Departure Scheduling in a Multi-airport System

Yanjun Wang, Minghua Hu
Nanjing University of Aeronautics and Astronautics

wangyj@nuaa.edu.cn, minghuahu@263.net
Contents

I. Motivation & objectives

II. Operational constraints of a multi-airport departure scheduling

III. Mathematical model & algorithm

IV. Experimental results

V. Conclusions
Contents

- I. Motivation & objectives
- II. Operational constraints of a multi-airport departure scheduling
- III. Mathematical model & algorithm
- IV. Experimental results
- V. Conclusions
The runway system capacity is one of the major constraints in the air transport system.

Two ways to enhance the runway operation performance:

- Building new runways. It is expensive and sometime impossible.
- Improving runway operations. The task is to optimally utilize runway capacity.
Why a multi-airport system?

- The previous studies mainly focused on a single airport departure scheduling. (Bolender 2000, Atkin et al. 2007, Balakrishnan et al, 2007)

- A multi-airport system is: a set of significant airports that serve commercial transport in a metropolitan region, without regard to ownership or political control of the individual airport. (R. de Neufville, and A. Odoni, 2003)

- “The transition from single-airport to multi-airport systems is and will remain a key mechanism by which the air transportation system scales and will meet growing demand in the future.” (P. A. Bonnefoy and R. J. Hansman, 2008)
Multi-airport systems in the world

Geographical distribution of multi-airport systems worldwide (cite from Bonnefoy et al.)
Objective

The purpose of departure scheduling in multi-airport is to determine an optimal sequence and takeoff time under different objectives.

- maximizing the runway/terminal throughput
- minimizing the average delay
- ensuring airlines’ or airports’ equities
- Others......
Contents

I . Motivation & objectives

II . Operational constraints of a multi-airport departure scheduling

III. Mathematical model & algorithm

IV. Experimental results

V . Conclusions
Departure constraints

- A. Minimum Takeoff Separation
- B. Departure Time Window
- C. Position Shift Constraints
- D. Multi-runway Operation
E. Traffic Interaction between Airports
Contents

I. Motivation & objectives

II. Operational constraints of a multi-airport departure scheduling

III. Mathematical model & algorithm

IV. Experimental results

V. Conclusions
Constraints of scheduling model

\[ d_i \geq e_i \quad \text{for all } i \in FL \]
\[ d_i = e_i \quad \text{if } c_i = 1, \quad i \in FL \]
\[ d_j \geq \max_{i \in FL|c_i < c_j , a_i = a_j} (d_i + S_{ij}) \]
\[ b_i \leq d_i \leq l_i \quad i \in F^c \]
\[ |c^j_i - o^j_i| \leq k \quad \text{for all } i \in F^a_j , j \in AD \]
\[ \begin{cases} 
| (d_i + t^p_i) - (d_j + t^p_j) | \geq \tau^p \\
 i, j \in FL, p \in PT \quad c_i > c_j, p_i = p_j = p
\end{cases} \]
Objective function of the model

- **Objective function of Model I:**
  \[ J^I(d_i) = \frac{\sum_{i \in FL} (d_i - t_i)}{N} \]

- **The average delay of airport \( j \):**
  \[ D^a_j = \frac{\sum_{i \in F^a_j} (d_i - t_i)}{N^a_j} \]

- **Objective function of Model II:**
  \[ J^H(d_i) = J^I(d_i) + \sum_{j \in AD} \left| D^a_j - J^I(d_i) \right|^{\alpha_j} \]
Aircraft scheduling problem is known as an NP-hard problem.

Various algorithms have been developed to solve this problem, such as GA algorithms (Xiao-bing Hu et al. 2005, 2008), dynamic programming based approach (Balakrishnan et al., 2006, 2007).
There are five essentials of the TS algorithm:

1. Initial solution;
2. Neighborhood searching;
3. Tabu list;
4. Measuring function;
5. Stop condition.
(1) Initial Solution

A sequence in order of ascending ETD with several adjustments will be the starting point for TS.
(2) Neighborhood Searching

A neighbor is generated by swapping the positions of two aircraft in \( X \) while complying with the CPS.

\[
\begin{array}{cccccccc}
A & B & C & D & E & F & G & \cdots \\
1 & 2 & 3 & 4 & 5 & 6 & 7 & \\
\end{array}
\]

\[
\begin{array}{cccccccc}
B & C & D & A & E & G & F & \cdots \\
\end{array}
\]

\[x\]

\[
\begin{array}{cccccccc}
B & C & D & A & F & G & E & \cdots \\
\end{array}
\]

An Effective Move (\( k = 2 \))

\[
\begin{array}{cccccccc}
B & C & D & A & E & G & F & \cdots \\
\end{array}
\]

An Invalid Move (\( k = 2 \))

The Maximum Position Shift of aircraft A is 2
(3) Tabu List

- The last 20 moves of each aircraft are stored in the tabu list.

