Integrated Traffic Flow Based Optimization of Airport and Terminal Area

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1. Background and problem description
2. Problem modeling
3. Solution approach
4. Results
5. Conclusion and perspective
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Air traffic evolution

✈ A continuous growth of the air traffic:

► Annual growth rate: 4.5%.
► Will be doubled in the following 15 years.

✈ Airport and TMA (Terminal Manoeuvring Area) Congestion.
► Safety issues.
► Operating costs.
Integrated research

arrival Management Problem
▶ Landing sequencing
▶ Mitigate congestion and conflicts resolution workload

Surface Management Problem
▶ Arriving aircraft taxi-in routes

departure Management Problem
▶ Take-off times and sequences for departing flights
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Integrated optimization of TMA and airport

Network abstraction:

- Airside: runways, taxiway network and terminals
- TMA: nodes and links
Network abstraction in TMA

Paris-CDG airport route network for arrivals: Graph($\mathcal{N}$, $\mathcal{L}$).
Given data for optimization

Given a flight $f \in \mathcal{F}$, the flight can be operated with three operations.

<table>
<thead>
<tr>
<th>Information</th>
<th>Arrival</th>
<th>Departure</th>
<th>Connected flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wake turbulence category $C_f$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Assigned terminal number $M_f$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Entry node $E_f$</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>TMA entry time $T_f^o$</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>TMA entry speed $V_f^o$</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Arrival runway $R_f^a$</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Departure runway $R_f^d$</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Scheduled off-block time $T_f^d$</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Turn around time $t_f^{ad}$</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Decision Variables

- TMA entry time $t_f$:
  \[ t_f = T_f^o + j\Delta T, \quad j \in \left[\Delta T_{min}/\Delta T, \Delta T_{max}/\Delta T\right], \quad j \in \mathbb{Z} \]

- TMA entry speed $v_f$:
  \[ v_f = V_f^{min} + j\Delta v, \quad j \in \left[0, (V_f^{max} - V_f^{min})/\Delta v\right], \quad j \in \mathbb{N} \]

- Arrival runway $r_f^a$.

- Pushback delay $p_f$:
  \[ p_f = \left\{ P_f^o + j\Delta T \right\}, \quad j \in \left[0, \Delta T_{max}/\Delta T\right], \quad j \in \mathbb{N} \]

\[ x_f = (t_f, v_f, r_f^a, p_f) \]
Traffic flow-based model

We measure the evaluation values distribution of each resource. Evaluation parameters:

- Time step/unit: $\Delta$ (1 min).
- Evaluation time parameter: $k$.
- Evaluation time interval: $L = k \cdot \Delta$.
- Evaluation start time $t$, $t_i = t_{i-1} + \Delta$.

Flow Based Flight Evaluation

$\downarrow \downarrow \downarrow \uparrow \uparrow$  
$t_1$  
$\downarrow \uparrow \uparrow \uparrow \downarrow \downarrow$  
$t_2$  
$\uparrow \uparrow \uparrow \downarrow \downarrow \uparrow \uparrow$  
$t_3$  
$\uparrow \downarrow \downarrow \uparrow \uparrow \uparrow \downarrow$  
$t_4$  
\vdots

$\uparrow$ Flight exit resource movement  
$\downarrow$ Flight entry resource movement
Link evaluation and runway evaluation

We evaluate the number of flights that enters a link/runway during evaluation time interval $t$ to $t + L$.

- $k = 10$.
- $L = 10$ mins.
Node evaluation

We estimate the conflicts resolution workload.

\[ E_n(t) = \frac{2N_s \sqrt{v_{l_i}^2 - 2v_{l_i}v_{l_j} \cos \theta_{ij} + v_{l_j}^2}}{v_{l_i}v_{l_j} \sin \theta_{ij}} \cdot E_{l_i}^{out}(t) E_{l_j}^{out}(t) \quad n \in \mathcal{N} \]

- \( N_s \): standard separation requirement of flights.
- \( E_{l_i}^{out}(t) \): number of flights that exits link \( l \) during \( t \) to \( t + L \).
**Airside evaluation**

We evaluate the *number of flights* at each time interval.

- $k=1$.
- $L = 1\text{min}$.

![Graph showing flight numbers and times](image_url)

- Upward arrows indicate aircraft in-block time.
- Downward arrows indicate aircraft off-block time.
Capacities constraints

- **Link capacity:**
  
  \[ C_l = \frac{M \cdot v_l}{K} \]

  - M: link separation 1 flight/ 5NM.
  - K= 1 hour/ L: time scale.
  - \( v_l \): average speed on link \( l \).

- **Node capacity:** \( C_n = 6 \) conflicts resolutions / hour.

