - Mukherjee and Hansen (2003)
  - Liu et al. (2005)
- Demand uncertainty
  - Vossen et al (2002)
  - Willemain (2002)
- Enroute airspace capacity
  - Nilim et al. (2002, 2004)
  - Mukherjee and Hansen (2004)

Research on Stochastic Ground Holding Problem

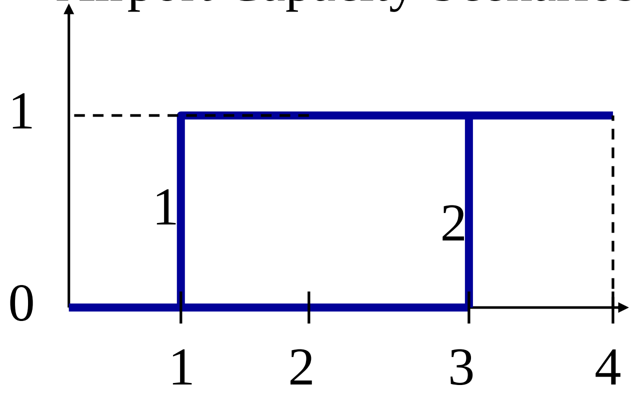
- Static Stochastic Optimization Models
  - Richetta and Odoni (1993)
  - Ball et al.(2003)
  - Considers multiple scenarios of airport capacity profile along with their probability of occurrence
  - Interesting properties of the IP formulation
  - Can be applied repeatedly ➔ “partially” dynamic

Research on Stochastic Ground Holding Problem

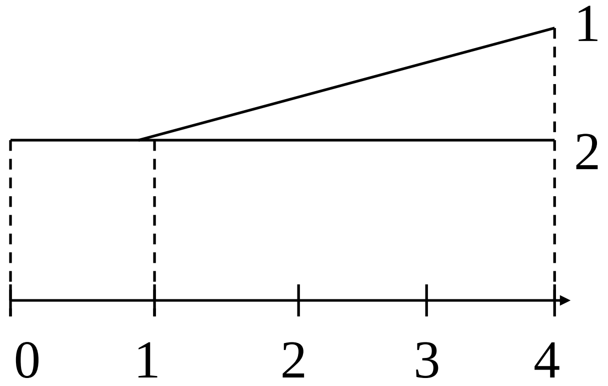
- (Partially) Dynamic Stochastic Optimization Model: Richetta and Odoni (1994)
  - Plans GDP in stages → utilizes updated information on capacity
  - Unable to revise ground delays once they are assigned, even if the flight hasn't departed. However, this increases predictability of flight departure times.
- Dynamic Stochastic Optimization Model: Mukherjee and Hansen (2003)
  - Capacity scenarios and scenario tree
  - Utilizes updated information on capacity to revise ground delays of flights
  - Can incorporate non-linear measures of ground delay

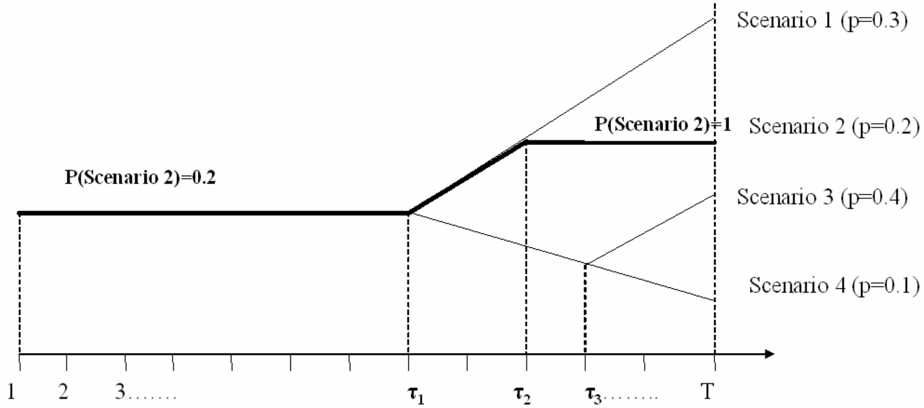
Scenarios and Scenario Tree

Airport Capacity Scenarios



Scenarios Tree





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)

