Integrated Optimization of Terminal Maneuvering Area and Airport

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ENAC – École Nationale de l’Aviation Civile

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Outline

1. Background and problem description
2. Problem modeling
3. Solution approaches
4. Simulation results
5. Conclusions and perspectives
According to Airbus global market forecast 2015-2034, air traffic will double in the next 15 years.

39 out of the 47 aviation mega cities are largely congested today.

- airport infrastructure is adequate
- airports with potential for congestion
- airports where conditions make it impossible to meet demand
Airport and surrounding terminal airspaces control is a complex problem.
Current research

- **Arrival Management Problem**
  - Landing sequencing
  - Ensure proper separation

- **Surface Management Problem**
  - Arriving aircraft taxi-in
  - Departing aircraft taxi-out

- **Departure Management Problem**
  - Take-off times and sequences for departing flights
  - Ensure proper separation
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Given data (1/3)

TMA arrival route network

- **Node-link graph**: $G(\mathcal{N}, \mathcal{L})$, $\mathcal{N}$ node set and $\mathcal{L}$ link set;
- One route is composed of several links, the first one starts from the entering point and the last link ends at the runway threshold.
Network abstraction

- **Overall terminal capacity**: number of gates
- **Taxi network capacity**: threshold of total allowed number of taxi-in and taxi-out aircraft
- **Runway type**: landing only, departure only, mixed mode
Given data (3/3)

Given a set of flights, $\mathcal{F} = \{1, \ldots, N_f\}$. Each flight can be in one of three operations: $\mathcal{F} = \mathcal{A} \cup \mathcal{D} \cup \mathcal{AD}$, where $\mathcal{A}$ stands for arrival, $\mathcal{D}$ for departure and $\mathcal{AD}$ for arrival-departure.

**Table**: Given information for each operation type

<table>
<thead>
<tr>
<th>Operation type</th>
<th>$\mathcal{A}$</th>
<th>$\mathcal{D}$</th>
<th>$\mathcal{AD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wake turbulence category</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Assigned terminal number</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Entering waypoint</td>
<td>√</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Initial entry time at TMA</td>
<td>√</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Initial speed at TMA</td>
<td>√</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Taxi-in duration</td>
<td>√</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Earliest off-block time</td>
<td>×</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Taxi-out duration</td>
<td>×</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Departure runway number</td>
<td>×</td>
<td></td>
<td>√</td>
</tr>
</tbody>
</table>
Decision variables

- \( t_f \in T_f \) entering time at TMA of flight \( f \in A \cup AD \), where

\[
T_f = \{ T_f^0 + j \Delta T \mid \Delta T_{\text{min}} / \Delta T \leq j \leq \Delta T_{\text{max}} / \Delta T, \ j \in \mathbb{Z} \}
\]

- \( v_f \in V_f \) entering speed at TMA of flight \( f \in A \cup AD \), where

\[
V_f = \{ V_f^{\text{min}} + j \Delta v_f \mid j \leq (V_f^{\text{max}} - V_f^{\text{min}}) / \Delta v_f, \ j \in \mathbb{N}, \}
\]

- \( r_f^a \in R_f \) landing runway of flight \( f \in A \cup AD \), where

\[
R_f = \text{Set of landing runways}
\]
Decision variables

- $t_f \in \mathcal{T}_f$ entering time at TMA of flight $f \in \mathcal{A} \cup \mathcal{AD}$, where

$$\mathcal{T}_f = \{T_f^0 + j\Delta T \mid \Delta T_{\text{min}} / \Delta T \leq j \leq \Delta T_{\text{max}} / \Delta T, \ j \in \mathbb{Z}\}$$

- $v_f \in \mathcal{V}_f$ entering speed at TMA of flight $f \in \mathcal{A} \cup \mathcal{AD}$, where

$$\mathcal{V}_f = \{V_f^{\text{min}} + j\Delta v_f \mid j \leq (V_f^{\text{max}} - V_f^{\text{min}}) / \Delta v_f, j \in \mathbb{N}, \}$$

