Impact analysis of a flexible air transportation system: Clip-Air

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EPFL

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Outline

1. Flexibility
2. Schedule Planning Model
3. Comparative Analysis
4. Conclusions
Outline

1. Flexibility
2. Schedule Planning Model
3. Comparative Analysis
4. Conclusions
Flexibility

- Flexibility in transportation systems
  - Robustness
  - Demand responsiveness
- Rail transportation ⇒ modularity in fleet
- Maritime transportation ⇒ standard unit loads, multi-modality
- Air transportation ⇒ decision support systems
Flexibility of Clip-Air

- Decoupling of wing and capsules:
  - Modularity
  - Multi-modality
- Mixed passenger and cargo transportation

... and can be combined with intelligent decision support tools:
- Demand management
- Disruption management
Flexibility of Clip-Air

- Decoupling of wing and capsules:
  - Modularity
  - Multi-modality
- Mixed passenger and cargo transportation

... and can be combined with intelligent decision support tools:
- Demand management
- Disruption management
Illustration - Modularity
Illustration - Modularity
Model framework

- Decisions
  - Fleet assignment
    - Assignment of wings to the flights
    - Assignment of capsules to the wings
  - Schedule - selected optional flights
  - Seat allocation to economy and business class
  - The spilled number of passengers

- Supply-demand interactions
  - Spill and recapture
  - Itinerary choice model
Model framework

- **Decisions**
  - Fleet assignment *Modularity*
    - Assignment of wings to the flights
    - Assignment of capsules to the wings
  - Schedule - selected optional flights
  - Seat allocation to economy and business class
  - The spilled number of passengers

- **Supply-demand interactions**
  - Spill and recapture
  - Itinerary choice model
    - *Demand management*
Integrated schedule planning model

\[
\begin{align*}
\text{Min} & \sum_{f \in F} (C_w^f x^w_f + \sum_{k \in K} C_{k,f} x_{k,f}) + \sum_{h \in H} \sum_{s \in S^h} \sum_{i \in (l_s \setminus l'_s)} (\sum_{j \in l_s} t_{i,j} - \sum_{j \in (l_s \setminus l'_s)} t_{j,i} b_{j,i}) p_i \text{ op. costs + loss of pax.} \\
\text{s.t.} & \sum_{k \in K} x_{k,f} = 1 \text{ mandatory flights} & \forall f \in F^M \\
& \sum_{k \in K} x_{k,f} \leq x^w_f \text{ wing-capsules} & \forall f \in F \\
& y^w_{a,t}^- + \sum_{f \in \text{ln}(a,t)} x^w_f = y^w_{a,t}^+ + \sum_{f \in \text{out}(a,t)} x^w_f \text{ flow cons. wings} & \forall [a, t] \in N \\
& \sum_{a \in A} y^w_{a,\text{min}E_a^-} + \sum_{f \in CT} x^w_f \leq R_w \text{ available wings} & \forall a \in A \\
& y^w_{a,\text{min}E_a^-} = y^w_{a,\text{max}E_a^+} \text{ cyclic wings} & \forall a \in A \\
& y^k_{a,t}^- + \sum_{k \in K} x_{k,f} = y^k_{a,t}^+ + \sum_{k \in K} x_{k,f} \text{ flow cons. capsules} & \forall [a, t] \in N \\
& \sum_{a \in A} y^k_{a,\text{min}E_a^-} + \sum_{k \in CT} k x_{k,f} \leq R_k \text{ available capsules} & \forall a \in A \\
& y^k_{a,\text{min}E_a^-} = y^k_{a,\text{max}E_a^+} \text{ cyclic capsules} & \forall a \in A 
\end{align*}
\]
Integrated schedule planning model

Min \( \sum_{f \in F} (C_w x_w^f + \sum_{k \in K} C_k x_k f) + \sum_{h \in H} \sum_{s \in S^h} \sum_{i \in (l_s \setminus l_s')} \sum_{j \in l_s} (\sum_{i \in (l_s \setminus l_s')} t_{i,j} - \sum_{j \in (l_s \setminus l_s')} t_{j,i} b_{j,i}) p_i \) \ op. costs + loss of pax.  