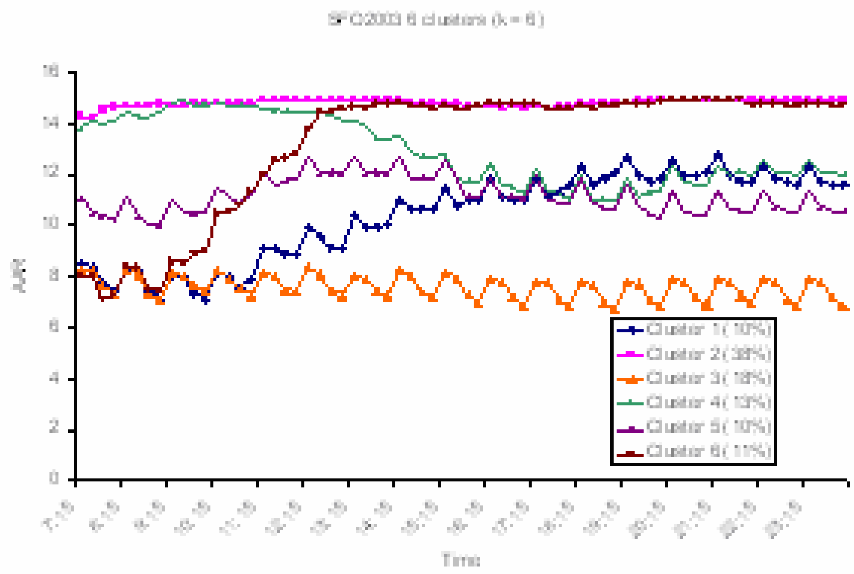
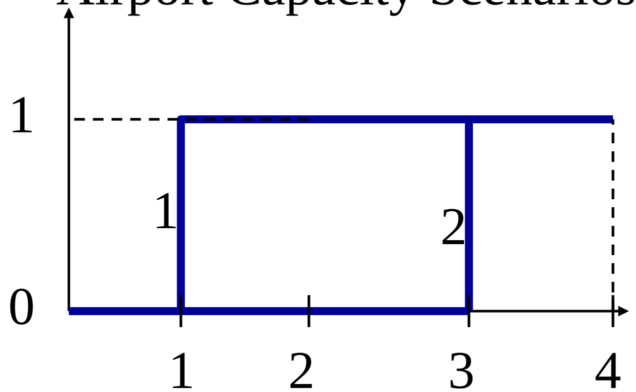
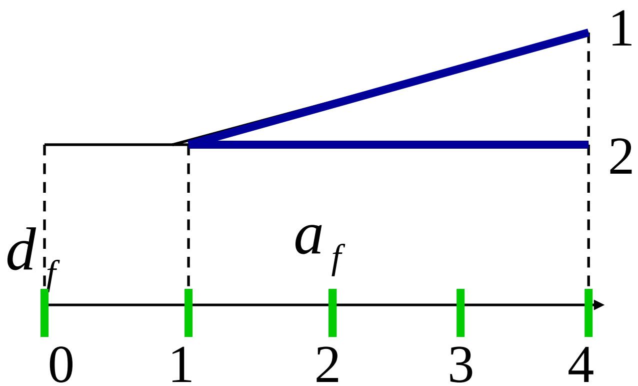


Illustration of the Decision Making Process

Airport Capacity Scenarios



Scenarios Tree



Our flight f is scheduled to depart during first time period and arrive by end of 2^{nd} time period

Decisions made during 1^{st} time period has to be same under both scenarios, because none of them can be distinguished at that time

If the flight is delayed by 1 time period, then it can be released under scenario 1 at beginning of time period 2

If the flight is released as scheduled, it will arrive under both scenarios 1 and 2, and hence face airborne delay of one time period if scenario 2 occurs

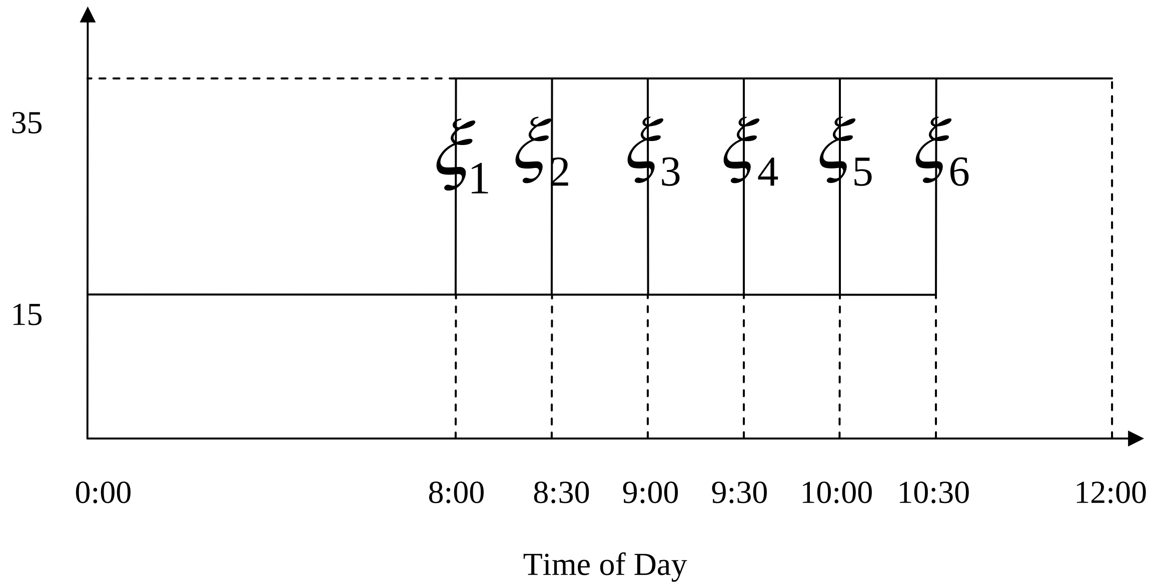
Otherwise it is delayed further and released during the 2^{nd} time period if scenario 2 occurs