- $r^a_f \in R_f$ landing runway of flight $f \in \mathcal{A} \cup \mathcal{AD}$, where

$$R_f = \text{Set of landing runways}$$

- $p_f \in \mathcal{P}_f$ pushback delay of flight $f \in \mathcal{D} \cup \mathcal{AD}$, where

$$\mathcal{P}_f = \{P_f^0 + j\Delta T \mid 0 \leq j \leq \Delta T^p_{\text{max}} / \Delta T, \ j \in \mathbb{N}\}$$
Decision variables

- \( t_f \in T_f \) entering time at TMA of flight \( f \in A \cup AD \), where
  \[
  T_f = \left\{ T_f^0 + j\Delta T \mid \Delta T_{\text{min}}/\Delta T \leq j \leq \Delta T_{\text{max}}/\Delta T, \quad j \in \mathbb{Z} \right\}
  \]

- \( v_f \in V_f \) entering speed at TMA of flight \( f \in A \cup AD \), where
  \[
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  \]

- \( r^a_f \in R_f \) landing runway of flight \( f \in A \cup AD \), where
  \[ R_f = \text{Set of landing runways} \]

- \( p_f \in P_f \) pushback delay of flight \( f \in D \cup AD \), where
  \[
  P_f = \left\{ P_f^0 + j\Delta T \mid 0 \leq j \leq \Delta T_{\text{max}}^p/\Delta T, \quad j \in \mathbb{N} \right\}
  \]

Decision vector:

\[ \mathbf{x} = (t, v, r, p) \]
Separation requirements

- Minimum horizontal separation of 3 NM in TMA
- Wake turbulence separation

<table>
<thead>
<tr>
<th>Category</th>
<th>Leading Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td>Heavy</td>
<td>4</td>
</tr>
<tr>
<td>Trailing Aircraft</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Light</td>
</tr>
</tbody>
</table>

**Table:** Separation minima for two successive aircraft, in NM

- Single-runway separation requirements
Wake turbulence separation:
- **Link conflict**
  - Node u
  - Link \( l = (u, v) \)
  - Node v
  - Flight \( f \)
  - Flight \( g \)

Minimum horizontal separation:
- **Node conflict**
  - Node n
  - Detection zone
  - Flight \( f \)
  - Flight \( g \)
Runway overload evaluation

We note the **accumulated time of separation violation** for all pairs of aircraft as an indicator for our runway evaluation.

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**Landing minimum separation times (in seconds)**

<table>
<thead>
<tr>
<th>Pred.\Succ.</th>
<th>Heavy</th>
<th>Medium</th>
<th>Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>96</td>
<td>157</td>
<td>207</td>
</tr>
<tr>
<td>Medium</td>
<td>60</td>
<td>69</td>
<td>123</td>
</tr>
<tr>
<td>Light</td>
<td>60</td>
<td>69</td>
<td>82</td>
</tr>
</tbody>
</table>

**Take-off minimum separation times (in seconds)**

<table>
<thead>
<tr>
<th>Pred.\Succ.</th>
<th>Heavy</th>
<th>Medium</th>
<th>Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>96</td>
<td>111</td>
<td>120</td>
</tr>
<tr>
<td>Medium</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Light</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>
We measure the maximum overload number and the total amount of time during which aircraft experience congestions.
Objective function

We minimize

\[ \gamma_a A(x) + \gamma_s S(x) \]

where

- \( A(x) \): the total number of conflicts in airspace, including:
  - Node conflicts
  - Link conflicts

- \( S(x) \): the airside capacity overload, including:
  - Runway overload
  - Terminal overload
  - Taxi network overload

- Weighting coefficients \( \gamma_a, \gamma_s \)
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Solution approaches

Using time decomposition approach combined with heuristic algorithm.

