Optimal Delay Allocation under High Flexibility Conditions during Demand-Capacity Imbalance

A theoretical approach to show the potential of the User Driven Prioritisation Process

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Outline

• Introduction, Motivation and Methodology
• Recall: Cost of delay and current UDPP features
• Problem of LVUCs and potential new UDPP features
• Flexibility vs. Equity
• Mathematical analysis and examples
• Conclusions and future work
Introduction

• Profitability in air transport industry is very sensitive to cost variations (profit margins might be as low as 1-2%). [Ref: IATA]

• DCB protects well the safety and capacity performances by applying delays in FPFS order when there is congestion at airports. However, DCB has no visibility of the impact of delay on AUs operations.

• AUs would like further flexibility to reduce the 'impact of delay' (cost of delay) during irregular operations.

• User-driven approach could be a good solution to achieve efficiency (while safety can be preserved) in the ATFM slot/delay allocation. [Ref: Fundamental Theorem of Welfare].
How to give flexibility to AUs while not impacting negatively to others?

- User-Driven Prioritisation Process (UDPP) is being developed in the context of SESAR
- Today, UDPP allows Enhanced Slot Swapping, which gives flexibility to some AUs with no impact to others

- But, what about Low Volume Users in Constraint (LVUC), i.e., AUs with a few flights (e.g., 3 or less)
Low Volume Users in Constraint (LVUCs)

- According to analysis of the last 20 AIRACs, *in the 85% of the hotspots the AUs have 3 flights or less* (they are LVUCs)
  - **Limited flexibility** in these cases
- About in *2/3 of the regulations* the AUs will have *1 flight* operated in a hotspot
  - **No flexibility with current UDPP**
- Some AUs are always LVUCs ➔ **Problem of access**
  - **It is mandatory to give access to LVUCs** in UDPP
- Important: *any AU can be an LVUC* (quite often indeed)
Motivation

• With this presentation we want:

  • To explore the **limits of flexibility beyond the current UDPP validated features** *(to include LVUCs).*

  • To know what is the **dominant strategy of an AU when he can optimise** his cost of delay subject to equity constraints

  • To show that **in theory** we could have a **win-win situation if:**

    • **Slot exchange is allowed between AUs**
    • Each AU tries to **optimise their own cost of delay**
    • AUs are constrained by **equity** rules *(‘what is taken from others must be given back at some point’)*
Methodology

- **High flexibility subject to equity** will be discussed.

- Via developing the *User Delay Optimisation Model* (UDOM) and analysing the results and implications.

- Hypothetical case to study:
  - The AU has **high/full flexibility to transfer its total baseline delay** (i.e., initial ATFM delay) among his flights.
  - For that purpose, the AU can **take flight sequence positions to other AUs (freely!)**.
  - The AU is subject to a particular **equity** constraint: **total baseline delay of the AU cannot be reduced**.
Operational Cost of delay for Airspace Users?

From AU: No way to Act on Delay -> Act on Operational Cost of the Delay

Cost of delay on 1 flight

Non-linear cost structure due to:
- PAX flow: transit, high yield passengers, rotations,…
- Resource Mgt. (cascade): curfew, crew constraints, pilots constraints, maintenance, ...

Slope = punctuality policy (reputation)

First max delay target (Margin of manoeuvre 1)

2nd max delay target (Margin of manoeuvre 2)

Delay

Each flight has its own particular complex cost structure only known by the AU
Recall: Current UDPP

UDPP Slot Swapping has demonstrated real benefits for AUs

In current UDPP flexibility is limited by the own number of flights in a hotspot and the re-scheduling limits (slots too far away are not feasible).
Potential new advanced UDPP features

The AU cannot improve the situation with current UDPP

New advanced UDPP features are needed to give access to LVUCs and potentially to increase flexibility for everyone (**slot exchange between AUs**).
LVUCs should have access throughout different hotspots

