Integrated Optimization of Arrival, Departure, and Surface Operations

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Outline

1. Background and problem description

2. Problem modeling
   - Macroscopic model (long-term decision)
   - Microscopic model (short-term decision)

3. Solution approach

4. Simulation results

5. Conclusions and perspectives
Outline

1. Background and problem description

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5. Conclusions and perspectives
The subject of airport capacity and delay has received a great amount of attention.
Towards integrated approach

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

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

- **Departure Management Problem**
  - Take-off times and sequences for departing flights
  - Ensure proper separation
1. Background and problem description

2. Problem modeling
   - Macroscopic model (long-term decision)
   - Microscopic model (short-term decision)

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5. Conclusions and perspectives
Integrated optimization of TMA and airport

The models are divided with regard to the temporal horizon of problem:

- **Macroscopic model** (long-term decision);
- **Microscopic model** (short-term decision).
Background and problem description

Problem modeling
- Macroscopic model (long-term decision)
- Microscopic model (short-term decision)

Solution approach

Simulation results

Conclusions and perspectives
Given data (1/3)

- Paris TMA route network for arrivals and departures: Node-link graph.
Given data (2/3)

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 a set of flights, each flight can be in one of three operations: arrival, departure and arrival-departure.

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

<table>
<thead>
<tr>
<th>Operation type</th>
<th>Arr</th>
<th>Dep</th>
<th>Arr-Dep</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>
</tbody>
</table>
Decision variables

- Entering time in TMA of arrival flight, $t_f$, where
  \[ T_f^0 - \Delta T_{\text{min}} \leq t_f \leq T_f^0 + \Delta T_{\text{max}} \]

- Entering speed in TMA of arrival flight, $v_f$, where
  \[ V_{f,\text{min}} \leq v_f \leq V_{f,\text{max}} \]

- Landing runway of arrival flight, $r_f$
Decision variables

- Entering time in TMA of arrival flight, $t_f$, where
  \[ T_f^0 - \Delta T_{\text{min}} \leq t_f \leq T_f^0 + \Delta T_{\text{max}} \]

- Entering speed in TMA of arrival flight, $v_f$, where
  \[ V_{f{\text{min}}} \leq v_f \leq V_{f{\text{max}}} \]

- Landing runway of arrival flight, $r_f^l$

- Pushback time of departure flight, $p_f$, where
  \[ P_f^0 \leq p_f \leq P_f^0 + \Delta T_{p{\text{max}}} \]

- Take-off runway of departure flight $r_f^d$
Decision variables

- Entering time in TMA of arrival flight, $t_f$, where

$$T_f^0 - \Delta T_{\text{min}} \leq t_f \leq T_f^0 + \Delta T_{\text{max}}$$

- Entering speed in TMA of arrival flight, $v_f$, where

$$V_{f}^\text{min} \leq v_f \leq V_{f}^\text{max}$$

- Landing runway of arrival flight, $r_f^l$

- Pushback time of departure flight, $p_f$, where

$$P_f^0 \leq p_f \leq P_f^0 + \Delta T_{p}^\text{max}$$

- Take-off runway of departure flight $r_f^d$

Decision vector: $\mathbf{x} = (t, v, l, p, d)$
Conflicts detection

- Minimum horizontal separation of 3 NM in TMA

- **Link conflict**
  - Flight $f$
  - Flight $g$
  - Node $u$
  - Link $l = (u,v)$
  - Node $v$

- **Node conflict**
  - Flight $f$
  - Detection zone
  - Node $n$
  - 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.

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

<table>
<thead>
<tr>
<th></th>
<th>Pred.</th>
<th>Succ.</th>
<th>Heavy</th>
<th>Medium</th>
<th>Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off</td>
<td>Heavy</td>
<td>96</td>
<td>111</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>
Terminal and taxi network overload evaluation

We measure the maximum overload number and the total amount of time during which aircraft experience congestions.

<table>
<thead>
<tr>
<th>Time</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>10:10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Capacity = 3

: Aircraft in-block time  
: Aircraft off-block time
Objective function

We minimize

$$\gamma_a A(x) + \gamma_s S(x) + \gamma_d D(x)$$

where

- **Total number of conflicts in airspace**, $A(x)$, including:
  - Node conflicts
  - Link conflicts

- **Airside capacity overload**, $S(x)$, including:
  - Runway overload
  - Terminal overload
  - Taxi network overload

- **Flight delays**, $D(x)$, defined as: deviation between the optimized and initial values of entering time in the TMA and pushback time.

