Incorporating the value of slots in airport slot scheduling decisions

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Lancaster University Management School

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Agenda

• Presentation’s objectives
• Motivation
• IATA world schedule guidelines (WSG) overview
• Related work
  Optimisation slot allocation models (SAM) considering elements of IATA’s WSG
  Multi-attribute decision-making (MADM) in air transport
• Proposed approach
  Illustrative application and results
• Discussion on current and future work
Objective

• Propose a mathematical optimisation airport slot allocation model that can consider the preferences of the stakeholders participating in the airport slot coordination process via:
  1. An indicative Analytical Hierarchy Process (AHP) tree structure which considers several airport slot characteristics so as to determine the Slot Valuation Index (SVI)
  2. A two-stage solution approach that:
     I. Calculates the SVI for all airport slot requests submitted at a single airport during a slot scheduling season; and
     II. Incorporates the SVI in an airport slot scheduling integer program (IP)
Motivation - IATA Worldwide Slot Guidelines

• The slot allocation process described in IATA (2019) is the dominant airport demand management mechanism in congested airports (>200 slot coordinated airports)

• The main part of this process is the initial slot allocation, carried out by the appointed coordinator

• The coordinator uses expert systems (e.g. Condor and Score GDC) to allocate the slots based on the rules and priorities
Motivation – recent research trends

• Mixed integer programming has proved to produce efficient airport slot schedules;

• Recently multi-objective optimisation models have been employed to grasp the problem’s requirements;

• However, all models assume that ‘a slot is slot’ and do not distinguish the differences in slots’ value; occurring from their differing characteristics (aircraft, distance, route serviced etc.);

• The inclusion of additional elements (e.g. rules and characteristics) increases the complexity of the models, leading to intractable computational times;
Motivation – research question

*Can we provide a measure for the value of slots capturing policy requirements and slot characteristics without increasing the complexity of the optimisation models?*
IATA WSG

Slot allocation principles and rules

General priorities → Primary criteria → Additional criteria → Displacement guidelines

Local guidelines

Initial (draft) slot schedule
## Airport slot allocation models considering certain IATA WSG

<table>
<thead>
<tr>
<th>Model</th>
<th>Primary criteria</th>
<th>Duration</th>
<th>Additional criteria</th>
<th>Displacement criteria</th>
<th>Fairness</th>
<th>Flexibility</th>
<th>PSO routes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zografos et al. (2012)</td>
<td>✔️ ✔️ ✔️</td>
<td>8.3.6</td>
<td>8.4.1.a 8.4.1.b 8.4.1.c 8.4.1.d 9.7.3.d 8.4.1.e</td>
<td>9.9.3.a 9.9.3.b 9.9.3.c 9.9.3.d 9.9.3.e 9.9.3.f</td>
<td>✔️ ✔️ ✔️</td>
<td>✔️ ✔️ ✔️</td>
<td>CR 95/93 (1993)</td>
</tr>
<tr>
<td>Zografos and Jiang (2016)</td>
<td>✔️ ✔️ ✔️</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✔️ ✔️ ✔️</td>
<td>✔️ ✔️ ✔️</td>
</tr>
<tr>
<td>Zografos et al. (2017)</td>
<td>✔️ ✔️ ✔️</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✔️ ✔️ ✔️</td>
<td>✔️ ✔️ ✔️</td>
</tr>
<tr>
<td>Ribeiro et al. (2018)</td>
<td>✔️ ☐ ☐</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✔️ ✔️ ✔️</td>
<td>✔️ ✔️ ✔️</td>
</tr>
<tr>
<td>Fairbrother and Zografos (2018a)</td>
<td>✔️ ✔️ ✔️</td>
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<td>✔️ ✔️ ✔️</td>
<td>✔️ ✔️ ✔️</td>
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<tr>
<td>Fairbrother and Zografos (2018b)</td>
<td>✔️ ✔️ ✔️</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✔️ ✔️ ✔️</td>
<td>✔️ ✔️ ✔️</td>
</tr>
</tbody>
</table>