\begin{align*}
&\text{s.t.} \sum_{k \in K} x_{k,f} = 1 \text{ mandatory flights} \\
&\sum_{k \in K} x_{k,f} \leq x_{w}^f \text{ wing-capsules} \\
&y_{a,t}^w + \sum_{f \in \text{In}(a,t)} x_f^w = y_{a,t}^w + \sum_{f \in \text{Out}(a,t)} x_f^w \text{ flow cons. wings} \\
&\sum_{a \in A} y_{a,\text{min} E_a^w} + \sum_{f \in \text{CT}} x_f^w \leq R_w \text{ available wings} \quad \forall \text{f} \in F \\
&y_{a,\text{min} E_a^w} = y_{a,\text{max} E_a^w} \quad \text{cyclic wings} \\
&y_{a,t}^k + \sum_{k \in K} x_{k,f} = y_{a,t}^k + \sum_{f \in \text{Out}(a,t)} \sum_{k \in K} x_{k,f} \text{ flow cons. capsules} \\
&\sum_{a \in A} y_{a,\text{min} E_a^k} + \sum_{f \in \text{CT}} k x_{k,f} \leq R_k \text{ available capsules} \quad \forall \text{f} \in F \\
&y_{a,\text{min} E_a^k} = y_{a,\text{max} E_a^k} \quad \text{cyclic capsules} \quad \forall \text{a} \in A
\end{align*}
Integrated schedule planning model

\[
\sum_{s \in S^h} \sum_{i \in (I_s \setminus I_s')} \delta_f^i D_i - \sum_{j \in I_s} \delta_f^i t_{i,j} + \sum_{j \in (I_s \setminus I_s')} \delta_f^i t_{j,i} b_{j,i} \leq \pi_{f,h} \text{ demand-supply} \\
\forall f \in F, h \in H
\]

\[
\sum_{h \in H} \pi_{f,h} \leq \sum_{k \in K} Q_k x_{k,f} \text{ available seats} \\
\forall f \in F
\]

\[
\sum_{j \in I_s} t_{i,j} \leq D_i \text{ spilled passengers} \\
\forall h \in H, s \in S^h, i \in (I_s \setminus I_s')
\]

\[
x_f^w \in \{0, 1\} \\
\forall f \in F
\]

\[
x_{k,f} \in \{0, 1\} \\
\forall k \in K, f \in F
\]

\[
y_{a,t}^w \geq 0 \\
\forall [a, t] \in N
\]

\[
y_{a,t}^k \geq 0 \\
\forall [a, t] \in N
\]

\[
\pi_{f,h} \geq 0 \\
\forall f \in F, h \in H
\]

\[
t_{i,j} \geq 0 \\
\forall h \in H, s \in S^h, i \in (I_s \setminus I_s'), j \in I_s
\]
Integrated schedule planning model

\[
\sum_{s \in S^h} \sum_{i \in (I_s \setminus I_s')} \delta^i_s D_i - \sum_{j \in I_s} \delta^i_j t_{i,j} + \sum_{j \in (I_s \setminus I_s')} \delta^i_j t_{j,i} b_{j,i} \leq \pi_{f,h} \text{ demand-supply} \\
\forall f \in F, h \in H \quad (10)
\]

\[
\sum_{h \in H} \pi_{f,h} \leq \sum_{k \in K} Q_k x_{k,f} \text{ available seats} \\
\forall f \in F \quad (11)
\]

\[
\sum_{j \in I_s} t_{i,j} \leq D_i \text{ spilled passengers} \\
\forall h \in H, s \in S^h, i \in (I_s \setminus I_s') \quad (12)
\]

\[x_f^w \in \{0, 1\} \quad \forall f \in F \quad (13)\]

\[x_{k,f} \in \{0, 1\} \quad \forall k \in K, f \in F \quad (14)\]

\[y_{a,t}^w \geq 0 \quad \forall [a, t] \in N \quad (15)\]

\[y_{a,t}^k \geq 0 \quad \forall [a, t] \in N \quad (16)\]

\[\pi_{f,h} \geq 0 \quad \forall f \in F, h \in H \quad (17)\]

\[t_{i,j} \geq 0 \quad \forall h \in H, s \in S^h, i \in (I_s \setminus I_s'), j \in I_s \quad (18)\]
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## Configuration - Comparison with Airbus A320

