Demand based airline scheduling

for a new generation of aircraft

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Clip-Air concept

- Flexible capacity
- Modular-detachable capsules
- Wing and capsule separation
- Multi-modality
- Passenger and cargo
- Sustainability
  - Gas emissions
  - Noise
  - Accident rates

Objectives

- Analyze the potential performance of Clip-Air by developing appropriate models
- Introduce demand notion in optimization models through appropriate demand models
- Develop solution methodologies for the integrated model
- Investigate multi-modality aspect of Clip-Air

Analysis on the potential performance of Clip-Air

- Compared to a fleet composed of standard planes...
  - Clip-Air carries on the average 5-10% more passengers by using 20-30% less capacity,
  - Clip-Air copes better with the insufficient transportation capacity,
  - Uses less aircraft/wing ⇒ less crew, simplified operations.
- The scheduling decisions are robust to the estimated cost figures of Clip-Air. Sensitivity analysis showed that Clip-Air is always better in the number of transported passengers and generates higher profit in 89% of the instances.
- A preliminary analysis is carried out on the multi-modality aspect of Clip-Air where the empty capsules are allowed to be repositioned via railways. The results show a potential increase in profit and transportation capacity.

Integration of demand model

Motivation: Demand responsive transportation systems

- Supply $\Rightarrow$ Flexibility provided by Clip-Air
- Demand $\Rightarrow$ integration of appropriate demand models

Demand model

- Simple models (e.g. linear, exp.) fail to represent the reality
- Integrated model becomes very sensitive to demand model parameters
- Appropriate models need to be developed

Itinerary choice model ▸ DCA

- Itinerary choice among the set of alternatives for each O-D pair
- Utility of each alternative is defined with the relevant variables
- Choice probability is defined by logit
- Estimation of the coefficients of the variables are done with maximum likelihood estimation

- **Revealed preferences (RP) data:** Booking data from a major European airline
  - Lack of variability
  - Price inelastic demand

Itinerary choice model

- RP data is combined with a **stated preferences (SP) data**
- For each itinerary i and class h the utility is defined as follows:

$$V_i^h = ASC_i + \beta_{fare}^h \cdot \ln(fare_i^h) + \beta_{time}^h \cdot time_i^h + \beta_{morning}^h \cdot morning_i^h$$

  - ASC_i : alternative specific constant
  - *fare* and *time* are interacted with non-stop/stop
  - *morning* is a dummy variable and 1 if the itinerary is a morning itinerary
- Time, cost and morning parameters are fixed to be the same for the two datasets.
- A scale parameter is introduced for SP to have equal variances.

Itinerary choice model

- Demand for class h for each itinerary i in market segment s:

$$\tilde{d}_i^h = D_s^h \frac{\exp(V_i^h)}{\sum_{j \in I_s} \exp(V_j^h)}$$

  - D_s^h is the total expected demand for class h and segment s.

- **Spill and recapture effects**: Capacity shortage $\Rightarrow$ passengers may be recaptured by other itineraries (instead of their desired itineraries)
- Recapture ratio is given by: $b_{i,j}^h = \dfrac{\exp(V_j^h)}{\sum_{k \in I_s \setminus i} \exp(V_k^h)}$
- *No-revenue* represented by the subset $I_s^{'} \in I_s$ for segment s.

Estimation results for the demand model

	β_{fare} non-stop	β_{fare} one-stop	β_{time} non-stop	β_{time} one-stop	$\beta_{morning}$
economy	-2.23	-2.17	-0.102	-0.0762	0.0283
business	-1.97	-1.97	-0.104	-0.0821	0.079

- **Price and time elasticity** of demand:

$$E^{P_i}_{price_i} = \frac{\partial P_i}{\partial price_i} \cdot \frac{price_i}{P_i}$$

For a selected OD pair...

- maximum price elasticity among economy itineraries is -2.16, and -1.95 for business.
- maximum time elasticity among economy itineraries is -0.33, and -0.36 for business.

Estimation results for the demand model

- **Value of time (VOT):**

$$VOT_i = \frac{\partial V_i / \partial time_i}{\partial V_i / \partial cost_i} = \frac{\beta_{time} \cdot cost_i}{\beta_{cost}}$$

For the same OD pair...

- VOT for economy, non-stop: 8 €/hour
- VOT for economy, one-stop: 19.8, 11, 9.2 €/hour
- VOT for business, non-stop: 21.7 €/hour

Integrated model - Supply part

$$Max \sum_{s\in S}\sum_{h\in H}\sum_{i\in(I_s\setminus I_s^{'})}(d_i^h - \sum_{\substack{j\in I_s\\ i\neq j}} t_{i,j}^h + \sum_{\substack{j\in(I_s\setminus I_s^{'})\\ i\neq j}} t_{j,i}^h b_{j,i}^h)p_i^h - \sum_{\substack{k\in K\\ f\in F}} C_{k,f}x_{k,f}: \text{ revenue - cost} \tag{1}$$

$$s.t. \sum_{k\in K} x_{k,f} = 1: \text{ mandatory flights} \qquad \forall f\in F^M \tag{2}$$

$$\sum_{k\in K} x_{k,f} \leq 1: \text{ optional flights} \qquad \forall f\in F^O \tag{3}$$

$$y_{k,a,t^-} + \sum_{f\in In(k,a,t)} x_{k,f} = y_{k,a,t^+} + \sum_{f\in Out(k,a,t)} x_{k,f}: \text{ flow conservation} \qquad \forall [k,a,t]\in N \tag{4}$$

$$\sum_{a\in A} y_{k,a,t_n} + \sum_{f\in CT} x_{k,f} \leq R_k: \text{ fleet availability} \qquad \forall k\in K \tag{5}$$