- completed
- on-going
- active
- planned
- planned

Previous time window

Current time window

Next time window

Update flights status in state space

Evaluate "Active" and "On-going" flight operations:
Airspace: nodes, links
Airport: runways, taxi network, terminals

Apply algorithms:
Simulated Annealing

24 hours
Simulated annealing

- At Init Temp: Unconditional Acceptance
- HILL CLIMBING
- Moved accepted with probability $e^{-\frac{\Delta E}{T}}$
- At Final Temp

Ma, Delahaye, Sbihi, Mongeau (ENAC)
Neighborhood selection (1/3)

Decision Changes
Airspace perfo
Runway perfo
Ground perfo

Aircraft list

\[ x_1 \quad x_i \quad x_N \]

Decision Changes
Airspace perfo
Runway perfo
Ground perfo

\[ A_1 \quad A_i \quad A_N \]

\[ R_1 \quad R_i \quad R_N \]

\[ G_1 \quad G_i \quad G_N \]
Neighborhood selection (2/3)

Example (Ground perfo):

<table>
<thead>
<tr>
<th>Flight</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground perfo</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

: Aircraft in-block time

: Aircraft off-block time

Capacity = 3
Neighborhood selection (2/3)

Example (Ground perfo):

<table>
<thead>
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<th>Flight</th>
<th>F1</th>
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<th>F3</th>
<th>F4</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground perfo</td>
<td>32</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Neighborhood selection (2/3)

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<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground perfo</td>
<td>32</td>
<td>47</td>
<td>47</td>
<td></td>
<td></td>
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Neighborhood selection (2/3)

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<th>F3</th>
<th>F4</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground perfo</td>
<td>32</td>
<td>47</td>
<td>47</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>
Example (Ground perfo):

<table>
<thead>
<tr>
<th>Flight</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground perfo</td>
<td>32</td>
<td>47</td>
<td>47</td>
<td>23</td>
<td>0</td>
</tr>
</tbody>
</table>
Neighborhood selection (3/3)

Neighborhood

Example:

<table>
<thead>
<tr>
<th>Flight</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground perfo</td>
<td>32</td>
<td>47</td>
<td>47</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>Percentage</td>
<td>21.5%</td>
<td>31.5%</td>
<td>31.5%</td>
<td>15.4%</td>
<td>0</td>
</tr>
</tbody>
</table>

- Roulette wheel selection
- change $v_f$ or $t_f$ if flight $f \in \mathcal{A}$
- change $p_f$ if flight $f \in \mathcal{D}$
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February 7, 2016: 562 departures, 554 arrivals.
Paris CDG airport layout
Conflicts evaluation

Node conflicts
Link conflicts

Number of conflicts

1.6499
0.2923
0.2657
0.2415

Sliding window i-1
Sliding window i
Sliding window i+1

Temperature
Initial gate occupancy for each terminal

<table>
<thead>
<tr>
<th>Terminal 1</th>
<th>Terminal 2</th>
<th>Terminal 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max gate occupancy</td>
<td>13</td>
<td>95</td>
</tr>
</tbody>
</table>

Time (in hours)

Number of flights

Terminal 1, Terminal 2, Terminal 3
Initial gate occupancy for each terminal

<table>
<thead>
<tr>
<th>Time (in hours)</th>
<th>Number of flights</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-24</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Number of Flights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal 1</td>
<td></td>
</tr>
<tr>
<td>Terminal 2</td>
<td></td>
</tr>
<tr>
<td>Terminal 3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Max gate occupancy</th>
<th>Imposed max capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal 1</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Terminal 2</td>
<td>95</td>
<td>90</td>
</tr>
<tr>
<td>Terminal 3</td>
<td>59</td>
<td>56</td>
</tr>
</tbody>
</table>
Figure: Comparison between initial gate occupancy and optimized one for terminal 2
Terminal overload evaluation (2/2)

(a) Terminal 1

(b) Terminal 3

**Figure**: Comparison between initial gate occupancy and optimized one for terminal 1 and 3
Taxi network overload evaluation

![Graph showing taxi network overload evaluation](image)

- **Initial occupancy**
- **Optimized occupancy**
- **Imposed capacity**
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Conclusions

- A TMA route network structure and an abstraction model of airport components
- Time sliding-window approach combined with simulated annealing
- Reaching conflict-free solutions and mitigating the airport overload by time-slot and speed change
Perspectives

Microscopic level optimization

- Taxi In and Taxi Out routes
- Pushback Time update
- This process is repeated by the mean of a sliding time window
Thank you for your attention!