Strategic planning of North Atlantic Oceanic air traffic based on a new wind-optimal route structure

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Overview

- How Oceanic Air Traffic is organized?
- Problem Modeling
- Optimization process
- Results
- Conclusions and perspectives
Air traffic management (ATM) is a system that assists and guides aircraft from a departure airport to a destination one. ATM operations are divided into three phases:

- strategic phase
- pre-tactical phase
- tactical phase
Flight profile

- Preflight
- Takeoff
- Departure
- En Route
- Descent
- Approach
- Landing
North Atlantic Airspace Boundaries
North Atlantic Airspace features

- The NAT air traffic is concentrated within two major opposite directional flows.
- Aircraft operating in the NAT are subject to very strong winds induced by the Jet Streams.
- The NAT airspace suffers from lack of surveillance means (Procedural Approach Control).
Organized Track System (OTS)
Time Constraint for Oceanic Traffic
How Does ADS-B Work?

The aircraft get their position from the GNSS constellation.

Then they simultaneously broadcast their position and other data to any aircraft, or ground station equipped to receive it.

Ground Stations then transmit the aircraft’s position to Air Traffic Control.
Time Constraint with ADS-B

Diagram showing the time constraint with ADS-B, indicating 2 minutes and 3 minutes of separation.
What is our problem?

Limitation of the OTS

- The tracks are not all wind optimal.
- Flight requests to change OTS track often get rejected from the safety prospective because of the large separation norms.
New Oceanic Track Network Design

Objective

Put as many aircraft in the jet and move the crossings at the entry and exit of the track network.
New Oceanic Track Network Design
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Assumptions

- Conflict resolution is performed within the NAT only.
- The desired aircraft speed is considered to be constant for the entire trajectory.
- Eastbound and westbound flows are treated independently.
Route structure model
Problem formulation

We consider a set of $N$ eastbound flights. Each flight $f$ is represented by a set of parameters which are:

- Entry and exit track to the OTS ($\text{Track}^f_{\text{In}}, \text{Track}^f_{\text{Out}} \in 1, 2, \ldots, Ny$),
- Track entry time ($T^f_{\text{In}}$),
- Flight level at waypoints ($FL^f_i \in 1, 2, \ldots, Nz$ where $i \in 1, 2, \ldots, Nx$),
- True airspeed in knots.
Decision variables

- \( ATrack^f_{in} = Track^f_{in} + \frac{1}{10} \) the assigned entry track.
- \( ATrack^f_{out} = Track^f_{Out} + \frac{1}{10} \) the assigned exit track.
- \( D^f_{in} \) the time delay at the entry point.
- \( Z^f_i = \frac{(FL^f_i - FL^f_{i-1})}{10} = \begin{cases} 1 & \text{if the flight climbs to the next level at waypoint } i \\ 0 & \text{otherwise} \end{cases} \)
  with \( Z^f_1 = 0 \).
- \( X^f_i = \begin{cases} 1 & \text{if the flight switches to the northern adjacent track at the waypoint } i \\ 0 & \text{if the flight continues with the same track} \\ -1 & \text{if the flight switches to the southern adjacent track at the waypoint } i \end{cases} \)
Constraints

- Time constraints at nodes and links.
  \[ \sum_{i=1}^{N_x-1} X_i^f = |ATErack_{out}^f - ATrack_{in}^f| \]
  \[ \sum_{i=1}^{N_x-1} Z_i^f = |FL_{out}^f - FL_{in}^f| \]
Conflict detection strategy

- A conflict is a violation of established separation norms.

- Conflicts at node level:

![Node Diagram](image)

- Conflicts at link level:

![Link Diagram](image)
### Objective function

<table>
<thead>
<tr>
<th>Most important criterion to minimize</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of conflicts on nodes ((C_n)) and links ((C_l)).</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other optimization criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cruising time (C).</td>
</tr>
<tr>
<td>Total entry delay (D).</td>
</tr>
<tr>
<td>Total deviation delay (R).</td>
</tr>
</tbody>
</table>
For each flight \( f \) we have the following

- from 0 to 20 minutes of delay.
- 3 possible entry tracks and 3 possible exit tracks.
- an average of 4 track changes which have to be spread among the 8 waypoint positions (= 70 options per flight)
- the total number of options is higher than 12600.

For 500 flights we have \( 12600^{500} \) options.

Highly combinatorial problem \( \Rightarrow \) Stochastic optimization methods
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Optimization process

Pre-processing the flight set using a sliding window method (SW).

The SA is applied to fix the decision variables of the active flights (on-going flights are considered as constraints).
Simulated annealing algorithm

\[ \text{Solution space} \quad \left[ A\text{Track}_{\text{in}}^{f}, A\text{Track}_{\text{out}}^{f}, D_{\text{in}}^{f}, X^{f}, Z^{f} \right] \]
Simulated annealing algorithm

$\text{Initial solution Temperature } T$

Solution space

$[\text{ATrack}^f_{\text{in}}, \text{Atrack}^f_{\text{out}}, D^f_{\text{in}}, X^f, Z^f]$
Simulated annealing algorithm

Initial solution
Temperature $T$

Accept solution
Temperature $T = \alpha * T$

Solution space

$[\text{ATrack}_{in}^f, \text{ATrack}_{out}^f, D_{in}^f, X^f, Z^f]$
Simulated annealing algorithm

Initial solution
Temperature $T$

Accept solution
Temperature $T = \alpha \times T$

Solution space

$[\text{ATrack}^f_{\text{in}}, \text{ATrack}^f_{\text{out}}, D^f_{\text{in}}, X^f, Z^f]$
Simulated annealing algorithm

- Initial solution
  Temperature $T$
- Solution space
  $[\text{ATrack}^f_{\text{in}}, \text{ATrack}^f_{\text{out}}, D^f_{\text{in}}, X^f, Z^f]$

- Accept solution
  Temperature $T = \alpha \cdot T$

- Accept solution with probability
  $e^{(E(s) - E(s'))/T}$
Simulated Annealing Evolution

Temperature

Exploration

Selection

Time
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Example of a conflict resolution
Example of a conflict resolution

**Figure:** Conflict resolution
Simulations are performed on two real NAT traffic days (3rd and 4th August, 2006). Each flight set contains respectively 331 and 378 flights.

<table>
<thead>
<tr>
<th>Test</th>
<th>03/08/2006</th>
<th>04/08/2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of flights</td>
<td>331</td>
<td>378</td>
</tr>
<tr>
<td>Number of conflicts</td>
<td>Before</td>
<td>1055</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>0</td>
</tr>
<tr>
<td>Number of flights changing their vertical profile</td>
<td>69</td>
<td>78</td>
</tr>
</tbody>
</table>
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Conclusions and perspectives

Conclusions

- A new route structure to schedule trans-Atlantic flights instead of the OTS is proposed.
- Stochastic optimization methods are addressed to tackle the problem.
- The computational results show a significant reduction of the number of conflicts.

Perspectives

- Use real jet streams to design the route structure and compare the optimized flight trajectories with the actual ones followed by the aircraft using the OTS.
- Evaluate the potential gain on fuel consumption when applying the proposed wind-optimal route structure.
Thank you for your attention