In the Static Model, decisions are made during the 1^{st} 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



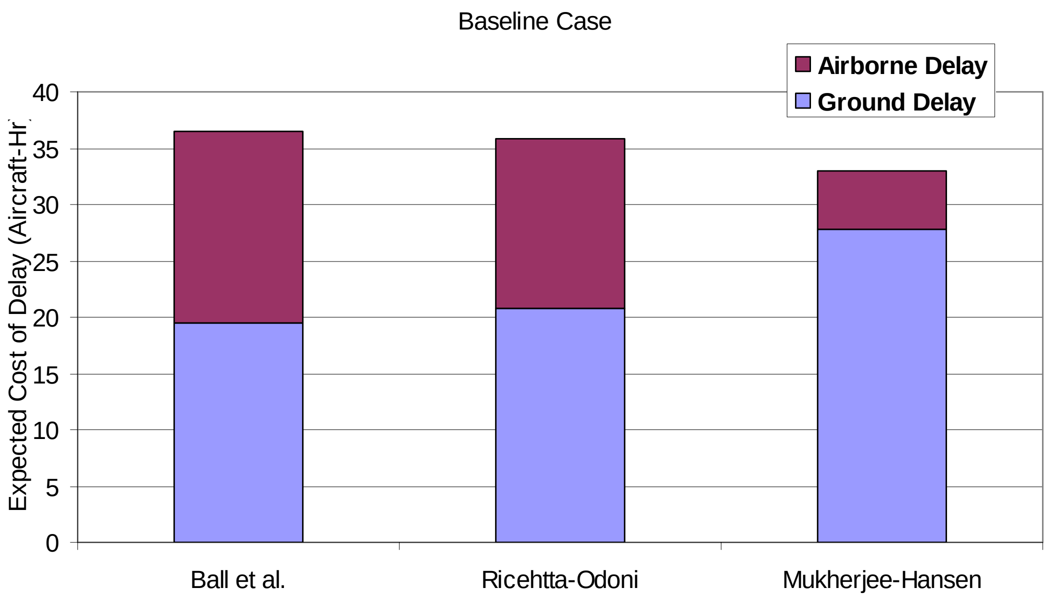
Probability Mass Function

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

$$\text{Cost Ratio } \lambda = 3$$

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



Ball et al. **Richetta-Odoni** **Mukherjee-Hansen**

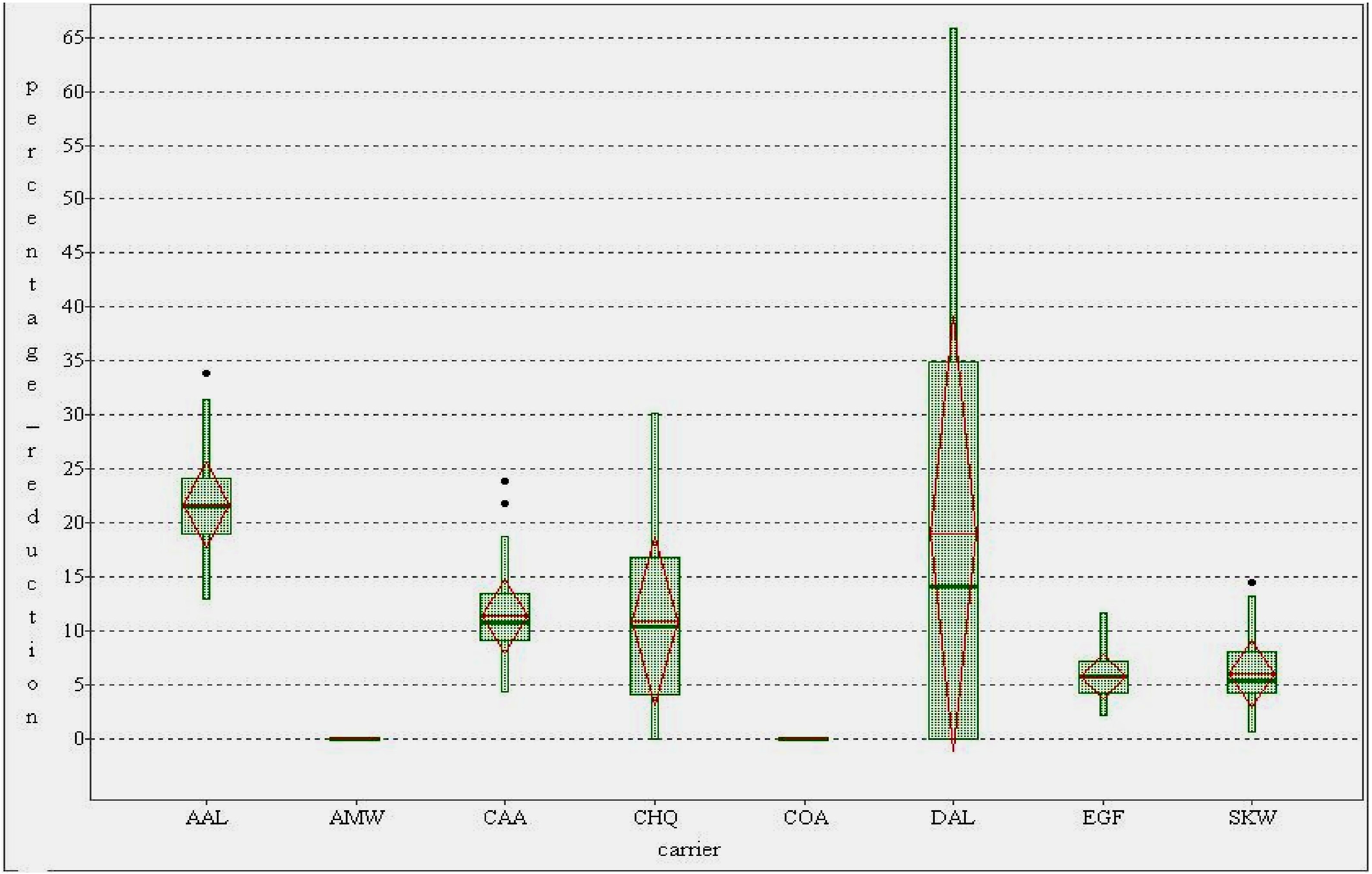
Application in CDM

