Designing Coordinated Initiatives for Strategic Traffic Flow Management

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Strategic Planning in Today’s Operation

Hours in advance, we know that there will be serious convective weather ...

What is the range of possible weather scenarios, and how likely are these scenarios to occur?

What does the range of ATM impacts look like?

What options will we have available to alleviate congestion, and when do we have to act?

This is currently done by multi-stakeholder teleconference, with limited analytical information and few useful strategy assessment tools.
What is FCM?

FCM aims to provide a scientific methodology for strategic TFM decision-making.

- Developing a common understanding of the problem for stakeholders.
- Providing a quantitative analysis of potential plans prior to implementation.
- Enabling fact-based discussions for strategic planning development.
How does it work?

Weather forecast shows potential for convective activity → Translate into prediction of ATM impact → Simulation computes impact on demand across network

Interface provides details of resource impact and enables what-if scenario planning of mitigation strategies

Before and After TMI

View
04:00Z

View
04:00Z
The simulation model (briefly)

- Weather-impact scenarios are forecasts of capacity reductions
  - Use ensemble forecasts or other methods to generate and translate
  - Define a few representative scenarios for planning
  - Modify nominal capacities as appropriate
- Demand estimates provide forecasts of flight times and routes, before they file
  - Represented as flow on an origin-destination-route (O-D-R) network
- Area of Interest determines network aggregation
  - Origin/destination nodes are airports or ‘clusters’ of airports
  - Routes are sector transits or Center transits
TMI Modeling: GDPs

A Ground Delay Program (GDP) sets a rate for arrivals at the target airport. Flow is delayed from departing at the origin airport.

Ground Delay Program Parameters
- Target Airport (set)
- Tier
- Rate
- Start time
- Duration
An Airspace Flow Program (AFP) sets a rate for flows crossing a defined boundary. Flow is delayed from departing at the origin airport.
Reroutes move pre-departure flows from one route to another. Reroutes are defined by a single origin-destination airport or by all flows using the route.

**Reroute Parameters**

- Origin-Destination Pair (set)
- Start time
- Duration
Evaluation Metrics

- Delay metrics
  - Ground delay
  - Sector delay
  - Distinguish congestion vs. TMI delay

- Reroute penalties
  - Fixed cost: Per demand cost for rerouting
  - Transit time: Per minute cost for longer reroutes

- Temporal Concentration Metrics
  - Using a variant of Hierfindahl-Hirshman Index, which measure market share

  \[
  \begin{bmatrix}
  1 & 0 & 1 & 0 & 1 \\
  0 & 1 & 1 & 1 & 0 \\
  \end{bmatrix} \rightarrow 3
  \]

  \[
  \begin{bmatrix}
  0 & 1 & 1 & 1 & 0 \\
  \end{bmatrix} \rightarrow 7
  \]

- Distinguishes ground and sector delay persistence

Objective function: Ground delay + 2* Sector delay + Fixed reroute + 2*Transit time
Our example

Weather forecast shows impact in Atlanta Center
- Calculate capacity reduction, generate representative scenarios

Evaluate very high impact scenario
- Use this prediction to reduce capacity, evaluate congestion

Traffic Impact Summary
- Sector delay: 429,543 minutes
- ~30% directly due to weather; remaining due to resulting congestion
- 80% of weather delay is in ZTL11 and ZTL20
- Flows to and from Atlanta Airport (ATL) are most affected
Parameter Sweep

<table>
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<tr>
<th>Parameter</th>
<th>Values</th>
<th># of levels</th>
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<td>Duration (hours)</td>
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GDP Parameters

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<td>Duration (hours)</td>
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AFP Parameters

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<tr>
<td>Duration (hours)</td>
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ZTL11 Reroute Parameters

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<th>Parameter</th>
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<td>Duration (hours)</td>
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ZTL20 Reroute Parameters

- Results in 82,038 feasible combinations
- Evaluated using a pre-configured cluster for design-through-simulation
  - 60 processors
- Total run time was ~35 hours
The optimal solution
Analyzing the Design Space

- Ground delay and sector delay ranges vary widely
  - Sector delay is order of magnitude higher
  - Becomes objective function driver
- Reducing weather delays also reduces congestion delays
- Ground delay not necessarily trade-off of sector delay
  - Can apply strategies that just add delay....
Identifying Critical Features

- Reroutes are critical to good solutions
  - Removes sector congestion without adding ground delay
  - Reroute penalties are small by comparison
- AFP start time is second most critical feature
  - Shouldn’t delay flights into the weather!

Color-coded by AFP start time: early, middle, late
Heuristic Optimization of the Design Space

- Heuristic approaches are useful for optimizing simulation models
  - No mathematical structural requirements
  - Use the objective function value to guide the search
  - Incorporates a degree of randomness
  - No guarantee of optimality

- Applied a basic Genetic Algorithm (GA) on design-by-simulation cluster
  - Finds optimal solution efficiently
  - Promising for analyzing large problems and possibly real-time application

<table>
<thead>
<tr>
<th># of Generations</th>
<th>% of Design Space</th>
<th>Computation Time (min)</th>
<th>% over Optimal</th>
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<td>30</td>
<td>1.8</td>
<td>53.13</td>
<td>8%</td>
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<tr>
<td>40</td>
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<td>50</td>
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<td>85.33</td>
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<tr>
<td>60</td>
<td>3.6</td>
<td>102.46</td>
<td>Optimal</td>
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Concentration Metrics and Pareto Front Analysis

- Temporal Concentration Metrics provide an alternate measure of strategy effectiveness
- Optimal strategies are on the Pareto front
  - All top 10 solutions are similar in design (parameter selection) and evaluation (metrics)
- This leads to further research questions...
  - What are the other Pareto optimal strategies?
  - How can we leverage GAs to populate Pareto front with varied designs?
Continuing Research

- The goal of FCM is to provide real-time decision support for strategic Traffic Flow Management
  - Identified critical design features of a solution
  - Successfully employed a heuristic search procedure to identify the optimal solution
- Continuing research focuses on improved design methods and visualization for decision making
  - Can the automation identify the critical features automatically?
    - Leverage to reduce computation time
  - How do we visualize design space for decision making?
  - What is the ‘right’ objective function?
    - Multiple decision makers with different goals
    - May be situation dependent
  - How do we develop robust solutions for weather and demand uncertainty?
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