A Distributed Air Traffic Flow Management Model for European Functional Airspace Blocks

Sameer Alam  
University of New South Wales,  
Canberra, Australia

Supatcha Chaimatanan  
Geo-informatics and Space Technology Dev. Agency, Bangkok, Thailand

Daniel Delahaye  
Ecole Nationale de l’Aviation Civile,  
Toulouse, France

Eric Feron  
Georgia Institute of Technology,  
Atlanta, USA
Outline

1. Background
   • Functional Airspace Block
2. Motivation
   • Distributed ATFM
   • Information Exchange for FAB
3. Proposed Approach
   • FAB-Flight Interaction Matrix
   • Trajectory Interaction
4. Methodology
5. Experiment Design
6. Results & Conclusions
Introduction

FIR: Fragmentation of airspace along national boundaries

- creates structural inefficiencies
- sub-optimal flight routing
- centralized ATFM
  - stake-holder input limited
  - pairwise reversal

Source: Eurocontrol
Functional Airspace Blocks (FAB)

“an airspace block based on operational requirements and established regardless of state boundaries, where the air navigation services and related functions is performance-driven and optimised through enhanced cooperation among ANSPs or an integrated provider” *

9 FAB initiatives

Source: Eurocontrol

Challenges:

ATFM and FAB

Gradual shift towards Distributed ATFM (from CFMU to NMOC)

• Decision making capabilities shared between stakeholders.
  • e.g. Ground Delay Program[1], Ration by Schedule [2]

• Limited to strategic planning
  • user role diminishes as planning interval becomes smaller

• Any future Distributed ATFM must consider FAB interaction

Research Questions

• How to implement ATFM strategies in FABs?
• How to develop a basis for information sharing among FAB to ensure conflict-free trajectories planning?
Proposed Solution

1. a distributed AFTM model for
   1. effective information sharing among the FABs
   2. distribute decision making among the FABs

2. a method to separate aircraft trajectories in space and time using
   1. departure-slot shifting
   2. en-route trajectory modification
Proposed Concept

The Actors:
- Airlines
- Airports
- ANSPs

The Role:
- Flight Plans
- Slots
- Capacity

The Director: CFMU

The Script:
- Revised Flight Plans

From Passive Viewers to Interactive Players:
- TFM Strategies
- FAB-Flight Interaction Matrix
- FAB A
- FAB B
- FAB C

- Identify Interactions
- Resolve Interactions
- No Interaction
- Interaction Free Flight Plans
FAB-Flight interaction Matrix

- A 2D matrix which captures the flight interaction information between and within FABs.

- One dimension of the matrix is termed Controlling FAB and the other dimension is termed Intermediate FAB.

<table>
<thead>
<tr>
<th>Controlling FABs</th>
<th>Intermediate FABs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FAB $I_A$</td>
</tr>
<tr>
<td>FAB $C_A$</td>
<td>(\text{INT}(C_A,I_A))</td>
</tr>
<tr>
<td>FAB $C_B$</td>
<td>(\text{INT}(C_B,I_A))</td>
</tr>
<tr>
<td>FAB $C_C$</td>
<td>(\text{INT}(C_C,I_A))</td>
</tr>
</tbody>
</table>

\[
\sum V = \sum U_A \quad \sum U_B \quad \sum U_C
\]
FAB-Flight interaction Matrix

- Controlling FAB and Intermediate FAB

For Flight A, FAB B is controlling FAB and FAB A and FAB C are intermediate FABs.

For Flight B, FAB B is controlling as well as intermediate FAB.
FAB-Flight interaction Matrix

\[ I_i = \begin{bmatrix} \text{INT}(C_j, I_A) & \text{INT}(C_j, I_B) & \ldots & \text{INT}(C_j, I_i) \end{bmatrix} \]

\[ C_j = \begin{bmatrix} \text{INT}(C_A, I_i) \\ \text{INT}(C_B, I_i) \\ \vdots \\ \text{INT}(C_N, I_i) \end{bmatrix} \]

Intermediate FABs

<table>
<thead>
<tr>
<th>\text{FAB}</th>
<th>\text{FAB I}_A</th>
<th>\text{FAB I}_B</th>
<th>\text{FAB I}_C</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{FAB C}_A</td>
<td>\text{INT}(C_A, I_A)</td>
<td>\text{INT}(C_A, I_B)</td>
<td>\text{INT}(C_A, I_C)</td>
</tr>
<tr>
<td>\text{FAB C}_B</td>
<td>\text{INT}(C_B, I_A)</td>
<td>\text{INT}(C_B, I_B)</td>
<td>\text{INT}(C_B, I_C)</td>
</tr>
<tr>
<td>\text{FAB C}_C</td>
<td>\text{INT}(C_C, I_A)</td>
<td>\text{INT}(C_C, I_B)</td>
<td>\text{INT}(C_C, I_C)</td>
</tr>
</tbody>
</table>

\[ \sum V = \sum U_A \quad \sum U_B \quad \sum U_C \]