- 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

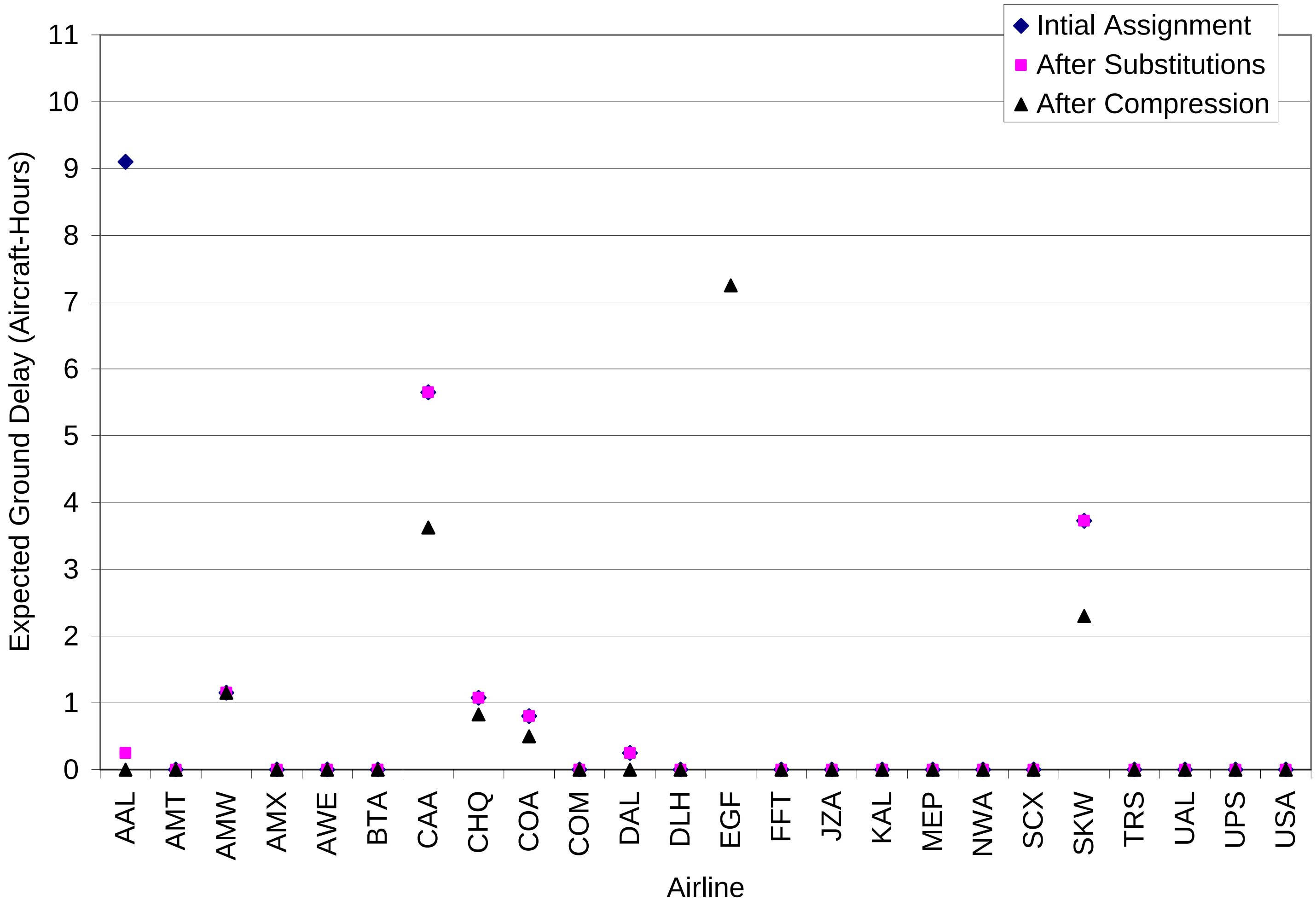
- Dynamic compression model that can be used by the FAA
  - An optimization model that works like the Compression Algorithm currently used by the FAA
  - Vacant slots (due to cancellations) are utilized by making substitutions, and priority is given to canceling airline
  - No flight is assigned a later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