- Two aspiration criteria:
  - when all solutions in candidate set are forbidden, then the solution with minimal objective value is chosen to unbind.
  - Although one solution is forbidden but its measuring function value is better than the value of the current best solution, then this solution can be unbound and return to the candidate set.
A new starting point will be selected from candidate set through the measuring function.

- We take the objective function as the measuring function.
(5) Stop Condition

- **Condition 1:** the algorithm has run for a predetermined number of iterative steps \( \text{MAX\_ITER} \).

- **Condition 2:** the objective value does not decrease in limited steps \( \text{MAX\_OPT} \).
(6) The Algorithm Procedure

Get an initial solution $x^{init}$
Let $N_{init}=0$, $N_{opt}=1$, $x^*=x^{init}$
Set tabu list $T=\emptyset$

YES

$N_{init}=\text{MAX\_ITER}$ or $N_{init}=\text{MAX\_OPT}$

NO

Generate neighborhood $N(x^{init})$
Then form candidate set $V(x^{init})$

Select the optimal in the $V(x^{init})$
Let $x^{new}=x^{opt}$, $N_{init}=N_{init}+1$

$J(x^{new}) < J(x)$

YES

Let $N_{opt}=1$, $x^*=x^{new}$, $N_{opt}=1$

Update tabu list $T$

NO

Let $N_{opt}=N_{opt}+1$

Terminate the algorithm
Output the result

8th ATM R&D Seminar
Contents

Ⅰ . Motivation & objectives

Ⅱ . Operational constraints of a multi-airport departure scheduling

Ⅲ . Mathematical model & algorithm

Ⅳ . Experimental results

Ⅴ . Conclusions
Flight data used in the experiment was drawn from the Operations Management Centre of Air Traffic Management Bureau, CAAC.

Statistics result on number of departure flights from 15:00 to 16:00
The minimum runway separation is 2 minutes as all aircraft types in experiment are either heavy or medium.

Minute-In-Trail requirement at departure fixes

<table>
<thead>
<tr>
<th>Fix</th>
<th>Minute-In-Trail Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSN</td>
<td>Flights to Hong Kong and Macao require an 8 minutes distance; others 5 minutes</td>
</tr>
<tr>
<td>PIKAS</td>
<td>7 minutes</td>
</tr>
<tr>
<td>SX</td>
<td>Flights which depart from the same airport require a 7 minutes distance; otherwise 3 minutes</td>
</tr>
<tr>
<td>ODULO</td>
<td>8 minutes</td>
</tr>
<tr>
<td>LAMEN</td>
<td>5 minutes</td>
</tr>
</tbody>
</table>
Three cases

- **Case A**: PUD is open while SHA is closed.

- **Case B**: SHA is open while PUD is closed.

- **Case C**: Both PUD and SHA are open during the period.
# Average Flight Delay

Comparative results on aircraft delay under different cases and policies (in minute per aircraft)

<table>
<thead>
<tr>
<th>Fix/Airport</th>
<th>Case A</th>
<th></th>
<th>Case B</th>
<th></th>
<th>Case C</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCFS</td>
<td>Model I.</td>
<td>FCFS</td>
<td>Model I.</td>
<td>FCFS</td>
<td>Model I.</td>
</tr>
<tr>
<td>HSN</td>
<td>7</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>18.375</td>
<td>8</td>
</tr>
<tr>
<td>LAMEN</td>
<td>4</td>
<td>4</td>
<td>—</td>
<td>—</td>
<td>14.5</td>
<td>7</td>
</tr>
<tr>
<td>ODULO</td>
<td>7</td>
<td>10.5</td>
<td>—</td>
<td>—</td>
<td>14.5</td>
<td>11.75</td>
</tr>
<tr>
<td>PIKAS</td>
<td>5.67</td>
<td>1.33</td>
<td>20</td>
<td>5.44</td>
<td><strong>27.17</strong></td>
<td><strong>12.92</strong></td>
</tr>
<tr>
<td>SX</td>
<td>4.33</td>
<td>1.67</td>
<td>19.44</td>
<td>12.56</td>
<td><strong>23.58</strong></td>
<td><strong>15.5</strong></td>
</tr>
<tr>
<td>ZSPD</td>
<td>6.1</td>
<td>2.95</td>
<td>—</td>
<td>—</td>
<td>15.95</td>
<td>10.25</td>
</tr>
<tr>
<td>ZSSS</td>
<td>—</td>
<td>—</td>
<td>19.72</td>
<td>9</td>
<td>29.11</td>
<td>14.5</td>
</tr>
<tr>
<td>Terminal</td>
<td>6.1</td>
<td>2.95</td>
<td>19.72</td>
<td>9</td>
<td><strong>22.18</strong></td>
<td><strong>12.26</strong></td>
</tr>
</tbody>
</table>
**Average flight delay**