Controlling FABs

Fight interactions \( U_j \), in a given FAB

Total flight interaction \( V \) in a given airspace \( A \)

\[ U_i = \sum_{i=1}^{N} \text{INT}(C_j, I_i) \]

\[ V = \sum_{j=1}^{N} U_j \]
## Methodology

### STEP 1: Identify the Intermediate FAB with highest number of flight interaction:

<table>
<thead>
<tr>
<th>Controlling FABs</th>
<th>Intermediate FABs</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAB $C_A$</td>
<td>INT($C_A, I_A$)</td>
</tr>
<tr>
<td>FAB $C_B$</td>
<td>INT($C_B, I_A$)</td>
</tr>
<tr>
<td>FAB $C_C$</td>
<td>INT($C_C, I_A$)</td>
</tr>
</tbody>
</table>

$$\sum V = \sum U_A \quad \sum U_B \quad \sum U_C$$

$$FAB \quad I_i = \text{MAX}(U_A, U_B, ..., U_N)$$
Methodology

STEP 2: For the Intermediate FAB $I_B$, identify the Controlling FAB which generated highest number of flight interaction:

\[
\sum V = \sum U_A + \sum U_B + \sum U_C
\]

\[
\text{FAB } C_j = \text{MAX}\left( \text{INT}(C_A, I_i), \text{INT}(C_B, I_i), ..., \text{INT}(C_N, I_i) \right)
\]
### Methodology

**STEP 3:** Apply ATFM strategies (Space-Time separation) on selected (fitness-proportional selection) flight in Controlling FAB $C_B$.

**STEP 4:** Update Flight plan.

<table>
<thead>
<tr>
<th>ATFM Strategy 1</th>
<th>ATFM Strategy 2</th>
<th>ATFM Strategy n</th>
</tr>
</thead>
</table>

#### Intermediate FABs

<table>
<thead>
<tr>
<th>FAB</th>
<th>$FAB_I_A$</th>
<th>$FAB_I_B$</th>
<th>$FAB_I_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FAB_C_A$</td>
<td>$INT(C_A, I_A)$</td>
<td>$INT(C_A, I_B)$</td>
<td>$INT(C_A, I_C)$</td>
</tr>
<tr>
<td>$FAB_C_B$</td>
<td>$INT(C_B, I_A)$</td>
<td>$INT(C_B, I_B)$</td>
<td>$INT(C_B, I_C)$</td>
</tr>
<tr>
<td>$FAB_C_C$</td>
<td>$INT(C_C, I_A)$</td>
<td>$INT(C_C, I_B)$</td>
<td>$INT(C_C, I_C)$</td>
</tr>
</tbody>
</table>

$$\sum V = \sum U_A \quad \sum U_B \quad \sum U_C$$
Methodology

**STEP 5:** Recompute Flight interactions using the revised flight plans

**STEP 6:** Update FAB-Flight Interaction Matrix

**STEP 7:** Repeat until the FAB-Flight Interaction Matrix returns ZERO interactions.
Trajectory Interactions

Measurement that indicates when two or more trajectories occupy the same space at the same period of time

Interactions, $\Phi_{i,k}$, at sampling point $P_{i,k}$ of trajectory $i$

the total interaction between trajectories, $\Phi_{tot}$, for a whole traffic situation:
Trajectory Interactions

- Situation when two or more trajectories have an effect on each other;
  - e.g. when trajectories occupy the same space at the same period of time.

Interaction ≠ conflicts
  - Take into account time duration of conflict

higher interactions \( \Phi = 4 \)
lower interactions \( \Phi = 1 \)
Interaction between trajectories taking into account uncertainties

- Interaction occurs when the *enlarged* protection volume overlap

\[ \Phi = 0 \]

\[ \Phi = 1 \]

without uncertainty

consider uncertainty
Interaction Detection

1. Airspace is discretized using a four-dimensional grid (3D space + time)
2. Size of each cell in the 4D grid is defined by the minimum separation requirement and the discretization time step.
3. For each given 4D coordinate point of each trajectory i, we identify which cell of the 4D grid contains that point.
4. For that given cell we successively check its surrounding cells (there are $3^3 = 27$ such neighbouring cells, including the cell itself.
5. If one cell is occupied by an aircraft other than aircraft i itself, the horizontal distance $(dh)$ and the vertical distance $(dv)$ between the corresponding aircraft coordinates are measured.
6. A violation of the protection volume is identified as interaction.
Interaction Detection

- Using too large sampling time step size, $t_s$, will cause missing conflicts
- To avoid missing conflicts, $t_s \leq 15$ seconds (N. Durand et al.)
Tractor separation maneuvers

• **Shift of departure times**
  - separate trajectories in time domain
  - positive (delay) or negative (advance)
Trajectory separation maneuvers

- Modify the shape of the *en-route segment* in the *horizontal* dimension using a *set of waypoints*
Optimization formulation

- allowed departure time shifts, \( \delta^i_a, \delta^i_d \)
- allowed max. route length extension, \( d_i \)
- allowed number of waypoints, \( M \)
Minimizing the Trajectory Interaction

Formulated as a mixed-integer optimization problem

$$\min_{u=(\delta, w)} \Phi_{tot}(u)$$

subject to

$$\delta_i \in \Delta_i,$$
$$w_{ix}^m \in W_{ix}^m,$$
$$w_{iy}^m \in W_{iy}^m,$$

for all $i = 1, \ldots, N, m = 1, \ldots, M$,
Minimizing the Trajectory Interaction

- A hybrid meta-heuristic approach

- Combines classical simulated annealing (SA) algorithm and two different local search (LS) modules.