Intra-Airline Substitution Benefits

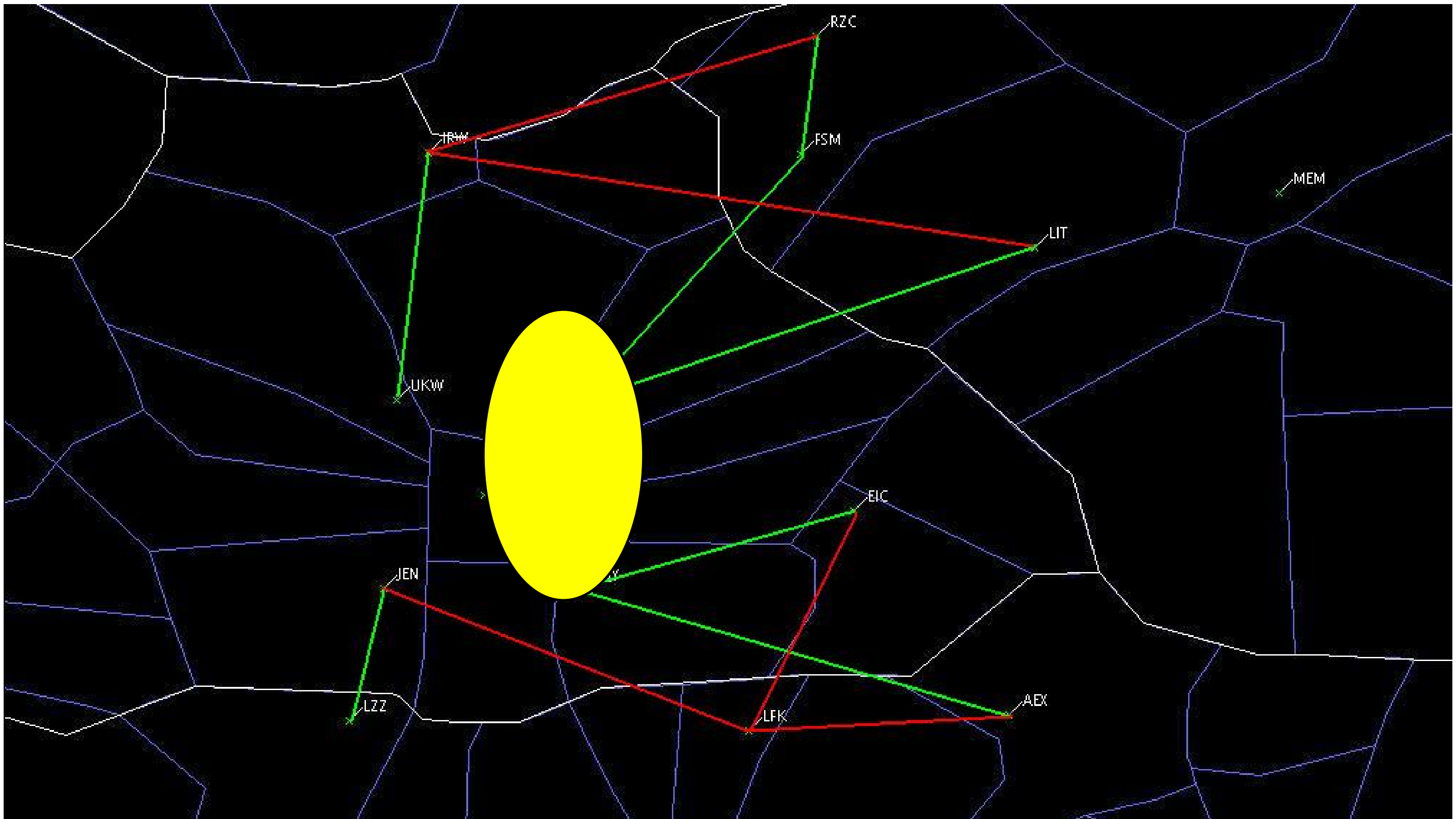
Percentage Reduction of Delay Cost



Benefits from Compression

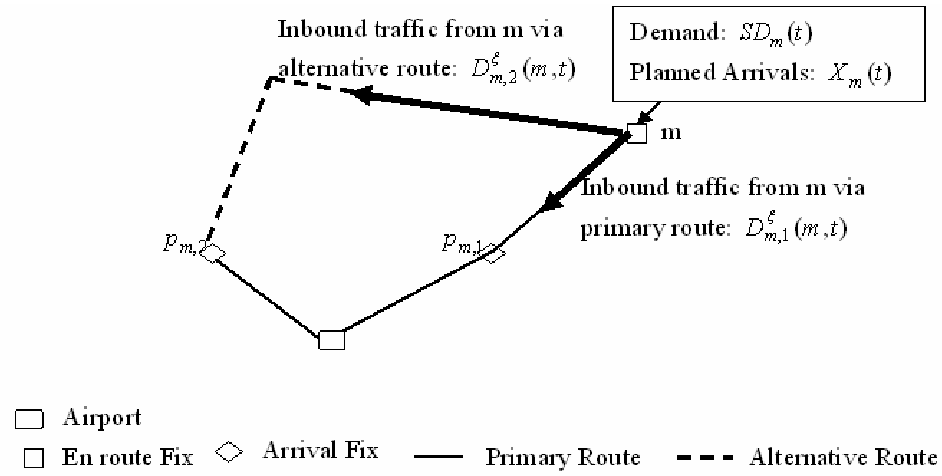


Enroute Airspace Capacity Problem

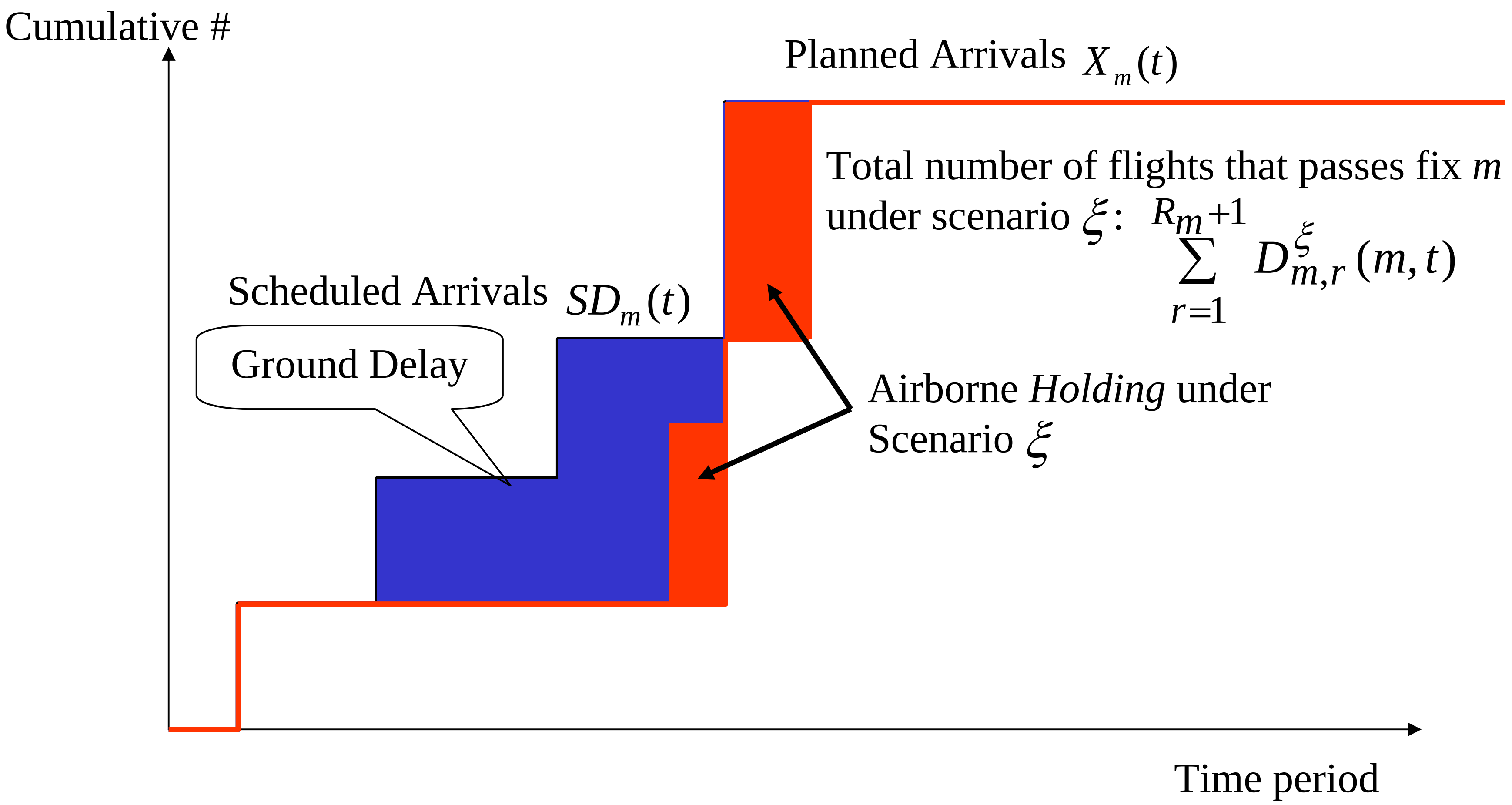


Model Formulation

- 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

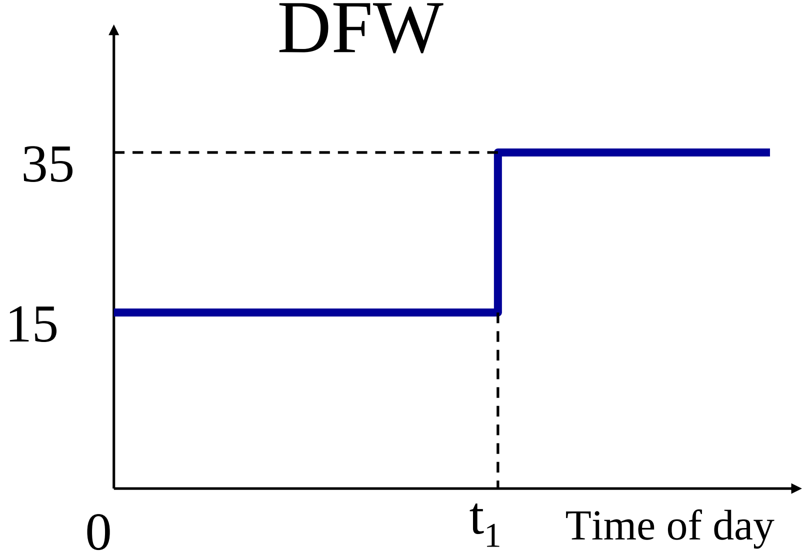


Delay Calculations

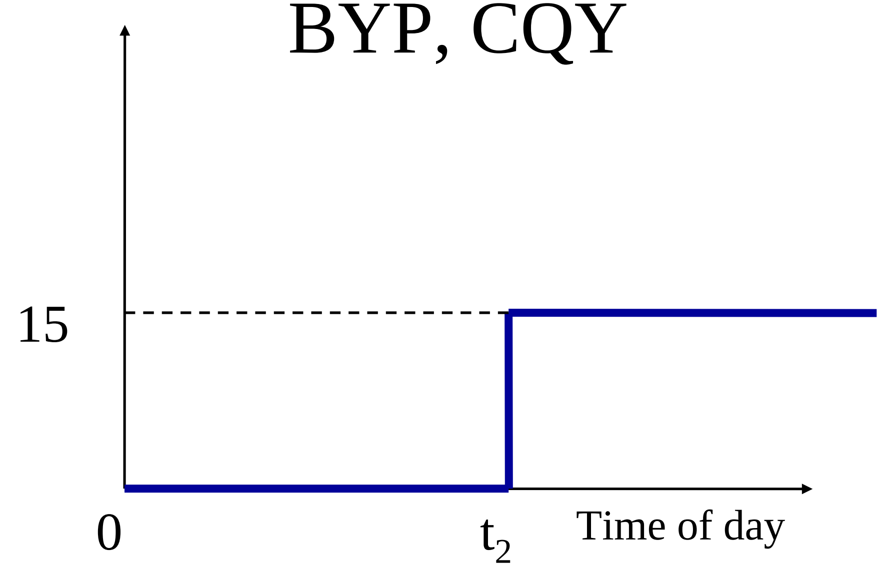


Capacity Scenarios

Airport:
DFW



Arrival Fixes:
BYP, CQY

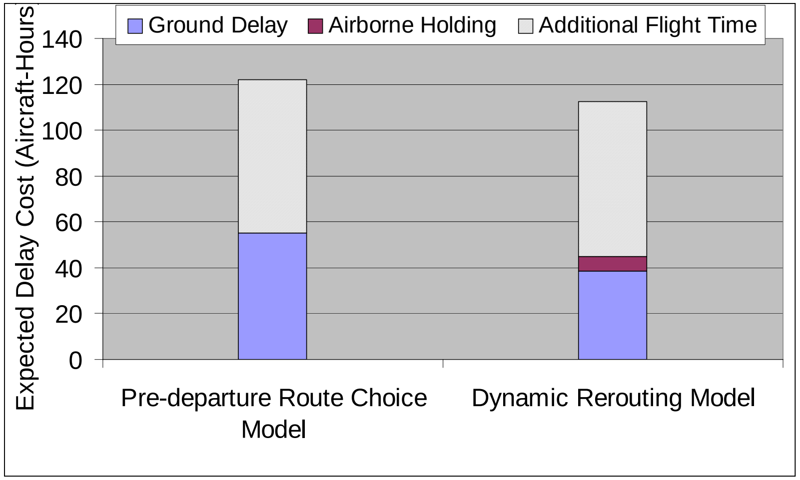


$$t_1 \text{ and } t_2 \in \{8:00, 8:30, 9:00, 9:30, 10:00\}$$

*5*5(=25) 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

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

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

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