**Notes:**
- Historic slot requests (8.3.2), Changes to historic slots (8.3.3), New entrants rules (8.3.4, 8.3.5), Year round operations (8.3.6), Effective period of operation (8.4.1.a), Type of service and market (8.4.1.b), Competitive factors when rejecting slots (8.4.1.c), Curfews (8.4.1.d, 9.7.3.d), Requirements of shippers and travellers (8.4.1.e), offers shall not place airlines in less favourable conditions than the ones held (9.9.3.a), acceptable/ unacceptable offers (9.9.3.c), consistent turnaround times (9.9.3.f), flexibility sections (9.9.3.b, 9.9.3.d, 9.9.3.e), addressed/ accurately addressed (✓ ✔️ ✔️), not addressed (✘), * partially considered, Fairness stands for transparency and non-discrimination of airlines.

* There is a parallel stream of research that considers airport slot scheduling in the US and does not consider IATA's WSG which is not illustrated in the table above.
## MADM in air transport

<table>
<thead>
<tr>
<th>Paper</th>
<th>Application area</th>
<th>Methods</th>
<th>Multiple stakeholders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zografos, Giannouli (2001)</td>
<td>ATFM system cost effectiveness</td>
<td>AHP</td>
<td>✓</td>
</tr>
<tr>
<td>Tsaur et al. (2002)</td>
<td>Airline efficiency</td>
<td>AHP, fuzzy numbers</td>
<td>×</td>
</tr>
<tr>
<td>Geimba De Lima et al. (2007)</td>
<td>Airline efficiency</td>
<td>AHP</td>
<td>×</td>
</tr>
<tr>
<td>Pestana Barros and Dieke (2007)</td>
<td>Airport efficiency</td>
<td>DEA</td>
<td>×</td>
</tr>
<tr>
<td>Madas and Zografos (2010)</td>
<td>Slot allocation policy selection</td>
<td>AHP</td>
<td>✓</td>
</tr>
<tr>
<td>Castelli and Pellegrini (2011)</td>
<td>4D trajectory window specification</td>
<td>AHP</td>
<td>✓</td>
</tr>
<tr>
<td>Kuo (2011)</td>
<td>Airline efficiency</td>
<td>VIKOR, GRA, fuzzy numbers</td>
<td>✓</td>
</tr>
<tr>
<td>Liou et al. (2011)</td>
<td>Airline efficiency</td>
<td>VIKOR</td>
<td>✓</td>
</tr>
<tr>
<td>Baltazar et al. (2014)</td>
<td>Airport efficiency</td>
<td>MACBETH, DEA</td>
<td>×</td>
</tr>
<tr>
<td>Zietsman and Vanderschuren (2014)</td>
<td>Airport efficiency</td>
<td>AHP</td>
<td>✓</td>
</tr>
<tr>
<td>Lupo (2015)</td>
<td>Airport efficiency</td>
<td>ELECTRE III, fuzzy numbers</td>
<td>✓</td>
</tr>
<tr>
<td>Olfat et al. (2016)</td>
<td>Airport efficiency</td>
<td>DEA</td>
<td>✓</td>
</tr>
<tr>
<td>Bongo and Ocampo (2017)</td>
<td>ATFM action selection</td>
<td>DEMATEL, ANP, TOPSIS, fuzzy numbers</td>
<td>×</td>
</tr>
<tr>
<td>Yang et al. (2017)</td>
<td>Multi-aircraft conflict resolution</td>
<td>TOPSIS</td>
<td>✓</td>
</tr>
<tr>
<td>Sidiropoulos et al. (2018)</td>
<td>Design of dynamic arrival and departure routes</td>
<td>AHP</td>
<td>✓</td>
</tr>
</tbody>
</table>
Proposed approach – AHP (Suitability)

- The MADM technique should be able to provide weights to the considered valuation criteria;
- The process and the results should be transparent and fairly understandable by the stakeholders;
- The technique should be easily converted to a group decision support tool allowing collaborative decision making under the participation of various stakeholders which may have conflicting views;
- The method should be able to consider both objective and subjective criteria and measurements;
- The method should be able to measure/consider the logical consistency of the responses; and
- The method should facilitate sensitivity analyses on its outcome;

Katsigiannis (2018)
Proposed approach – AHP (1/3)

• The lower level of the tree consists of slot request characteristics which can be used to consider the additional slot allocation criteria which are illustrated in Level 1;

• The goal is to assign weights to each node of the hierarchy so as to determine the importance of each slot characteristic;

• The indication of a suitable opinion aggregation function is required when multiple experts fill the questionnaire (e.g. weighted mean or weighted geometric mean);
Proposed approach – AHP (2/3)

What is the relative importance of indicator $X$ over indicator $Y$ regarding the upper level criterion $Z$?
**Proposed approach – AHP (3/3)**

What is the relative importance of indicator $X$ over indicator $Y$ regarding the upper level criterion $Z$?