- LS allows the system to intensify the search around a potential candidate solution while the SA allows the system to escape from a local trap and thereby ensuring the exploration of the solution space.

- The proposed hybrid algorithm combines the SA and the local search algorithm such that the LS is considered as an inner loop of the SA, which will be performed when a pre-defined condition is satisfied.
Hybrid SA / local search algorithm

- Order of execution of each metaheuristic
  - Probability to carry out SA step, $P_{SA}$
    \[
    P_{SA}(T) = P_{SA,min} + (P_{SA,max} - P_{SA,min}) \cdot \frac{T_0 - T}{T_0},
    \]
  - Probability to run the local search, $P_{Loc}$
    \[
    P_{Loc}(T) = P_{Loc,min} + (P_{Loc,max} - P_{Loc,min}) \cdot \frac{T_0 - T}{T_0},
    \]
  - Probability of carrying out both SA and Loc successively, $P_{SL}$
    \[
    P_{SL}(T) = 1 - (P_{SA}(T) + P_{Loc}(T))
    \]
Experiment Design

<table>
<thead>
<tr>
<th>No.</th>
<th>FAB name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baltic FAB</td>
</tr>
<tr>
<td>2</td>
<td>Blue Med</td>
</tr>
<tr>
<td>3</td>
<td>FAB Central Europe</td>
</tr>
<tr>
<td>4</td>
<td>Danube FAB</td>
</tr>
<tr>
<td>5</td>
<td>FAB Europe Central</td>
</tr>
<tr>
<td>6</td>
<td>NEFAB</td>
</tr>
<tr>
<td>7</td>
<td>NUAC program</td>
</tr>
<tr>
<td>8</td>
<td>SW Portugal-Spain FAB</td>
</tr>
<tr>
<td>9</td>
<td>FAB UK Ireland</td>
</tr>
</tbody>
</table>

- One full day en-route air traffic over the Europe **26,122 flight**

- Two Cases:
  - Centralized ATFM (Flight with highest interaction selected for ATFM)
  - Distributed ATFM (Flight selected based on FAB-Flight interaction Matrix)
## Experiment Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discretization time step, $\Delta t$</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Discretization time step for possible departure-time shift, $\delta_s$</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Maximum departure time shift, $\delta_a = \delta_d := \delta$</td>
<td>120 minutes</td>
</tr>
<tr>
<td>Maximum allowed route length extension coefficient, $d_i$</td>
<td>0.20</td>
</tr>
<tr>
<td>Maximum allowed flight level shifts, $l_{i,\text{max}} := l_{\text{max}}$</td>
<td>2</td>
</tr>
<tr>
<td>Maximum number of virtual waypoints, $M$</td>
<td>3</td>
</tr>
</tbody>
</table>

Computing Resource: UNIX platform with 2.4 GHz processor and 32 GB memory
## Results

<table>
<thead>
<tr>
<th>N</th>
<th>ATFM strategy</th>
<th>initial $\Phi_{tot}^D$</th>
<th>final $\Phi_{tot}^D$</th>
<th>solved interactions</th>
<th>no. of iterations</th>
<th>cpu time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26,122</td>
<td>Distributed</td>
<td>266,318</td>
<td>0</td>
<td>100%</td>
<td>509,924</td>
<td>369.67</td>
</tr>
<tr>
<td></td>
<td>Centralized</td>
<td>0</td>
<td>0</td>
<td>100%</td>
<td>632,002</td>
<td>563.53</td>
</tr>
</tbody>
</table>
Results

Distributed ATFM model

Centralized ATFM model
Results

Distributed ATFM model

Centralized ATFM model

At 30% of process
Results

Distributed ATFM model

At 70% of process

Centralized ATFM model

At 70% of process
Results

Distributed ATFM model

CPU Time: 369 min
Iterations: 509,924

Centralized ATFM model

CPU Time: 563 min
Iterations: 632,002
Results

Distributed ATFM model

Centralized ATFM model
Conclusions

• Distributed ATFM model performs much better (computationally and convergence) than centralized ATFM model for FAB scenario and is viable for strategic planning as well as pre-tactical planning purpose.

• FFI Matrix allows for implementation of FAB specific ATFM strategy

• Augmenting Heuristic Search with local search provide effective mechanism for exploration and exploitation of search space.

• Both models yield interaction-free solution.

• Further analysis needed using a combination of Distributed ATFM strategies for individual FAB.
Questions, Feedback, Comments

Sameer Alam
Email: s.alam@adfa.edu.au

Supatcha Chaimatanan
Email: supatcha@gistda.or.th

Daniel Delahaye
Email: delahaye@recherche.enac.fr

Eric Feron
Email: feron@gatech.edu