- **Weighting coefficients** $\gamma_a$, $\gamma_s$, $\gamma_d$
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Given data (1/2)

Airport route network (Paris CDG, west configuration)

- Meta-gate
- Holding point
- Runway entry/exit
- Intersection
Given data (2/2)

- Wake turbulence category, \( C_f \);
- Meta-gate, \( M_f \);
- Runway entry point for departure or runway exit point for arrival, \( E_f \);
- Initial holding point at runway threshold, \( H_f \);
- A set of alternate routes depending on the origin and the destination, \( R_f \).
Given data (2/2)

- Wake turbulence category, $C_f$;
- Meta-gate, $M_f$;
- Runway entry point for departure or runway exit point for arrival, $E_f$;
- Initial holding point at runway threshold, $H_f$;
- A set of alternate routes depending on the origin and the destination, $R_f$.

From the output of the macroscopic level, we have the following input for the microscopic level:

- Assigned landing time for arrival, $L_f$;
- Assigned landing runway for arrival, $R^l_f$;
- Assigned off-block time for departure, $P_f$;
- Assigned departure runway for departure, $R^d_f$. 
Preprocessed routes set using radar data

- Analyzing 13 days of real traffic (February 2016)
- West configuration in CDG
- In total **510 combinations** of different pairs (runway meta-gate)

**TABLE:** Route options count

<table>
<thead>
<tr>
<th>Route options distributions</th>
<th>Number of options</th>
</tr>
</thead>
<tbody>
<tr>
<td>342</td>
<td>1</td>
</tr>
<tr>
<td>159</td>
<td>2–5</td>
</tr>
<tr>
<td>9</td>
<td>6–9</td>
</tr>
</tbody>
</table>

\[ \sum 510 \]

**Figure:** Route example followed by 309 aircraft
Preprocessed routes set using radar data

4 route options example
Preprocessed routes set using radar data

4 route options example
Preprocessed routes set using radar data

4 route options example
Preprocessed routes set using radar data

4 route options example
Preprocessed routes set using radar data

4 route options example
Preprocessed routes set using radar data

4 route options example
Decision variables

For arrivals:

- Taxi-in route, $r_f$
- Holding time (time spent in runway crossing queues), $t_f^h$
- Holding point, $h_f$

For departures:

- Pushback time, $p_f$
- Taxi-out route, $r_f$
- Holding time (waiting time at take-off runway threshold), $t_f^h$
Decision variables

For arrivals:

- Taxi-in route, $r_f$
- Holding time (time spent in runway crossing queues), $t_f^h$
- Holding point, $h_f$

For departures:

- Pushback time, $p_f$
- Taxi-out route, $r_f$
- Holding time (waiting time at take-off runway threshold), $t_f^h$
Constraints

- Minimum taxi separation of 60 meters between two aircraft

- Take-off single-runway separation requirements, in seconds.

<table>
<thead>
<tr>
<th>Category</th>
<th>Leading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td>Trailing</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>96</td>
</tr>
<tr>
<td>Medium</td>
<td>120</td>
</tr>
<tr>
<td>Light</td>
<td>120</td>
</tr>
</tbody>
</table>

- Holding point capacity
  - For arrivals: 1 or 2
  - For departures: depends on runway pressure
Ground conflict detection

- **Link conflict**
  - Flight $f$
  - Flight $g$
  - Node $u$
  - Link $l = (u,v)$
  - Node $v$

- **Node conflict**
  - Flight $f$
  - Flight $g$
  - Node $n$
  - Detection zone
  - $R_n$
Runway conflict

Interactions between departures and arrival crossings are taken into account at the microscopic level.

<table>
<thead>
<tr>
<th>Pred.\Succ.</th>
<th>Heavy</th>
<th>Medium</th>
<th>Light</th>
<th>Cross</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>96</td>
<td>120</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>Medium</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Light</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Cross</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

- Particular case (Triangle inequality)
  - Sequence: Heavy Departure – Crossing – Medium Departure

![Diagram of runway interactions](image)
Objective function

We minimize

\[ C + \alpha \sum_{f \in D} (p_f - P_f) + \beta \sum_{f \in F} t_f^h \]

where

- **Total number of conflicts**, \( C \);
- **Total pushback delay**, \( \sum_{f \in D} (p_f - P_f) \);
- **Total holding time**, \( \sum_{f \in F} t_f^h \);
- \( \alpha \) and \( \beta \) : weighting coefficients.
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Solution approaches

Using **time decomposition approach combined with heuristic algorithm.**
Simulated annealing

Unconditional Acceptance

Moved accepted with probability $e^{-\frac{\Delta E}{T}}$

AT INIT TEMP.

