Potential Operational Benefits of Multi-layer Point Merge System on Dense TMA Operation

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ICRAT 2016
Outline

1 Background
   - Requirements and goal
   - Relative work

2 ML-PM Based Arrival Trajectory Optimization
   - Framework of ML-PM based trajectory optimization
   - Case study: scenarios design

3 Numerical Results and Analysis
   - Input data and RHC-SA parameter settings
   - Numerical results

4 Conclusion and Perspectives
   - Conclusion
   - Perspectives
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Requirements

- Increasing the **efficiency** of flights arriving at busy airports is one of the most challenging topics in Air Traffic Management (ATM) research.

- In order to **match the requirements** in dense TMA operation, **improve flight efficiency** and **increase runway throughput simultaneously**, our solution is to develop an advanced trajectory operations model named **Multi-Layer Point Merge (ML-PM) System**.
Research idea

ML-PM System

"red" and "bleu" sequencing legs are separated horizontally by minimum 2NM

These segregated layers are vertically separated, upper layer for Heavy aircraft, medium one for Medium aircraft and lower one for Light aircraft. They have the same projection on horizontal plan.
ML-PM System

- More efficient to build an optimal sequence, compared to speed regulation
- Group vertically Heavy/Medium/Light aircraft into different layers
- Less uncertainties due to closer to the airport
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Previous work

[Liang et al., 2015] : case study Beijing Capital International Airport (BCIA)

- Design a ML-PM route network on horizontal profile
- Build a mathematical model for this optimization problem
- Apply a dynamical method to solve this problem: Receding Horizon Control with Simulated Annealing (RHC-SA)
- Make some initial simulations with real operational data

A Framework of Point Merge-based Autonomous System for Optimizing Aircraft Scheduling in Busy TMA.
In 5th SESAR Innovation Days, Bologna, Italy.
Previous work

**Sliding window**

![Sliding window diagram](image)

**Example of scenario**

![Scenario before and after](image)
Current work (ICRAT2016)

- Make an assessment of potential benefits gained by this novel ML-PM system in order to be used for reference during possible future development.

- Enhance the previous studies by considering flight altitude changes and speed changes.
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ML-PM route network for BCIA

1. Classic point merge system

2. ML-PM system for BCIA

Multi-layers on the Sequencing legs:
1) W2-W3-W4
2) W5-W6-W7
3) W8-W9-W10
4) W14-W15-W16
Framework of ML-PM based trajectory optimization

Mathematical optimization model

A set of aircraft $f_i$ $(i = 1, \ldots, n)$ arrive in TMA, they need to land on two runways 01-19 and 18R-36L separately and efficiently without conflict.

- **Variables**: entry time $t_i^e$ and entry speed $v_i^e$ at TMA, turning time on sequencing leg $t_i^{turn}$.

- **Constraints**: ICAO separation requirement ($s_{i,j}^{radar}$, $s_{i,j}^{WT}$), allowable changes on decision variables ($\delta v_i^e \in [-12\%, +12\%]$, $\delta t_i^e \in [-5\text{ min}, +5\text{ min}]$), pre-defined speed change profile.

- **Objective**: to minimize a sum of conflicts, delay and runway throughput with consideration of different stakeholder’s interests.
Mathematical optimization model

Speed profile

- blue for "Medium" aircraft
- red for "Heavy" aircraft

- on sequencing leg
- on merging zone
- on final leg

Process of approach

Entry of TMA
Entry of PM
Turning M1
Turning M2
FAF
TDZ
## Conflict detection

### Type of conflict:
- Node conflicts
- Link conflicts
- Merge conflicts

**Note**

Merge conflicts will be transferred into Node conflicts and Link conflicts.

Merge conflicts are transferred into time-based Node conflicts + Link conflicts
Mathematical optimization model

Objective function

\[ z = \text{Min } \alpha T + \beta D + C \]  \hspace{1cm} (1)

\[ T = \frac{m}{n} \text{Max}\{S^1, S^2, \ldots, S^m\} \]  \hspace{1cm} (2)

\[ D = \frac{1}{n} \sum_{i=1}^{n} (t^l_i - \text{ETA}^l_i) \]  \hspace{1cm} (3)

\[ C = \sum_{i=1}^{n} (c^\text{node}_i + c^\text{link}_i) \]  \hspace{1cm} (4)

* \( T \) average landing interval
* \( D \) average delay
* \( C \) sum of conflicts
* \( n \) number of aircraft
* \( S^m \) make span on runway \( m \)
* \( t^l_i \) actual landing time of aircraft \( i \)
* \( \text{ETA}^l_i \) estimated time of lading of aircraft \( i \)
* \( c^\text{node}_i, c^\text{link}_i \) conflicts in nodes and links
* \( \alpha = 0.0015, \beta = 0.001 \) weighting parameters, user-defined parameters.
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Performance indices

**Fuel consumption and \( CO_2 \) emission indices**

\[
J_i = \int_{t_i^e}^{t_i^l} \mu_a dt = \mu_a (t_i^l - t_i^e)  \quad (5)
\]

\[
E_i^{CO_2} = 3.16 \times J_i = 3.16 \times \mu_a (t_i^l - t_i^e)  \quad (6)
\]

- \( J_i \) - fuel consumption for aircraft \( i \), \( E_i^{CO_2} \) - \( CO_2 \) emission for aircraft \( i \),
- \( \mu_a \) - average fuel consumption per minute for aircraft \( i \), and \( \mu_a = 25\, \text{kg/\text{min}} \) for this case.
Three scenarios

- Baseline with penalty on conflict resolution (Baseline)
- Traditional PM with unique layer on sequencing legs (PM-No group)
- Advanced PM with multi-layer on sequencing legs (PM-Group)
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Based on the operational data at BCIA on **Nov.6th 2015**, the input data for scenario simulations are prepared, the arrival flights from **10:00 to 12:00** are analyzed.

