Dynamically Generating Operationally-Acceptable Route Alternatives Using Simulated Annealing

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Original route has predicted weather blockage:
Delay the flight on the ground until the weather moves?
Reroute the flight? Reroute it with an altitude cap?
Fly over the weather? Time-of-arrival constraint?

Could use this airspace for efficiency, but would generate unusual flow patterns (complexity)

This sector has high demand and will likely be congested, leading to delays

Original route: Can ground delay to wait for weather to move, or apply 4D constraint (if equipped) for additional precision

Preserves arrival time, but requires coordination with additional facility (ZTL), and trailing weather may intensify

Increased flying time, and what if the weather moves faster?

Would also like to consider the business objectives of the flight operator, existing flow management initiatives, airport capacity constraints, etc.
Traditional Approaches for Designing Reroute Options

Database of Alternatives

• Decision makers use Playbook Routes, CDRs, SWAP, etc.
  – Readily available routes with inherent operational acceptability
  – Offers limited options that cannot account for dynamic constraints and objectives

Free Flight Networks

• Generate situation-specific reroutes dynamically
  – Flexibility arises from a large option space
  – Computational performance dictates model complexity

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Origin</th>
<th>Destination</th>
<th>Departure FL</th>
<th>Route</th>
<th>Sector</th>
<th>Departure Time</th>
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<td>J95</td>
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<td>ELIOT</td>
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</table>
Applicability of Terrestrial Rerouting Networks to Dynamic Aircraft Rerouting

- Network models derived from interconnectivity of roads
  - A finite number of connections between two points
  - All connections operationally acceptable

- Inventory historical routes
  - Historical routes do NOT necessarily connect origin and destination

- Create database of fix-pair connections from historically flown routes
  - Each fix-pair is operationally-acceptable

Weyns, et al. 2007
Metrics of Operational Acceptability

- **Normalized Distance**: Additional miles flown
- **O-D Flow Factor**: does the route “go with the flow?”
  - Characterized by fix-to-fix route segment frequency distribution, specific to airport origin/destination cluster.
- **Route Blockage**: desirability of segment based on predicted weather coverage
- **Lateral Deviation**: surrogate for coordination complexity
- **Global Conformity**: Relative Usage
- **Sector Congestion**: Predicted overall demand relative to MAP
- **Airline Schedule Disruption**: Nonlinear evaluation of reroute delay
- **ATC Facility Cost**: Facility Changes Required
- **ATC Point-Out**: Transits less than 120 sec

\[ b_{t(i,j)}^{(i,j)} = 1 \text{ if } h_{t(i,j)}^{(i,j)} \leq h_f \]
\[ = 0 \text{ otherwise} \]

\[ B_{(i,j)} = \sum b_{t(i,j)}^{(i,j)}/T, \text{ for all } t \geq \text{LAT}(t_{\min}) \]
Previous Approach: K-shortest Path (KSP)

- Construct the fix-pair network; Assign arc costs
  - Distance
  - O-D Flow Conformity
  - Route Blockage
- Use KSP to generate reroute options
- Evaluate reroute options by all operational acceptability metrics
- Only considers reroutes; options such as ground delay, altitude changes are computationally intractable

<table>
<thead>
<tr>
<th>Network Parameters</th>
<th>Parameter Values</th>
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<tr>
<td>Semi-major Axis</td>
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<tr>
<td>Semi-minor Axis</td>
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<tr>
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<tr>
<td>Number of Arcs</td>
<td>7580</td>
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</tbody>
</table>
Simulated Annealing (SA)

Flight Info
- Original Route
- Deviation Point
- Rejoin Point

Construct Network
- Define Nodes and Arcs
- Calculate Arc Costs

Fix Segment Database

Flow Factor Database

Arc Cost Weighting Factors

Weather Prediction

Objective Function Weighting Factors

Generate Initial Solution:
Dijkstra’s Shortest Path Algorithm

Perturb Solution Using 1 of 7 Methods
- Single or Double Inclusion
- Single or Double Replacement
- Single or Double Removal
- Ground Delay

Simulated Annealing

Evaluate Perturbed Solution using Operational Acceptability Metrics

Keep or Reject Perturbed Solution based on Cooling Schedule Criteria

Update Temperature until System is Frozen (terminates)

Best Route Alternative and Associated Metrics
Perturbation by Inclusion

- Inclusion adds a sequence of arcs to the route
- Insertion fix position and sequence are selected uniformly at random
- Single Inclusion: Adds one fix
- Double Inclusion: Add two fixes
Perturbation by Replacement

- Replacement exchanges a sequence of arcs in the route
- Replacement fix position and sequence are selected uniformly at random
- Single Replacement: Exchanges one fix
- Double Replacement: Exchanges two fixes
Perturbation by Removal

- Removal deletes a sequence of arcs in the route
- Removal fix position is selected uniformly at random
- Single Removal: Deletes one fix
- Double Removal: Deletes two fixes
Generating Flight Alternatives

- SA Alternatives generated as best 5 (max) from 15 trials
  - Single set of SA parameters chosen
- Evaluate using equally-weighted metrics in objective function
  - Priorities would be assigned by users
- Compare SA-generated alternatives to:
  - Historic (previously flown) reroutes taken from database
  - KSP reroutes optimized within the network
    - Distance more heavily weighted in arc cost
    - 200 reroutes generated and evaluated
Avoiding Weather En-route: First Example

**Historic Alternatives**

- **Hist. 2** travels west to LYH to reconnect with original route, intersects weather.
- **Hist. 1** travels **straight** from GVE to CLT.