Comparative results on aircraft delay under different cases and policies (in minute per aircraft)

<table>
<thead>
<tr>
<th>Fix/Airport</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCFS</td>
<td>Model I.</td>
<td>FCFS</td>
</tr>
<tr>
<td>HSN</td>
<td>7</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>LAMEN</td>
<td>4</td>
<td>4</td>
<td>—</td>
</tr>
<tr>
<td>ODULO</td>
<td>7</td>
<td>10.5</td>
<td>—</td>
</tr>
<tr>
<td>PIKAS</td>
<td>5.67</td>
<td>1.33</td>
<td>20</td>
</tr>
<tr>
<td>SX</td>
<td>4.33</td>
<td>1.67</td>
<td>19.44</td>
</tr>
<tr>
<td>ZSPD</td>
<td>6.1</td>
<td>2.95</td>
<td>—</td>
</tr>
<tr>
<td>ZSSS</td>
<td>—</td>
<td>—</td>
<td>19.72</td>
</tr>
<tr>
<td>Terminal</td>
<td>6.1</td>
<td>2.95</td>
<td>19.72</td>
</tr>
</tbody>
</table>
## Average time intervals

<table>
<thead>
<tr>
<th>Fix/Airport</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCFS</td>
<td>Model I.</td>
<td>FCFS</td>
</tr>
<tr>
<td>HSN</td>
<td>8.43</td>
<td>8.43</td>
<td>—</td>
</tr>
<tr>
<td>LAMEN</td>
<td>41</td>
<td>35</td>
<td>—</td>
</tr>
<tr>
<td>ODULO</td>
<td>9</td>
<td>15</td>
<td>—</td>
</tr>
<tr>
<td>PIKAS</td>
<td>27</td>
<td>23</td>
<td>9.75</td>
</tr>
<tr>
<td>SX</td>
<td>22.5</td>
<td>21</td>
<td>9.75</td>
</tr>
<tr>
<td>ZSPD</td>
<td>3.42</td>
<td>3.42</td>
<td>—</td>
</tr>
<tr>
<td>ZSSS</td>
<td>—</td>
<td>—</td>
<td>4.71</td>
</tr>
</tbody>
</table>
## Time intervals at PIKAS & SX

<table>
<thead>
<tr>
<th></th>
<th>PIKAS</th>
<th>SX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCFS</td>
<td>Model I</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>11</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Average</td>
<td>8</td>
<td>7.09</td>
</tr>
</tbody>
</table>
Departure time and sequence for flights under different policies

Airport/Fix

Fix: LAMEN
Fix: ODULO
Fix: PIKAS
Fix: HSN
Fix: SX

FCFS Departure Sequence
Optimized Departure Sequence

Airport: SHA
Airport: PUD
Comparison of Model I and Model II

(a) Average delay of terminal and airports, Model I
(b) Average delay of terminal and airports, Model II
(c) Comparative result on terminal delay between Model I and Model II
(d) Comparative result on difference delay of airports between Model I and Model II
Contents

Ⅰ. Motivation & objectives

Ⅱ. Operational constraints of a multi-airport departure scheduling

Ⅲ. Mathematical model & algorithm

Ⅳ. Experimental results

Ⅴ. Conclusions
Conclusions

- The limited capacity of departure fixes is the main factor confining the growth of departure flow in multi-airport system.

- Optimizing the utilization of the shared departure fixes will result in an enhancement of terminal capacity.

- Interaction of departure traffic between airports can bring the inequality among airports. Fortunately this can be eliminated by a reasonable departure control strategy.
Some improvement to the departure scheduling may be including the airliners’ preferences in the model.

Integrating the scheduling of departure and arrival flows in terminal area will be another challenging aspect in ATFM field.
Thank You!