The AU cannot improve the situation with current UDPP

New advanced UDPP features are needed to give access to LVUCs (slot exchange between AUs and possibly throughout multiple hotspots)
The higher the immediate impact to others and the longer the time for compensation, the more difficult to develop and validate an equitable UDPP method.
It might be more difficult to prove equity in case of crossed compensations among AUs (but more flexibility is expected).
USER DELAY OPTIMISATION MODEL (UDOM)
Description of parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>$[0, +\infty)$</td>
<td><em>Delay of a flight</em> ($d_0$ means $d=0$)</td>
</tr>
<tr>
<td>$U_0$</td>
<td>$[0, +\infty)$</td>
<td><em>Max utility</em> of a flight when its $d=0$</td>
</tr>
<tr>
<td>$N$</td>
<td>$[0, +\infty)$</td>
<td>Number of flights operated by an AU in the reference period</td>
</tr>
<tr>
<td>$\varepsilon_i$</td>
<td>$(-\infty, +\infty)$</td>
<td><em>Elasticity</em> of the utility function of flight $i$. Used to simplistically characterise (continuous model) different operational flight margins</td>
</tr>
<tr>
<td>$\rho_i$</td>
<td>$[0,1]$</td>
<td>Probability of a flight $i$ for being affected/delayed by a hotspot</td>
</tr>
<tr>
<td>$\delta_i$</td>
<td>$[0, +\infty)$</td>
<td><em>Average delay expected</em> for flight $i$ in the route operated (i.e., typical delay from hotspots on that route)</td>
</tr>
<tr>
<td>$d_i$</td>
<td>$[0, +\infty)$</td>
<td><em>Baseline (random) delay</em> for flight $i$</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>$(-\infty, +\infty)$</td>
<td><em>Delay shift</em>, to increase or reduce the delay of flight $i$</td>
</tr>
<tr>
<td>$d_i^*$</td>
<td>$[0, +\infty)$</td>
<td><em>Optimal delay</em> for flight $i$ in the actual hotspot</td>
</tr>
<tr>
<td>$d'_i$</td>
<td>$(-\infty, +\infty)$</td>
<td><em>Shifted delay</em>, i.e., delay difference between the optimal delay and the baseline delay, for flight $i$.</td>
</tr>
</tbody>
</table>
Utility of a flight

Utility can be understood as the value perceived by a particular AU if a given slot is allocated to a particular flight operated (directly related with the economic profits).

Continuous model (simplification)

Different $U_0$ and $\epsilon$ to model different carriers:

$$U(d) = \frac{\epsilon}{2} d^2 + U_0$$

$\forall d \geq 0, U_0 > 0, \epsilon < 0$

Utility = Profit – Delay Cost
Each AU will receive the utility of all its flights, the ones without delay and the ones with delay.

\[
\bar{U} = \sum_{i=1}^{N} U_i\left(d_0\right)(1 - \rho_i) + \sum_{i=1}^{N} U_i\left(\delta_i\right)\rho_i
\]

- **Sum of utilities of flights operated without delay**
- **Sum of utilities of flights operated with delay**
- **Expected long-term utility for the AU**
- **Delay = 0**
- **Average delay expected for flight \(i\)**
- **Probability of flight \(i\) of being regulated and delayed**
- **Probability of flight \(i\) of not being delayed**
The average long-term utility perceived by an AU will be always below the ideal case in which there is no delay.
**UDOM: Flexibility and Equity**

**High Flexibility:** in case of a hotspot, the AU would be allowed to freely change the delay of its flights with a *delay shift, \( \tau \)*

\[
U(d + \tau) = \frac{\xi}{2}(d + \tau)^2 + U_0
\]

The *delay shift* is added to the baseline delay of a flight.