## RHC-SA parameter settings

<table>
<thead>
<tr>
<th>Elements</th>
<th>Configuration setting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sliding window</strong></td>
<td></td>
</tr>
<tr>
<td>Size of the window</td>
<td>2400 seconds</td>
</tr>
<tr>
<td>Window shifting interval</td>
<td>900 seconds</td>
</tr>
<tr>
<td><strong>Simulated annealing</strong></td>
<td></td>
</tr>
<tr>
<td>Initial temperature for heating</td>
<td>0.01</td>
</tr>
<tr>
<td>Heating rate</td>
<td>1.1</td>
</tr>
<tr>
<td>Maximum number of transition for heating or cooling</td>
<td>500</td>
</tr>
<tr>
<td>Cooling rate</td>
<td>0.99</td>
</tr>
<tr>
<td>Cooling stopping criterion</td>
<td>$T &lt; 0.0001 * T_{init_cool}$</td>
</tr>
<tr>
<td>Neighborhood selection $P_{Turn}$</td>
<td>0.25</td>
</tr>
<tr>
<td>Neighborhood selection $P_{Speed}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>
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Numerical results

Comparing features:

- Conflict resolution
- Flight efficiency
- Runway throughput and delay
- Performances of ML-PM system
Numerical results

- Conflict resolution
  All scenarios with no-conflict after optimization, one example in one sliding window:

Note: During all the process of optimization, time-based separation between each pair of aircraft must not violate the 90s **minimum separation condition** on the merge point.
Numerical results

- Flight efficiency

**Table:** Flight Efficiency in Three Scenarios

<table>
<thead>
<tr>
<th>Type of scenario</th>
<th>Total flight time (min)</th>
<th>Total fuel consumption (kg)</th>
<th>Total $CO_2$ emission (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>2358</td>
<td>58955</td>
<td>186297</td>
</tr>
<tr>
<td>PM-No group</td>
<td>2332</td>
<td>58307</td>
<td>184252</td>
</tr>
<tr>
<td>PM-Group</td>
<td>2221</td>
<td>55528</td>
<td>175471</td>
</tr>
</tbody>
</table>
Numerical results

- Runway throughput and delay

**Table: Capacity and Delay Performance in Three Scenarios**

<table>
<thead>
<tr>
<th>Type of scenario</th>
<th>Average Delay (min)</th>
<th>Make Span (min)</th>
<th>Ave. Land Interval (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>4.34</td>
<td>142.52</td>
<td>3.06</td>
</tr>
<tr>
<td>PM-No group</td>
<td>3.92</td>
<td>139.23</td>
<td>2.99</td>
</tr>
<tr>
<td>PM-Group</td>
<td>3.33</td>
<td>137.09</td>
<td>2.95</td>
</tr>
</tbody>
</table>
Numerical Results and Analysis

Performance of ML-PM system

Table: Decision Variables in PM-Group Scenario (ML-PM)

<table>
<thead>
<tr>
<th>Level of adjustment on variables</th>
<th>Number of aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Entry Speed</td>
</tr>
<tr>
<td>Zero</td>
<td>15.05%</td>
</tr>
<tr>
<td>Slight</td>
<td>10.75%</td>
</tr>
<tr>
<td>Little</td>
<td>4.30%</td>
</tr>
<tr>
<td>Moderate</td>
<td>20.43%</td>
</tr>
<tr>
<td>High</td>
<td>12.90%</td>
</tr>
<tr>
<td>Strong</td>
<td>36.56%</td>
</tr>
</tbody>
</table>
Numerical results

Performance of ML-PM system

- Landing interval (min):
  - group_PM_18R-36L: 2.10
  - group_PM_19-01: 4.22

- Makespan (min):
  - group_PM_18R-36L: 122
  - group_PM_19-01: 135
Numerical results

- Performance of ML-PM system

![Bar chart showing performance of ML-PM system](chart.png)
Numerical results

- Performance of ML-PM system

![Graph showing altitude over time for different entry points.](image)
Numerical results

- Performance of ML-PM system
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Conclusion

- **Conflict-free trajectories** are generated in the numerical simulations.

- The horizontal and vertical profile of ML-PM route network of BCIA are designed in detail, and continuous speed change profile is also described in order to realize a **continuous descent approach profile**.

- The related flight efficiency indices are analyzed, the results have shown a **significant improvement** of ML-PM system, compared with Baseline and PM-No group.
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Perspectives

- The route network design in this paper is limited to BCIA. For another airport, it is necessary to build a new route network with horizontal and vertical designs based on local operation reality. However, the design procedures are not complex.

- Outlook
  - Depth-study of current model, such as improve the efficiency of search algorithm
  - Breadth-study, such as refinement of the methodology
Thank you for your attentions!

Any questions?
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