AT FINAL TEMP.

NUMBER OF ITERATIONS

OBJECTIVE FUNCTION
Neighborhood selection (Macroscopic level)

Aircraft list

$\begin{array}{cccc}
    x_1 & x_i & x_N \\
\end{array}$

Decision Changes

Airspace perfo

$\begin{array}{cccc}
    A_1 & A_i & A_N \\
\end{array}$

Runway perfo

$\begin{array}{cccc}
    R_1 & R_i & R_N \\
\end{array}$

Ground perfo

$\begin{array}{cccc}
    G_1 & G_i & G_N \\
\end{array}$
### Neighborhood selection (Microscopic level)

**Aircraft list**

| $x_1$ | $x_i$ | $x_N$ |

**Decision Changes**

| $T_1$ | $T_i$ | $T_N$ |

**Take-off performance**

| $G_1$ | $G_i$ | $G_N$ |

**Ground performance**

| $R_1$ | $R_i$ | $R_N$ |

**Runway crossing performance**

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Ma, Delahaye, Sbihi, Scala (ENAC, HvA) Integrated Optimization of Arrival, Departure, and Surface Operations
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Case study (Macroscopic level)

- 342 Heavy (24%), 1093 Medium (76%)
- Paris CDG airport layout
Conflicts evaluation (Macroscopic level)

Number of conflicts without runway assignment
Number of conflicts with runway assignment
Total delays without runway assignment
Total delays with runway assignment

Ma, Delahaye, Sbihi, Scala (ENAC, HvA)

Integrated Optimization of Arrival, Departure, and Surface Operations
Terminals and taxiway occupancy (Macroscopic level)

The graph shows the number of flights over time, with different lines representing various occupancy scenarios:

- **Initial Terminal Occupancy** (red line)
- **Optimized Terminal Occupancy** (green line)
- **Initial Taxi Occupancy** (blue line)
- **Optimized Taxi Occupancy** (orange line)

The graph indicates periods of high and low occupancy, with markers at specific times (e.g., 137 flights at time 7 hours, 31 flights at time 11 hours) to highlight changes in occupancy.
Landing runway throughput (Macroscopic level)

A more balanced runway throughput

<table>
<thead>
<tr>
<th>Period</th>
<th>Runway throughput from radar data</th>
<th>Runway throughput from optimized results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26L</td>
<td>27R</td>
</tr>
<tr>
<td>06:00-07:00</td>
<td>32 (48%)</td>
<td>34 (52%)</td>
</tr>
<tr>
<td>07:00-08:00</td>
<td>16 (53%)</td>
<td>14 (47%)</td>
</tr>
<tr>
<td>08:00-09:00</td>
<td>25 (60%)</td>
<td>17 (40%)</td>
</tr>
<tr>
<td>09:00-10:00</td>
<td>31 (62%)</td>
<td>19 (38%)</td>
</tr>
<tr>
<td>10:00-11:00</td>
<td>20 (67%)</td>
<td>10 (33%)</td>
</tr>
</tbody>
</table>

The period between 9:00 and 10:00 is extracted and used as input for the Microscopic level model.
Results of period 9:00–10:00 at Microscopic level

- **Initial case**: without runway assignment;
- **Assigned case**: with runway assignment.

### Delay comparison between Initial case and Assigned case

<table>
<thead>
<tr>
<th>Delay component</th>
<th>Initial case</th>
<th>Assigned case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival holding time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Departure holding time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Departure pushback delay</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total delay (in seconds)
1. Background and problem description

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   - Macroscopic model (long-term decision)
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An optimization approach to solve the integrated airport management problem considering arrival, departure and surface operations in a two-level approach:

- **Macroscopic level**: sequencing arrivals and departures and mitigating the airport congestion;

- **Microscopic level**: receiving the optimized flight information from the macroscopic level, and deciding ground control parameters: pushback time, taxi routes, holding time etc.
Perspectives

- Including **uncertainty** analysis (arrival times, pushback times, taxi times...)
- Testing more **scenarios at both levels**
- Extend the approach to several **coordinated airports** to minimize the overall congestion
Thank you for your attention!