**Equity:** to avoid potential system abuses, the model forces an equity constraint to AUs: baseline delay cannot be reduced

\[
\sum_{i=0}^{N} \tau_i = 0
\]

The sum of *delay shifts* must be zero.
UDOM: General optimisation model

Under high flexible-equitable conditions an AU with \( N \) flights faces the following optimisation problem

\[
\max_{\tau_1, \ldots, \tau_N} \bar{U} = \sum_{i=1}^{N} U_i \left( d_0 \right) \left( 1 - \rho_i \right) + \sum_{i=1}^{N} U_i \left( \delta_i + \tau_i \right) \left( \rho_i \right)
\]

s.t. \( \sum_{i=1}^{N} \tau_i = 0 \)

Optimal Delay per flight:

\[
\tau_i^* = \frac{\sum_{j=1}^{N} \delta_j}{\sum_{j=1}^{N} \varepsilon_j \rho_j} - \delta_i
\]
**Example:** LVUC with 3 flights in the same hotspot.

\( \rho = 1 \) (hotspot is actually happening)

\( \delta \Rightarrow \) we use actual (random) delay instead of average delay

**F1 Utility**

\( U_0 = 500 \)

\( \varepsilon_{f_1} = -2 \)

\( \tau_{f_1}^* \approx 21 \)

**F2 Utility**

\( U_0 = 500 \)

\( \varepsilon_{f_2} = -10 \)

\( \tau_{f_2}^* \approx -7 \)

**F3 Utility**

\( U_0 = 500 \)

\( \varepsilon_{f_3} = -9 \)

\( \tau_{f_3}^* \approx -14 \)

*Optimised sequence*

*Delay shift between flights (sum equal to zero)*
Example: LVUC with 3 flights in the same hotspot.

Baseline Utility:

$$U_{BD} = U_{f1}(5) + U_{f2}(12) + U_{f3}(20) = 475 - 220 - 1300 = -1045$$

Optimised Utility:

$$U_{UD}^* = U_{f1}(5 + 21) + U_{f2}(12 - 7) + U_{f3}(20 - 14) =$$

$$= -176 + 375 + 338 = +537$$

Optimised expected utility (UDPP) $+537$

Expected utility (FPFS) $-1045$

Maximum affordable utility (no delay) $1500$

Baseline Utility

Optimised Utility
How to give flexibility to LVUCs? Case study of access to LVUCs

- Realistic scenario (simulated!): HUB (blue), Low Cost (green) and LVUCs (red and orange)

- With UDOM the LVUC1 (red) wants to transfer 25 minutes of delay from the second flight to the first one

- With the delay exchange LVUC1 could save 30% of costs

- LVUC2 (orange) with 1 flight only could use User Delay Optimisation Model (UDOM) over the time (multiple hotspots)
### Realistic case study results