<table>
<thead>
<tr>
<th>Response</th>
<th>Description</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
<td>X, Y contribute equally to $Z$</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
<td>Experience and judgement strongly favour $X$ over $Y$</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
<td>X is favoured over $Y$ to the greatest extent possible regarding $Z$</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
<td>X is favoured over $Y$ to the greatest extent possible regarding $Z$</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values</td>
<td>Y is more important than $X$ regarding $Z$</td>
</tr>
<tr>
<td>Reciprocals (1/2, ..., 1/9)</td>
<td>The inverse significance is assigned</td>
<td></td>
</tr>
</tbody>
</table>

(Saaty, 1989)
Proposed approach – Illustrative example (Preferences 1/2)

- A questionnaire with pairwise comparisons among all red-coloured criteria is completed;

<table>
<thead>
<tr>
<th>Level 1 criteria</th>
<th>Load</th>
<th>Schedule type</th>
<th>Connectivity</th>
<th>Flight reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Schedule type</td>
<td>1/2</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Connectivity</td>
<td>1/4</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flight reach</td>
<td>1/3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 2 criteria</th>
<th>Domestic</th>
<th>International</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>International</td>
<td>1/2</td>
<td>1</td>
</tr>
</tbody>
</table>

* This example is supplied in order to illustrate the applicability of the method and does not reflect the views of other stakeholder groups
### Proposed approach – Illustrative example (Preferences 2/2)

<table>
<thead>
<tr>
<th>Level 3 criteria</th>
<th>Cargo</th>
<th>Passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo</td>
<td>1</td>
<td>1/2</td>
</tr>
<tr>
<td>Passenger</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 3 criteria</th>
<th>New</th>
<th>Existing</th>
</tr>
</thead>
<tbody>
<tr>
<td>New route</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Existing route</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

#### Domestic

<table>
<thead>
<tr>
<th>Level 3 criteria</th>
<th>Short</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short haul</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Long haul</td>
<td>1/5</td>
<td>1</td>
</tr>
</tbody>
</table>

#### International

<table>
<thead>
<tr>
<th>Level 3 criteria</th>
<th>Short</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short haul</td>
<td>1</td>
<td>1/7</td>
</tr>
<tr>
<td>Long haul</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>
Proposed approach – Illustrative application (Criteria weights)
Let $v_m = \sum_{j \in J} o_{m,j} w_j$ be the value of slot request $m$, where $J$ is the set of level 3 criteria.
Proposed approach – Illustrative application (Case study 1/4)
Proposed approach – Illustrative application (Case study 2/4)

**Input sets**

- \( M \): set of request series denoted by \( m \);
- \( M^{\text{Arr}}(\text{Dep}) \): set of arrival (departure) series;
- \( P \subseteq M \times M \): set of paired requests \((m_{\text{Arr}}, m_{\text{Dep}})\) indexed by \( p \);
- \( D \): set of days in scheduling season denoted by \( d \);
- \( D_m \): set of days that slot \( m \) is to operate;
- \( C \): set of capacity duration lengths indexed by \( c \);
- \( T = \{1, \ldots, |T|\} \): set of time intervals per day based on \( c \);
- \( K \): set of movement types denoted by \( k \).