- **Airside capacity.**

<table>
<thead>
<tr>
<th>Landing Runway</th>
<th>Departure Runway</th>
<th>Terminal 1</th>
<th>Terminal 2</th>
<th>Terminal 3</th>
<th>Taxiway</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/h</td>
<td>40/h</td>
<td>20</td>
<td>130</td>
<td>25</td>
<td>19</td>
</tr>
</tbody>
</table>
Objective function

- First metric: **average congestion** during time horizon $T$.
- Second metric: the **maximum overload** during time horizon $T$.

$$G(x) = \sum_{s \in S} \gamma_s \left[ \frac{1}{T} \sum_{t \in T} \max(E_s(t) - C_s, 0) \cdot \Delta \right]$$

$$+ \sum_{s \in S} \gamma_s \left[ \max_{t \in T} \max(E_s(t) - C_s, 0) \right]$$
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Simulated annealing

- Temperature
- Objective function
- Neighborhood
- Stopping criterion
# Neighborhood solution selection

<table>
<thead>
<tr>
<th></th>
<th>Airspace performance</th>
<th>Ground performance</th>
<th>Total performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>$a_1$</td>
<td>$g_1$</td>
<td>$m_1$</td>
</tr>
<tr>
<td>$f_2$</td>
<td>$a_2$</td>
<td>$g_2$</td>
<td>$m_2$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$f_N$</td>
<td>$a_N$</td>
<td>$g_N$</td>
<td>$m_N$</td>
</tr>
</tbody>
</table>

$$p_a^f = \frac{a_f}{m_f} \quad p_g^f = \frac{g_f}{m_f}$$

- We choose a random number $n \in [0, 1]$ for the decision variable choosing:

<table>
<thead>
<tr>
<th></th>
<th>$f \in \mathcal{A}$</th>
<th>$f \in \mathcal{AD}$</th>
<th>$f \in \mathcal{D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n &lt; p_a^f$</td>
<td>$t_f, v_f$</td>
<td>$n &gt; p_a^f$</td>
<td>$t_f, v_f$</td>
</tr>
<tr>
<td>$n &gt; p_a^f$</td>
<td>$t_f, v_f, r_f^a$</td>
<td>$n &lt; p_a^f$</td>
<td>$t_f, v_f, r_f^a, p_f$</td>
</tr>
<tr>
<td>$n &lt; p_a^f$</td>
<td>$t_f, v_f, r_f^a$</td>
<td>$n &gt; p_a^f$</td>
<td>$t_f, v_f, r_f^a, p_f$</td>
</tr>
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<td>$t_f, v_f, r_f^a$</td>
<td>$n &lt; p_a^f$</td>
<td>$t_f, v_f, r_f^a, p_f$</td>
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<td>$t_f, v_f, r_f^a$</td>
<td>$n &lt; p_a^f$</td>
<td>$t_f, v_f, r_f^a, p_f$</td>
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<td>$t_f, v_f, r_f^a, p_f$</td>
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Case study

- Paris-CDG airport, real data of 18th February 2016 from 7:00 AM to 9:40 AM.
- Heavy and medium flights with a mix ratio of $23\% : 77\%$. 

![Graph showing flight paths and distances from BANOX to OKIPA, with points marked at MOPAR, Rwy27R, IF27R, PG562, PG564, LORNI, RWY26L.](image-url)
Link and node optimization results

Link optimization results

Node optimization results

![Graphs showing link and node optimization results.](image-url)
Runway optimization results

- **27R**: Initial $E_r$, Optimized $E_r$, Imposed capacity
- **26L**: Initial $E_r$, Optimized $E_r$, Imposed capacity
- **27L**: Initial $E_r$, Optimized $E_r$, Imposed capacity
- **26R**: Initial $E_r$, Optimized $E_r$, Imposed capacity

Number of flights entering the runway / 10 mins
Terminal and taxiway occupancy

**Taxiway**

```
Number of flights  Time
0 5 10 15 20 25 30
7:00 7:20 7:40 8:00 8:20 8:40 9:00 9:20 9:40
```

**Terminal 2**

```
Number of flights  Time
80 90 100 110 120 130 140
7:00 7:20 7:40 8:00 8:20 8:40 9:00 9:20 9:40
```
Robustness test

- Reference case: flight by flight conflicts evaluation.
- Perturbations are implemented on TMA entry time.
- Average values of objective and sub-objectives of each model.

<table>
<thead>
<tr>
<th></th>
<th>Traffic flow-based model</th>
<th>Flight by flight conflict evaluation model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perturbations</td>
<td>Perturbations</td>
</tr>
<tr>
<td>Average congestion</td>
<td>± 0.5min</td>
<td>±1min</td>
</tr>
<tr>
<td>conflicts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Node</td>
<td>6.585</td>
<td>10.1</td>
</tr>
<tr>
<td>Link</td>
<td>0.474</td>
<td>0.963</td>
</tr>
<tr>
<td>Runway</td>
<td>0</td>
<td>0.064</td>
</tr>
<tr>
<td>Taxiway</td>
<td>0</td>
<td>0.00134</td>
</tr>
<tr>
<td>Terminal</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>7.06</td>
<td>11.136</td>
</tr>
</tbody>
</table>
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Conclusions

An optimization approach to solve the integrated management problem of airport and terminal area on macroscopic level.

- Network abstraction.
- Traffic flow-based model.
- Adapted simulated annealing algorithm.

Mitigating the network congestion as well as the potential conflicts resolution workload in TMA.
Perspectives

▶ Test more scenarios with the proposed model.

▶ Extend the approach to multiple airports.
Thank you for your attention!