<table>
<thead>
<tr>
<th></th>
<th>Clip-Air</th>
<th>A320</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Capacity</strong></td>
<td>3x150 (450 seats)</td>
<td>150 seats</td>
</tr>
<tr>
<td><strong>Engines</strong></td>
<td>3 engines</td>
<td>2 engines</td>
</tr>
<tr>
<td><strong>Maximum Aircraft Weight</strong></td>
<td>139t (+78%)</td>
<td>78t</td>
</tr>
<tr>
<td></td>
<td>173.5t (+11%)</td>
<td>2x78t (156t)</td>
</tr>
<tr>
<td></td>
<td>208t (-11%)</td>
<td>3x78t (234t)</td>
</tr>
</tbody>
</table>
Operating costs for *Clip-Air*

- Based on standard flight operating costs
- Adjustment based on weight differences:
  - Fuel costs $^1$ (25.3%)
  - Airport and air navigation charges $^2$ (6%)
- Crew cost $^1$ (24.8%) is separated between wing (flight crew) and capsules (cabin crew):
  - flight crew constitutes a 60% of the total crew cost
  - gain of 30% with 2 capsules
  - gain of 40% with 3 capsules

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$^1$IATA, 2010
$^2$Castelli and Ranieri, 2007; ICAO, 2012
Conservative Assumptions

- *Fleet composition*
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size
Conservative Assumptions

- Fleet composition
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- Operating cost of Clip-Air is higher
Conservative Assumptions

- Fleet composition
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- Operating cost of Clip-Air is higher

- The repositioning of capsules is ignored
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
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- The repositioning of capsules is ignored

- Other cost figures are also expected to be reduced: maintenance, number of engines
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size
- Operating cost of Clip-Air is higher
- The repositioning of capsules is ignored
- Other cost figures are also expected to be reduced: maintenance, number of engines
- Only passenger transportation
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size

- Operating cost of Clip-Air is higher

- The repositioning of capsules is ignored

- Other cost figures are also expected to be reduced: maintenance, number of engines

- Only passenger transportation

- Total fleet investment cost is ignored
Conservative Assumptions

- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size
- Operating cost of Clip-Air is higher
- The repositioning of capsules is ignored
- Other cost figures are also expected to be reduced: maintenance, number of engines
- Only passenger transportation
- Total fleet investment cost is ignored
- The schedule and the demand is assumed to remain the same
Towards results

• Input: data from a major European airline company
  • set of optional and mandatory flights
  • set of airports
  • set of itineraries: demands and fares
  • set of aircraft for the standard fleet

• Performance measures
  • ASK: available seat kilometers
  • TPASK: transported pax. per available seat kilometers

• Tests:
  • Network effect
  • Fleet composition
  • Available capacity
  • Sensitivity analysis on the costs
### Network effects - Airport pair

#### Data

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Airports</td>
<td>2</td>
</tr>
<tr>
<td>Flights</td>
<td>38</td>
</tr>
<tr>
<td>Density (Flights/route)</td>
<td>19</td>
</tr>
<tr>
<td>Passengers</td>
<td>13,965</td>
</tr>
<tr>
<td>Itineraries</td>
<td>45</td>
</tr>
<tr>
<td>Standard fleet types</td>
<td>A320(150), A330(293), B747-200(452)</td>
</tr>
</tbody>
</table>

#### Results

<table>
<thead>
<tr>
<th></th>
<th>Standard fleet</th>
<th>Clip-Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost</td>
<td>1,607,166</td>
<td>1,725,228</td>
</tr>
<tr>
<td>Spill costs</td>
<td>604,053</td>
<td>448,140</td>
</tr>
<tr>
<td>Revenue</td>
<td>2,419,306</td>
<td>2,575,219</td>
</tr>
<tr>
<td>Profit</td>
<td>812,140</td>
<td>849,991 (+4.66%)</td>
</tr>
<tr>
<td>Transported pax.</td>
<td>10,276</td>
<td>11,035 (+7.39%)</td>
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<tr>
<td>Flight count</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Total flight duration</td>
<td>3135 min</td>
<td>3135 min</td>
</tr>
<tr>
<td>Used fleet</td>
<td>2 A320</td>
<td>7 wings</td>
</tr>
<tr>
<td></td>
<td>5 A330</td>
<td>12 capsules</td>
</tr>
<tr>
<td>Used aircraft</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Used seats</td>
<td>1765</td>
<td>1800</td>
</tr>
<tr>
<td>ASK</td>
<td>78,388,063</td>
<td>79,942,500</td>
</tr>
<tr>
<td>TPASK (×10⁻⁵)</td>
<td>13.11</td>
<td>13.80</td>
</tr>
</tbody>
</table>