**Parameters**

- \( t_m \): requested time for slot series \( m \);
- \( T_{\text{max},p}, T_{\text{min},p} \): maximum and minimum turnaround times of paired request \( p \);
- \( u_{d,t,c}^{k} \): capacity for movement \( k \) for period \([t, t+c)\) on day \( d \) based on time scale \( c \);
- \( a_{d,m} \): \( \begin{cases} 1, \text{if series } m \text{ is requested on day } d \\ 0, \text{ otherwise} \end{cases} \) and
- \( v_m \): valuation index of slot request \( m \)

**Decision variables and expressions**

\[
\mathbf{x}_{t,m} = \begin{cases} 1, \text{ if request } m \text{ is allocated to time } t \\ 0, \text{ otherwise} \end{cases}
\]

**Objective function**

\[
\min Z = \sum_{m \in M} \sum_{t \in T} |t - t_m| x_{t,m} v_m
\]

**Subject to:**

\[
\sum_{t \in T} x_{m,t} = 1, \forall m \in M
\]

\[
\sum_{m \in M} \sum_{k \in K} \sum_{t \in \{t,t+c-1\}} a_{d,m} x_{t,m} \leq u_{d,t,c}^{k}, \forall k \in K, d \in D, c \in C, t \in T
\]

\[
\sum_{t \in T} x_{t,m_{\text{Dep}}} t - \sum_{t \in T} x_{t,m_{\text{Arr}}} t = t_m^\text{Dep} - t_m^\text{Arr} = T_{\text{max}} - T_{\text{min}}, \forall p \in P
\]

(Zografos et al., 2012)

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**Agenda and Objectives**
- Motivation
- IATA WSG
- Related work (SAM, MADM)
- Proposed approach
- Current and future work
## Proposed approach – Illustrative application (Case study 3/4)

<table>
<thead>
<tr>
<th>Priority levels</th>
<th>Total displacement</th>
<th>with ( v_m )</th>
<th>without ( v_m )</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>229</td>
<td>229</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>697</td>
<td>711</td>
<td>-1.97%</td>
<td></td>
</tr>
<tr>
<td>NE</td>
<td>676</td>
<td>676</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>12941</td>
<td>11707</td>
<td>10.54%</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14543</strong></td>
<td><strong>13323</strong></td>
<td><strong>9.16%</strong></td>
<td></td>
</tr>
</tbody>
</table>
Proposed approach – Illustrative application (Case study 4/4)

Gains(-)/ Losses(+) per airline

-200%  0%  200%  400%  600%  800%  1000%  1200%  1400%
Current work– Conclusions

+ The proposed solution methodology compliments airport SAM optimisation models.

+ It may assign valuation weights to each slot based on the subjective judgements of the stakeholders, concerning numerous policy requirements without adding up to the complexity of the optimisation models.

+ The consideration of the slot characteristics does impact the slot scheduling outcome.

• There is a trade-off between the inclusivity and simplicity of the AHP-tree that has to be considered

  - The subjective judgements require the consultation of multiple experts per stakeholder group

  - The pairwise preference data may be difficult to obtain
Future work

- Tree validation by industry experts (inclusion and exclusion of criteria and associations based on their significance);

- Collection of preference data (questionnaires, online surveys);
References (1/3)


References (2/3)

• Zografos, K., Jiang, Y., 2016. Modelling and solving the airport slot scheduling problem with efficiency, fairness, and accessibility considerations.
Backup slide – The main steps of the AHP

1. Decomposition of the problem into criteria, subproblems and alternatives;
2. Collection of pairwise preference data according to the fundamental scale of absolute numbers;
3. Generation of the pairwise comparisons of the alternatives with respect to different criteria and the criteria themselves (square matrix of size $n$)
   - the diagonal elements of the matrix are equal to one;
   - if the element of the $i^{th}$ row is better than the one in the $j^{th}$ column then the value of cell $(i, j)$ is more than one and less than in the opposite occasion;
4. Data normalisation
   - computation of the division of each entry towards the sum of each column for each element $(w_{ij})$;
5. Priority extraction (eigenvectors) for each alternative under each criterion by adding the normalised values given Step 4 per row and dividing by this summation with the number of alternatives;
6. Calculation of the consistency ratio (CR): $CR = \frac{Consistency\ Index\ (CI)}{Random\ index\ (RI)}$, where:
   - $CI = (Max.\ eigen\ value - n)/(n - 1)$; and
   - $RI = CI$ (randomly generated matrix);
   - Saaty (2005) proposes that $CI$ should be more than 0.1 in order to have consistent judgements.
7. The rating of each alternative is multiplied by the weights of the criteria and the sub-criteria
8. Report of the final scores for each criterion and alternative.