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

$$Y^{q}_{f,t} = \begin{cases} X^{q}_{f,t+Arr_f-Dep_f}\ ;\ if & t + Arr_f - Dep_f \le T \\ 1 & otherwise \end{cases}$$

W^{q}_{t} = number of aircraft subject to airborne queuing delay at time t for one or more time periods, under scenario q

Objective Function

$$Min \sum_{q\in\{1..Q\}} P_q \times \left\{ \left[\sum_{f\in\{1..F\}} \sum_{t=Arr_f}^{T+1} \left(t - Arr_f\right) \times (X^q_{f,t} - X^q_{f,t-1}) \right] + \lambda \times \sum_{t=1}^{T} W^q_t \right\}$$

Constraints

Decision variables are non decreasing

$$X^q_{f,t} - X^q_{f,t-1} \geq 0; \quad \forall f \in \Phi, q \in \Theta, t \in \{Arr_f..T+1\}$$

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

$$W^q_{t-1} - W^q_t + \sum_{f\in\Phi} \left(X^q_{f,t} - X^q_{f,t-1} \right) \leq M^q_t; \quad t \in \{1..T+1\}, q \in \Theta$$

Feasibility Conditions

$$W_0^q = W_{T+1}^q = 0$$

$$X_{f,T+1}^q = 1 \qquad \forall f \in \Phi,\ q \in \Theta$$

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

$$Y_{f,t}^{S_1^i} = \ldots = Y_{f,t}^{S_k^i} = \ldots\ldots = Y_{f,t}^{S_{N_i}^i} \; ; \qquad f \in \Phi, t \in \{1..T\}; S_k^i \in \Omega_i : \mathrm{N}_i \geq 2 \;\; and \;\; o_i \leq t \leq \mu_i$$

Dynamic Substitution Model

Airline-specific objective function:

$$z = \sum_{f \in F_a} \sum_{\xi \in \Theta} P\{\xi\} \times \sum_{t = Arr_f}^{T+1} c(f, t - Arr_f) \times (X^{\xi}_{f,t} - X^{\xi}_{f,t-1})$$

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)

$$\sum_{f \in F_a} (X^{\xi}_{f,t} - X^{\xi}_{f,t-1}) \le \nu^{\xi}_{a,t}; \quad \forall t \in \Gamma, \xi \in \Theta$$

Coupling (or non-anticipativity) constraints:

$$Y^{S^i_1}_{f,t} = \ldots = Y^{S^i_k}_{f,t} = \ldots = Y^{S^i_{N_i}}_{f,t} ; \quad \forall f \in F_a, t \in \Gamma, S^i_k \in \Omega_i : N_i \ge 2 \text{ and } o_i \le t \le \mu_i$$

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

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

Constraints Continued

Scenario-specific airport capacity constraints

$$\sum_{f \in G} (X^{\xi}_{f,t} - X^{\xi}_{f,t-1}) + W^{\xi}_{t-1} - W^{\xi}_{t} \leq M^{\xi}_{t}; \quad \forall t \in \Gamma, \xi \in \Theta$$

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

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

Coupling constraints

$$Y^{S^i_1}_{f,t} = \ldots = Y^{S^i_k}_{f,t} = \ldots = Y^{S^i_{N_i}}_{f,t}; \quad \forall f \in G, t \in \Gamma, S^i_k \in \Omega_i : N_i \geq 2 \text{ and } o_i \leq t \leq \mu_i$$