Clip-Air does not have any advantage in terms of the aircraft size.
Network effects - Hub and spoke

### Data

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Airports</td>
<td>5</td>
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<tr>
<td>Flights</td>
<td>26</td>
</tr>
<tr>
<td>Density (Flights/route)</td>
<td>3.25</td>
</tr>
<tr>
<td>Passengers</td>
<td>9,573</td>
</tr>
<tr>
<td>Itineraries</td>
<td>37</td>
</tr>
<tr>
<td>Standard fleet types</td>
<td>A320(150), A330(293), B747-200(452)</td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th></th>
<th>Standard fleet</th>
<th>Clip-Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost</td>
<td>817,489</td>
<td>938,007</td>
</tr>
<tr>
<td>Spill costs</td>
<td>484,950</td>
<td>393,677</td>
</tr>
<tr>
<td>Revenue</td>
<td>1,247,719</td>
<td>1,338,992</td>
</tr>
<tr>
<td>Profit</td>
<td>430,230</td>
<td>400,985 (-6.80 %)</td>
</tr>
<tr>
<td>Transported pax.</td>
<td>5,031</td>
<td>5,721 (+13.71 %)</td>
</tr>
<tr>
<td>Flight count</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td>Total flight duration</td>
<td>1850 min</td>
<td>1700 min</td>
</tr>
<tr>
<td>Used fleet</td>
<td>5 A320</td>
<td>6 wings</td>
</tr>
<tr>
<td></td>
<td>2 A330</td>
<td>12 capsules</td>
</tr>
<tr>
<td></td>
<td>1 B747</td>
<td></td>
</tr>
<tr>
<td>Used aircraft</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Used seats</td>
<td>1788</td>
<td>1800</td>
</tr>
<tr>
<td>ASK</td>
<td>46,860,500</td>
<td>43,350,000</td>
</tr>
<tr>
<td>TPASK (×10^-5)</td>
<td>10.74</td>
<td>13.20</td>
</tr>
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</table>
### Network effects - Peer-to-peer network

#### Data

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
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<tbody>
<tr>
<td>Airports</td>
<td>4</td>
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<tr>
<td>Flights</td>
<td>98</td>
</tr>
<tr>
<td>Density (Flights/route)</td>
<td>8.17</td>
</tr>
<tr>
<td>Passengers</td>
<td>28,465</td>
</tr>
<tr>
<td>Itineraries</td>
<td>150</td>
</tr>
<tr>
<td>Standard fleet types</td>
<td>A320(150), A330(293), B747-200(452)</td>
</tr>
</tbody>
</table>

#### Results

<table>
<thead>
<tr>
<th></th>
<th>Standard fleet</th>
<th>Clip-Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost</td>
<td>3,189,763</td>
<td>3,117,109</td>
</tr>
<tr>
<td>Spill costs</td>
<td>982,556</td>
<td>978,683</td>
</tr>
<tr>
<td>Revenue</td>
<td>5,056,909</td>
<td>5,060,782</td>
</tr>
<tr>
<td>Profit</td>
<td>1,867,146</td>
<td>1,943,673 (+ 4.1 %)</td>
</tr>
<tr>
<td>Transported pax.</td>
<td>20,840</td>
<td>21,424 (+ 2.8 %)</td>
</tr>
<tr>
<td>Flight count</td>
<td>91</td>
<td>84</td>
</tr>
<tr>
<td>Total flight duration</td>
<td>6650 min</td>
<td>6160 min</td>
</tr>
<tr>
<td>Used fleet</td>
<td>7 A320</td>
<td>13 wings</td>
</tr>
<tr>
<td></td>
<td>10 A330</td>
<td>28 capsules</td>
</tr>
<tr>
<td></td>
<td>3 B747</td>
<td></td>
</tr>
<tr>
<td>Used aircraft</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Used seats</td>
<td>5336</td>
<td>4200 (- 21.3 %)</td>
</tr>
<tr>
<td>ASK</td>
<td>502,695,667</td>
<td>366,520,000</td>
</tr>
<tr>
<td>TPASK (×10⁻⁵)</td>
<td>4.15</td>
<td>5.85</td>
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</tbody>
</table>
Network effects