<table>
<thead>
<tr>
<th>AU name</th>
<th>Total flights</th>
<th>Baseline delay</th>
<th>Assigned delay</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>HUB</td>
<td>52</td>
<td>1388</td>
<td>1373</td>
<td>15</td>
</tr>
<tr>
<td>LC1</td>
<td>8</td>
<td>250</td>
<td>253</td>
<td>-3</td>
</tr>
<tr>
<td>LC2</td>
<td>12</td>
<td>461</td>
<td>470</td>
<td>-9</td>
</tr>
<tr>
<td>OA1</td>
<td>6</td>
<td>227</td>
<td>224</td>
<td>3</td>
</tr>
<tr>
<td>OA2</td>
<td>2</td>
<td>32</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>OA3</td>
<td>2</td>
<td>59</td>
<td>62</td>
<td>-3</td>
</tr>
<tr>
<td>OA4</td>
<td>1</td>
<td>33</td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td>LVUC1</td>
<td>3</td>
<td>94</td>
<td>94</td>
<td>0</td>
</tr>
<tr>
<td>OA6</td>
<td>4</td>
<td>113</td>
<td>113</td>
<td>0</td>
</tr>
<tr>
<td>OA7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OA8</td>
<td>6</td>
<td>208</td>
<td>211</td>
<td>-3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>98</strong></td>
<td><strong>2865</strong></td>
<td><strong>2865</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AU name</th>
<th>% Flights</th>
<th>% B.Delay</th>
<th>% A.Delay</th>
<th>Difference</th>
<th>NIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>HUB</td>
<td>54.17%</td>
<td>48.45%</td>
<td>47.92%</td>
<td>1.08%</td>
<td>-3</td>
</tr>
<tr>
<td>LC1</td>
<td>8.33%</td>
<td>8.73%</td>
<td>8.83%</td>
<td>-1.20%</td>
<td>-3</td>
</tr>
<tr>
<td>LC2</td>
<td>12.50%</td>
<td>16.09%</td>
<td>16.40%</td>
<td>-1.95%</td>
<td>-3</td>
</tr>
<tr>
<td>OA1</td>
<td>6.25%</td>
<td>7.92%</td>
<td>7.82%</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>OA2</td>
<td>2.08%</td>
<td>1.12%</td>
<td>1.12%</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>OA3</td>
<td>2.08%</td>
<td>2.06%</td>
<td>2.16%</td>
<td>-5.08%</td>
<td>-3</td>
</tr>
<tr>
<td>OA4</td>
<td>1.04%</td>
<td>1.15%</td>
<td>1.15%</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>LVUC1</td>
<td>3.13%</td>
<td>3.28%</td>
<td>3.28%</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>OA6</td>
<td>4.17%</td>
<td>3.94%</td>
<td>3.94%</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>OA7</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>OA8</td>
<td>6.25%</td>
<td>7.26%</td>
<td>7.36%</td>
<td>-1.44%</td>
<td>-3</td>
</tr>
</tbody>
</table>

Max extra delay per flight impacted by the LVUC1 actions
Example: two flights operated by an LVUC in different times. Probability of being delayed at this airport at that time = 0.2 Average delay at this airport and at that time = 15 min.

Utility

\[
U_0 = 500
\]

\[
U = \max_{\tau_1} \left[ U_{f1}(d_0) + U_{f2}(d_0) \right][1 - \rho] + \left[ U_{f1}(\delta + \tau_1) + U_{f2}(\delta - \tau_1) \right](\rho)
\]

\[
\tau_{f1}^* = 10; \tau_{f2}^* = -10
\]

Optimisation:

\[
\begin{align*}
\mathcal{U}^* = 1000 &+ \left[ U_{f1}(15 + \tau^*) + U_{f2}(15 - \tau^*) \right](0.2) = \\
&= 1000(0.8) + \left( \frac{25}{2} - \frac{10}{2} \right)^2 = 850 \quad \text{Optimised sequence}
\end{align*}
\]

\[
\begin{align*}
\mathcal{U} = 1000 &+ \left( U_{f1}(15) + U_{f2}(15) \right)(0.2) = \\
&= 1000(0.8) + \left( \frac{25}{2} 15^2 - \frac{10}{2} 15^2 \right) = 730 \quad \text{Baseline sequence}
\end{align*}
\]
Conclusions

• An hypothetical case has been studied with UDOM
• **High flexibility** has been given to an AU to minimise its own global delay costs. The AU had **full freedom to transfer delay** among its flights and to **take (freely) flight sequence positions from other AUs**.
• After imposing a **constraint of equity** (**total AU’s delay must remain the same**), it is shown that:
  a) There is an **optimal level of delay** for each flight ⇒ **AUs would like to participate even if they are not obliged**.
  b) The **equity condition increases flexibility** in the system (because the AU is forced to offer positions to other AUs ⇒ “Equity creates market”)
  c) If the number of LVUCs is not too large, the **impact to others might be negligible**
  d) **Smooth coordination might be possible** with a reduced set of simple UDPP rules
  e) AUs could be just **focused on optimising their own operations**
Future work

• **Cost model and optimisation model will be updated** with more realistic curves.

• High Flexibility will be given to LVUCs while **co-existing with current UDPP features** (for non-LVUCs)

• More effort must be dedicated to develop validation scenarios (more difficult to **demonstrate equity in the long-term**)
Any Questions?