**KSP Alternatives**

- **KSP 1&2** vector around blocked segment.
- **KSP 3-5** travel east to avoid weather, reconnect at MAYOS.
Avoiding Weather En-route: First Example (Cont’d)

• SA reroutes show same behavior as KSP
  – All options follow STAR
  – No guarantee of optimality with SA
  – Fine tuning of parameters can improve solutions

• For this case, raising convergence criteria may benefit solutions

SA Alternatives

SA 1 vectors around blocked segment, reconnects at MAYOS

Deviation point

SA 2 travels east to avoid weather, reconnect at MAYOS
Metric Comparison for First Example

The graph compares different metrics for three scenarios: Historic, KSP, and SA. The metrics are normalized and include:

- ATC Point-out Cost
- ATC Facility Cost
- Airline Schedule Disruption
- Sector Congestion
- Global Flow Conformance
- Lateral Deviation
- Route Blockage
- O-D Flow Factor
- Distance
Avoiding Weather Pre-departure: Second Example

**Historic Alternatives**
- Hist. 3 & 5 travel west to LYH to reconnect with original route.
- Hist. 1, 2, & 4 travel to MXE then to GVE on original route then head east to CLT.

**Deviation point**

**SA Alternatives**
- SA. 5 travels west out of LGA to MOL with a 5 min ground delay.
- SA. 3 travels original route to GVE and vectors west to reconnect with STAR.
- SA. 1, 2, & 4 travel mostly on original route to GVE, then head east to reconnect with original STAR (SA. 4 direct to CLT).
Metric Comparison for Second Example

![Graph showing metric comparison for different scenarios: Historic, KSP, SA. The graph displays normalized metric values for various factors including ATC Point-out Cost, ATC Facility Cost, Airline Schedule Disruption, Sector Congestion, Global Flow Conformance, Lateral Deviation, Route Blockage, O-D Flow Factor, and Distance.]
Avoiding Weather Just Prior to Departure: Third Example

Historic Alternatives

- Hist. 1-3 travel east from GVE to reconnect directly with CLT

KSP Alternatives

- Net. 1-5 travel east from GVE to GSO then reconnect with original route at various points
Avoiding Weather Just Prior to Departure: Third Example (Cont’d)

• SA reroute is same as 2nd KSP reroute
  – No guarantee of optimality with SA
  – Fine tuning of parameters can improve solutions
• For this case, relaxing convergence parameters may provide multiple solutions

SA. 1 travel east from GVE to GSO then reconnects with original STAR at GIZMO
Metric Comparison for Third Example
Computational Effort: Initial Analysis for Third Example

- Network generation a significant cost
  - Estimating route blockage a significant expense
- Metric evaluation expensive; SA evaluates metrics for each perturbation
- SA evaluates ground delay in addition to reroutes
- For efficiency SA must be parallelized

<table>
<thead>
<tr>
<th>Network Size/ Solution Effort</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Nodes</td>
<td>797</td>
</tr>
<tr>
<td>Number of Arcs</td>
<td>7129</td>
</tr>
<tr>
<td>Network Generation Time</td>
<td>10.2 (sec)</td>
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<tr>
<td>KSP Solution and Evaluation Time</td>
<td>22 (sec)</td>
</tr>
<tr>
<td>Total SA Solution Time</td>
<td>48 (sec)</td>
</tr>
<tr>
<td>Single SA Solution Time</td>
<td>3.3 (sec)</td>
</tr>
</tbody>
</table>
Conclusions and future work

• SA provides route alternatives that are comparable to KSP in overall operational acceptability
  – Can provide solutions in cases where KSP cannot
  – Captures ground delay; can capture altitude changes, etc. without significant computation costs
  – By parallelizing SA, significant computation reductions can be achieved

• Future work
  – SA parameters need tweaking
    • Efficient parameters are likely a function of network size/complexity
  – Enhance route alternative diversity
    • Explore SA as a means of defining diverse route options
  – Examine network definition for multi-flight problems
    • Single network reduces computation costs
    • Analyzing multiple flights enables flow considerations
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How SA Works

Current solution: $x$
Current cost: $C(x)$

Perturb
$x \rightarrow x_p$

Evaluate:
$C(x_p)$

Compare:
$\Delta C = C(x_p) - C(x)$

Probability of acceptance:
$P(\Delta C) = \exp(-\Delta C/T)$

$P(\Delta C) > \text{random number}$

$\Delta C \leq 0$

Update:
$x = x_p$
$C(x) = C(x_p)$

$C(x) < C(x_b)$

$xb = x$
$C(x_b) = C(x)$
Flight Option Generator (FOG) provides the mechanism for developing congestion resolution and delay recovery actions, and for negotiating specific flight objectives.
Design Methodology Overview

Perform SME Interviews

- Identify Operationally Acceptable Qualities for Reroutes
- Develop Quantifiable Metrics for Reroutes

Define Network using Historic Fix Segments

- Quantify Arc Costs Using Relevant Parameters
- Define Flight Specific Route Alternatives
- Evaluate and Rank Options by Operational Acceptability Metrics
- Provide Set of Reroutes and Metrics to Decision Makers for Evaluation

Iterate until Reroutes Capture Operationally Acceptable Qualities