Evaluating a New Formulation for Large-Scale Traffic Flow Management

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• Important to consider scope of model for ATM
  – Single model addressing every time scale or possible action would be basically impossible
• Suggest a modular approach:
General Aims of Strategic TFM

- **Strategic planning**
  - Useful at beginning of busy day to help stakeholders understand conditions

- **Predicting congestion**
  - Consider interactions and based on multiple disruptions

- **Coordinating traffic management initiatives**
  - Essential function with multiple ground/air rationing initiatives

- **Dynamic airspace configuration**
  - Include flexibility in model to allow for future changes
Introduce two strategies in this work to improve strategic TFM:

- Reduced airspace complexity: only represent capacitated disruptions
- Accurate delay propagation: to understand coordination of initiatives and effects of airline plans
Reduced Airspace Complexity

- **Reduce number of capacitated elements**
  - This is one of the primary drivers of model complexity, but most elements of wide area are relatively uncongested

- **Focus only on congested elements**
  - These are the real issue of concern

- **Avoid compounding errors of setting capacities**
  - Capacities are uncertain (particularly for airspace) so avoid repeating the same potentially erroneous methodology
• Goal: concentrate efforts on potentially congested regions
• Propagation of delays from early flights to later flights has dramatic impact on operations
  – May be a difficult phenomenon to track on a large scale, as in strategic TFM
  – Model must have information about number of aircraft and their relationships to one another
Flight Pairing Approach

• Identify flight pair operated by same aircraft
• Force subsequent flight pairs to operate consecutively
• Problems:
  – Difficult to identify pairs without proprietary data
  – Limited flexibility

Delay accrued to each subsequent flight
Flight Pair Problems

- Flight pairing provides little of the flexibility actually available to airlines
  - Does not allow for aircraft swaps: an important phenomenon during irregular operations
Fleet Tracking Approach

- Identify fleets of aircraft within each airline
- Require **conservation of flow** at each airport for each fleet (rather than by flight pairs)
  - Any aircraft that is ready may operate any outgoing flight within same fleet
For each time interval, track for each fleet:

- Arriving flights (from other airports)
- Departing flights (to other airports)
- Originating flights (beginning operational day)
- Waiting flights (flights previously arrived, now waiting)

Problems:

- Defining fleets without proprietary data is difficult
- May add significant complexity to a model
- Depending on fleet definitions, may reflect greater flexibility than actually exists
• Using flow model at every airport for every fleet creates too much complexity

• To reduce complexity:
  – Use flight pairs for small airline presence
    • Reflects reality that 1-2 flights go in, only those same aircraft may come out
  – Use flow models for larger airline presence
    • More realistic for hub operations where many flights go in and out at certain times
Incorporating New Features

• Chose to add enhancements to existing IP formulation: Bertsimas, Lulli, Odoni (BLO) model
• Evolution of Bertsimas, Stock Patterson models
• Combines ground holding, airborne holding, and route choice decisions
• Models individual flights
  – Results must be aggregated to examine flows
• Supports rich set of cost functions
  – Using weight function of ground and airborne delay – determining system-optimal plan
Model Formulation

\[ \sum_{f \in F, O^f = k} \left( w_{f,k,t}^f - w_{f,k,t-1}^f \right) \leq D_{k,t} \]

\[ \sum_{f \in F, D^f = k} \left( w_{f,k,t}^f - w_{f,k,t-1}^f \right) \leq A_{k,t} \]

\[ I_{v,t} = I_{v,t-1} + \sum_{f \in F} \sum_{e \in e_v^f} \left( w_{e,t}^f - w_{e,t-1}^f \right) - \sum_{f \in F} \sum_{x \in X_v} \left( w_{x,t}^f - w_{x,t-1}^f \right) \leq V_{v,t} \]

\[ I_{v,0} = 0 \]

\[ w_{O_2,t}^f \leq w_{D_1,t-g}^f \]

\[ z_{k,t-1}^h + \sum_{f \in F} \sum_{D^f = k, H^f = h} \left( w_{f,k,t}^f - w_{f,k,t-1}^f \right) + P_{k,t}^h = z_{k,t-1}^h + \sum_{f \in F} \sum_{O^f = k, J^f = h} \left( w_{f,k,t}^f - w_{f,k,t-1}^f \right) \]

\[ z_{k,t}^h = 0 \]

\[ \text{Capacity constraints} \]

\[ \text{Routing constraints} \]

\[ \text{Flight connection constraints} \]

\[ \text{Structural constraints} \]

\[ \text{Objective function} \]

\[ \min_{f \in F} \left[ \sum_{t \in T_{D^f}} \left( \sum_{t \in T_{O^f}} \left( C_a \left( t - R_{d}^f \right)^{1+\varepsilon} \right) \left( w_{D^f,t}^f - w_{D^f,t-1}^f \right) \right) \right] \]
Case Study

- July 20, 2005 with 0900Z WSRP (for 1300Z)
Case Study Input Data

• 3 disruptions
  – Main disruption in Upper Midwest: capacitated at 25% of nominal throughput
  – Other disruptions: treated as impassible

![Graph showing relationship between weather coverage and capacity](image)
Case Study Input Data

• 19,710 flights
  – Assumed 20 aircraft fleets (1 for each carrier)
  – Accurate historical schedule used

• 264 airports
  – Capacitated at IFR capacity if weather forecast nearby, VFR otherwise

• Routes
  – Default route: Great Circle
  – Alternate route: arbitrary, but 25% longer than GC
What flow *should* look like to minimize delays as specified

Model pushed throughput under line using delays & rerouting
Case Study Analysis

- Lower than expected, due to uncaptured factors
Case Study Analysis

- Demonstrates utility of included reroute option
Conclusions & Contributions

• Enhancements reduce complexity to allow for analysis of more sophisticated case studies
  – Reduced airspace complexity
  – Improved tracking of propagated delays
• Model strategically delays/cancels flights in accordance with disruptions
  – Solution time reasonable for the large number of features/amount of data included
Continuing Work

- Explore other uses for model
  - Dynamically generating constraints
  - Predicting user behavior
  - Identifying appropriate TFM initiatives

- Strengthen implementation of delay propagation model
  - Largely a data availability/processing issue

- Develop more complex case study
  - Greater realism/complexity for flight plans and capacity representations
  - Compare model output with realized conditions