- Enhanced performance when...
  - High flight density
  - Well connected network
Fleet composition

The same data as peer-to-peer network
Available capacity

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Airports</td>
<td>5</td>
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<tr>
<td>Flights</td>
<td>100</td>
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<tr>
<td>Density (Flights/route)</td>
<td>6.25</td>
</tr>
<tr>
<td>Passengers</td>
<td>35,510</td>
</tr>
<tr>
<td>Itineraries</td>
<td>140</td>
</tr>
</tbody>
</table>

- Standard fleet types:
  - A319(124), A320(150), A321(185), A330(293), A340(335), B737-300(128), B737-400(146), B737-900(174), B747-200(452), B777(400)

- Map of France and Switzerland showing flight routes.
Available capacity

![Available capacity graph](image)
Sensitivity analysis on the cost of Clip-Air

The same data used for the test on the available capacity
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Conclusions

- Clip-Air better utilizes the capacity
Conclusions

- Clip-Air better utilizes the capacity
  - More passengers...
Conclusions

- Clip-Air better utilizes the capacity
  - More passengers...
  - ... with less allocated capacity
Conclusions

- Clip-Air better utilizes the capacity
  - More passengers...
  - ... with less allocated capacity
- Clip-Air deals better with the insufficient capacity
Conclusions

- Clip-Air better utilizes the capacity
  - More passengers...
  - ... with less allocated capacity
- Clip-Air deals better with the insufficient capacity
- Results are robust to the cost values of Clip-Air
Conclusions

- Clip-Air better utilizes the capacity
  - More passengers...
  - ... with less allocated capacity
- Clip-Air deals better with the insufficient capacity
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Conclusions

- Clip-Air better utilizes the capacity
  - More passengers...
  - ... with less allocated capacity

- Clip-Air deals better with the insufficient capacity

- Results are robust to the cost values of Clip-Air

Different wing and capsule sizes

- Clip-Air has a strength with one single wing/capsule type
- Different sizes can be studied
- Small wings/capsules: easier transport
Multi-modality of Clip-Air capsules

- Clip-Air capsules can be transferred via other means of transport
- Empty capsule management
- Demand fluctuations
- Unbalanced demand
- European market - railways
Thank you very much for your attention!

Any question?
Spill and recapture \textbf{Model}

\begin{align*}
V_i &= -[2.23(-3.48) \times \text{nonstop}_i + 2.17(-3.48) \times \text{stop}_i] \times \ln(p_i/100) \\
&\quad - [0.102(-2.85) \times \text{nonstop}_i + 0.0762(-2.70) \times \text{stop}_i] \times \text{time}_i \\
&\quad + 0.0283(1.21) \times \text{morning} \\
&\forall i \in I_s, s \in S^{\text{econ.}} \\

V_i &= -[1.97(-3.64) \times \text{nonstop}_i + 1.96(-3.68) \times \text{stop}_i] \times \ln(p_i/100) \\
&\quad - [0.104(-2.43) \times \text{nonstop}_i + 0.0821(-2.31) \times \text{stop}_i] \times \text{time}_i \\
&\quad + 0.0790(1.86) \times \text{morning} \\
&\forall i \in I_s, s \in S^{\text{bus.}} \\

b_{i,j} &= \frac{\exp(V_j)}{\sum_{k \in I_s \setminus \{i\}} \exp(V_k)} \\
&\forall h \in H, s \in S^h, i \in (I_s \setminus I_s'), j \in I_s,
\end{align*}
### Spill and recapture

<table>
<thead>
<tr>
<th></th>
<th>class</th>
<th>nonstop</th>
<th>morning</th>
<th>time</th>
<th>price</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-B₁</td>
<td>E</td>
<td>0</td>
<td>1</td>
<td>250</td>
<td>300</td>
<td>-2.67</td>
</tr>
<tr>
<td>A-B₂</td>
<td>E</td>
<td>0</td>
<td>0</td>
<td>250</td>
<td>300</td>
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