Introduction

Airport Collaborative Decision Making (A-CDM)

- Departure Management (DMAN) is a key feature of A-CDM
  - Anticipate runway take-off sequences and delays
  - Transfer delay to gate, without penalizing the traffic flow
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- Gate occupancy is increased for delayed departures
  - Airport layout must provide enough gates ← expensive
  - Allocation must be robust enough ← NOT easy
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- Gate occupancy is increased for delayed departures
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→ Need for a good initial gate allocation
In This Article...

- Estimate additional gate occupancy due to DMAN at Paris-CDG
- Define and test an initial gate allocation method to optimize its robustness w.r.t. departure delays
- Evaluate the scalability of this scheme w.r.t. traffic growth
Outline

1. Related Works
2. DMAN process
3. Gate Allocation Problem
4. Results
Related Works

- A-CDM program
- Share information and anticipate delays at the airport → to optimize the traffic
- Now implemented at many (28) European airports FRANKFURT, LONDON HEATHROW, PARIS-CDG, etc.
- Aircraft runway scheduling [Deau 2009]

Possible objectives for the GAP

- Minimize the allocation costs defined by airlines and airport manager [Simonis 2007] with Constraint Programming
- Optimize passengers walking distance [Kim 2013] with Tabu Search
- Optimize robustness w.r.t. uncertainties ← quite limited → minimize variance of idle times [Bolat 2001] ≡ minimize sum of their squares
Optimization Robustness

Gate1 | flight1 | flight2 |

Gate2 | flight3 | flight4 |
Optimization Robustness

CONFLICT!!!

Gate1 | flight1 | flight2

Gate2 | flight3 | flight4
Optimization Robustness

Gate 1 | flight 1 \( i_{12} \) flight 2 | flight 3 \( i_{34} \) flight 4 |
# Optimization Robustness

**Initial Allocation:**

<table>
<thead>
<tr>
<th>Gate1</th>
<th>flight1</th>
<th>flight2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate2</td>
<td>flight3</td>
<td>flight4</td>
</tr>
</tbody>
</table>

**Optimized Allocation:**

<table>
<thead>
<tr>
<th>Gate1</th>
<th>flight1</th>
<th>flight4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate2</td>
<td>flight3</td>
<td>flight2</td>
</tr>
</tbody>
</table>
Optimization Robustness

Initial Allocation:

CONFLICT!!!

Optimized Allocation:

No more CONFLICT
Outline

1. Related Works
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Simulation of the Departure Process at Paris-CDG airport

- Two pairs of an arrival and a departure runway → takeoff sequencing does not directly interfere with landing
- The terminal and the runway of each flight is fixed
Departure Management

EOBT: Estimated Off Block Times
+ Minimal Taxi Out Times (depending on the terminal)
Minimal Take Off Times

Runway scheduling

TSAT: Target Start Up Approval Times
- Calibrated Taxi Out Times (depending on the terminal)
TTOT: Target Take Off Times

- Runway scheduling w.r.t. minimal time separations
- Additional gate occupancy for departure: TOBT - EOBT
Optimal Runway Scheduling

Decision Variables
- The TTOT of each considered departures
  \[ \mathcal{T} = \{ t_i, \forall i \in \{1, n\} \} \]
  Domain: \( T_{i}^{\min} \leq t_i, \forall i \in \{1, n\} \)

Constraints
- Minimal separation times between each aircraft
  \[ t_i + \text{Sep}_{i,j} \leq t_j \text{ OR } t_j + \text{Sep}_{j,i} \leq t_i, \forall i \neq j \in \{1, n\} \]

Criterion
- Minimize the total delay:
  \[ f = \sum_{1 \leq i \leq n} t_i - T_{i}^{\min} \]

Solved with Branch and Bound algorithm with Rolling Horizon
Outline

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Gate Allocation Problem

- $\mathcal{F}$: the set of all flights
- $\mathcal{G}$: the set of all gates

Decision Variables
- The gate assigned to each flight, among compatible ones
- $\mathcal{X} = \{x_i \in \{j \text{ s.t. } g_j \in \mathcal{G}_i\}, \forall f_i \in \mathcal{F}\}$

Constraints
- Overlapping aircraft cannot be scheduled at the same gate
- $\forall i \neq i', [f_i^s, f_i^e] \cap [f_{i'}^s, f_{i'}^e] \neq \emptyset \Rightarrow x_i \neq x_{i'}$
**Gate Allocation Problem**

**Criterion**

- Robustness: one of the most crucial objectives
- Minimize sum of idle time square
- \[ f = \sum_{g_j \in G} c_j, \text{ with } c_j \text{ the cost of a single gate } g_j \]

Cost \( c_j \) of gate \( g_j \): \( \frac{t_1^2}{1} + \frac{t_2^2}{2} + \frac{t_3^2}{3} + \frac{t_4^2}{4} \)
Gate Allocation Problem

- Modeled in Integer Linear Programming [bolat 2001]
- Solved with Gurobi
- Optimal solutions proved for all instances

Terminal F: 200 flights/day among 30 gates (less than 30 min)

Table: Comparison of initial and robust gate allocation for one day of traffic at Paris-CDG, terminal F.

<table>
<thead>
<tr>
<th></th>
<th>Idle times (minutes)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Av.</td>
<td>Std Dev</td>
</tr>
<tr>
<td>Init</td>
<td>1</td>
<td>63</td>
<td>48</td>
</tr>
<tr>
<td>Robust</td>
<td>2</td>
<td>76</td>
<td>26</td>
</tr>
</tbody>
</table>
Outline

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Ten heaviest days of actual traffic at Paris-CDG airport, July 2017
Data Processing and DMAN Simulation

- Ten heaviest days of actual traffic at Paris-CDG airport, July 2017
  → *Observed* gate allocation
Data Processing and DMAN Simulation

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  \[ \rightarrow \text{Observed gate allocation} \]
- Re-assignment to optimize \textbf{Robustness}
Data Processing and DMAN Simulation

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  - Re-assignment to optimize Robustness
  - *Robust* gate allocation
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  - *Observed* gate allocation
- Re-assignment to optimize Robustness
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- DMAN Simulation → new Target Off-Block Times (*delayed*)
Data Processing and DMAN Simulation

- Ten heaviest days of actual traffic at Paris-CDG airport, July 2017
  → *Observed* gate allocation
- Re-assignment to optimize Robustness
  → *Robust* gate allocation
- DMAN Simulation → new Target Off-Block Times (delayed)
  → *Additional gate occupancy*
Data Processing and DMAN Simulation

- Ten heaviest days of actual traffic at Paris-CDG airport, July 2017
  → Observed gate allocation
- Re-assignment to optimize Robustness
  → Robust gate allocation
- DMAN Simulation → new Target Off-Block Times (delayed)
  → Additional gate occupancy

Gate Conflict

- Less than 2 min between the arrival time of a flight and the departure of the previous one at the same gate

\[ t \leq 2 \text{ min} \rightarrow \text{CONFLICT!} \]

No enough time for push back of \( f_1 \)
Increased Traffic

- Add flight on the same gate but different time
- Estimate the effects of traffic increase (3% and 5%) on:
  - Additional gate occupancy induced by the DMAN
  - Gate conflicts
## Terminals Information

Number of flights and gates by terminal (per day on average)

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Flights</th>
<th>Gates</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>49</td>
<td>17</td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>C</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>D</td>
<td>83</td>
<td>18</td>
</tr>
<tr>
<td>E</td>
<td>111</td>
<td>23</td>
</tr>
<tr>
<td>F</td>
<td>185</td>
<td>27</td>
</tr>
<tr>
<td>J</td>
<td>76</td>
<td>20</td>
</tr>
<tr>
<td>K</td>
<td>53</td>
<td>19</td>
</tr>
<tr>
<td>L</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>X</td>
<td>27</td>
<td>6</td>
</tr>
</tbody>
</table>
Additional Gate Occupancy

![Additional Gate Occupancy Graph]
### Additional Gate Occupancy by Terminal

Additional gate occupancy by terminal (min per day on average)

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Actual</th>
<th>3 %</th>
<th>5 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20.6</td>
<td>23.2</td>
<td>23.6</td>
</tr>
<tr>
<td>B</td>
<td>3.5</td>
<td>4.2</td>
<td>4.9</td>
</tr>
<tr>
<td>C</td>
<td>8.7</td>
<td>9.4</td>
<td>10.3</td>
</tr>
<tr>
<td>D</td>
<td>24.2</td>
<td>25.9</td>
<td>27.5</td>
</tr>
<tr>
<td>E</td>
<td>45.6</td>
<td>50.9</td>
<td>53.1</td>
</tr>
<tr>
<td>F</td>
<td>52.6</td>
<td>59.8</td>
<td>62.3</td>
</tr>
<tr>
<td>J</td>
<td>30.1</td>
<td>30.9</td>
<td>31.8</td>
</tr>
<tr>
<td>K</td>
<td>33.6</td>
<td>35.1</td>
<td>37.5</td>
</tr>
<tr>
<td>L</td>
<td>10.2</td>
<td>13.8</td>
<td>12.5</td>
</tr>
<tr>
<td>X</td>
<td>8.2</td>
<td>8.3</td>
<td>10.2</td>
</tr>
<tr>
<td>others</td>
<td>70.4</td>
<td>77.25</td>
<td>77.75</td>
</tr>
</tbody>
</table>
Gate Conflicts Due to Delayed Departures

![Bar chart showing number of gate conflicts with actual and robust results for different traffic levels (3% and 5%).]

![Bar chart showing duration of gate conflicts with actual and robust results for different traffic levels (3% and 5%).]
Number of Gate Conflicts due to DMAN

Number of gate conflicts due to the DMAN.

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Actual</th>
<th>3%</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Init</td>
<td>Init</td>
<td>Init</td>
</tr>
<tr>
<td></td>
<td>Robust</td>
<td>Robust</td>
<td>Robust</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>11</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>E</td>
<td>14</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>F</td>
<td>22</td>
<td>27</td>
<td>40</td>
</tr>
<tr>
<td>J</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>K</td>
<td>9</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>L</td>
<td>6</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>X</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>others</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
## Duration of Gate Conflicts due to DMAN

Duration of Gate Conflicts due to the DMAN (in min).

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Actual</th>
<th></th>
<th>3 %</th>
<th></th>
<th>5 %</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Init</td>
<td>Robust</td>
<td>Init</td>
<td>Robust</td>
<td>Init</td>
<td>Robust</td>
</tr>
<tr>
<td>A</td>
<td>12</td>
<td>0</td>
<td>21</td>
<td>0</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>8</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>29</td>
<td>0</td>
<td>26</td>
<td>0</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>33</td>
<td>0</td>
<td>42</td>
<td>0</td>
<td>44</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>41</td>
<td>0</td>
<td>39</td>
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<td>64</td>
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</tr>
<tr>
<td>J</td>
<td>4</td>
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<td>4</td>
<td>0</td>
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<td>K</td>
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<td>6</td>
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<td>8</td>
<td>0</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>others</td>
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<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>
Conclusion

- A way to estimate additional gate occupancy due to DMAN
- Can be analyzed for each terminal to point out the most affected ones
- A way to compute optimal robust solutions for GAP on a really busy international airport (Paris-CDG)
- Resulting allocation appears very efficient at Paris-CDG airport even in case of 5% traffic increase

Further Work

- Confirm and enrich results using fast time simulations
- Robustness can be tested in more realistic and difficult conditions
- Same approach can also be applied to other airports