$$y_{k,a,minE_a^-} = y_{k,a,maxE_a^+}: \text{ cyclic schedule} \qquad \forall k\in K, a\in A \tag{6}$$

$$\sum_{s\in S}\sum_{i\in(I_s\setminus I_s^{'})} \delta_{i,f} d_i^h - \sum_{\substack{j\in I_s\\ i\neq j}} \delta_{i,f} t_{i,j}^h + \sum_{\substack{j\in(I_s\setminus I_s^{'})\\ i\neq j}} \delta_{i,f} t_{j,i}^h b_{j,i}^h \leq \sum_{k\in K} \pi_{k,f}^h: \text{ capacity} \qquad \forall h\in H, f\in F \tag{7}$$

$$\sum_{h\in H} \pi_{k,f}^h = Q_k x_{k,f}: \text{ seat capacity} \qquad \forall f\in F, k\in K \tag{8}$$

$$x_{k,f}\in\{0,1\} \qquad \forall k\in K, f\in F \tag{9}$$

$$y_{k,a,t}\geq 0 \qquad \forall [k,a,t]\in N \tag{10}$$

$$\pi_{k,f}^h \geq 0 \qquad \forall h\in H, k\in K, f\in F \tag{11}$$

Integrated model - Demand part

$$\sum_{\substack{j \in I_s \\ i \neq j}} t_{i,j}^h \leq d_i^h : \textit{ total spill} \qquad \forall s \in S, h \in H, i \in (I_s \setminus I_s^{'}) \tag{12}$$

$$\tilde{d}_i^h = D_s^h \frac{\exp(V_i^h)}{\sum_{j \in I_s} \exp(V_j^h)} : \textit{ logit demand} \qquad \forall s \in S, h \in H, i \in I_s \tag{13}$$

$$b_{i,j}^h = \frac{\exp(V_j^h)}{\sum_{k \in I_s \setminus i} \exp(V_k^h)} : \textit{ recapture ratio} \qquad \forall s \in S, h \in H, i \in (I_s \setminus I_s^{'}), j \in I_s \tag{14}$$

$$d_i^h \leq \tilde{d}_i^h : \textit{ realized demand} \qquad \forall h \in H, i \in I \tag{15}$$

$$0 \leq p_i^h \leq UB_i^h : \textit{ upper bound on price} \qquad \forall h \in H, i \in I \tag{16}$$

$$t_{i,j}^h \geq 0 \qquad \forall s \in S, h \in H, i \in (I_s \setminus I_s^{'}), j \in I_s \tag{17}$$

$$b_{i,j}^h \geq 0 \qquad \forall s \in S, h \in H, i \in (I_s \setminus I_s^{'}), j \in I_s \tag{18}$$

Model extension for Clip-Air

- Decision variables for the assignment of wing and capsules:
  $x_f^w \in \{0,1\}$
  $x_{k,f} \in \{0,1\}$ for $k \in \{1,2,3\}$
- Operating cost:

$$\sum_{f \in F} C_f^w x_f^w + \sum_{k \in K} C_{k,f} x_{k,f}$$

- Constraints:

$$\sum_{k \in K} x_{k,f} = 1 \qquad \forall f \in F^M\text{: } \textit{mandatory flights}$$

$$\sum_{k \in K} x_{k,f} \leq x_f^w \qquad \forall f \in F\text{: } \textit{capsule - wing}$$

Example data instance

Data from a major European airline: set of flights, itineraries, aircraft, airports

Airports	3 (CDG, MRS, LYS)
Flights	26
Passengers	1459 (1352 economy, 107 business)
Capsule capacity	31 seats
Standard fleet types	ERJ135 (37), ERJ145 (50), A319 (79), BAE300(100), A318 (123)

	Fixed demand-price	**Integrated model**
Operating cost	160,653	159,774
Revenue	216,149	233,355
Profit	55,496	73,581
Transported pax.	997 (936 E, 61 B)	1006 (948 E, 58 B)
Flight count	22	22
Average pax/flight	45	46
Total Flight Hours	28h50	28h50
Used fleet	1 ERJ135, 4 ERJ145, 1 A319	1 ERJ135, 3 ERJ145, 1 A319
Used capacity	316 seats	266 seats

Impact of the demand model integration

CDG-LYS pair, total demand 253 (226 business, 27 economy), all non-stop.

	class	expected demand	morning	Fixed demand-price: demand	Fixed demand-price: fixed price	Integrated model: demand	Integrated model: realized price
1	E	33	0	34	175	37	183
2	E	33	0	0	175	0	200
3	E	34	1	**37**	175	**50**	175
4	B	7	1	**10**	409.5	**7**	450
5	E	34	1	**40**	175	**30**	200
6	B	7	0	0	409.5	0	450
7	E	33	0	0	175	0	200
8	B	7	0	7	409.5	7	450
9	E	33	0	30	175	30	200
10	E	28	0	29	185	17	185
11	B	6	0	6	425	4	425

TRANSP-OR

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Clip-Air vs Standard planes

	Standard fleet	**Clip-Air**
Operating cost	159,774	178,921
Revenue	233,355	267,957
Profit	73,581	89,036
Transported pax.	1006 (948 E, 58 B)	1136 (1069 E, 67 B)
Flight count	22	26
Average pax/flight	46	44
Total Flight Hours	28h50	33h30
Used fleet	1 ERJ135, 3 ERJ145, 1 A319	9 capsules
	5 aircrafts	6 wings
Used capacity	266 seats	279 seats
Running time	2h45	0h19

Conclusions and future work

- Demand model: Challenging with the available data!
- Integration of demand notion: further analysis of the impacts
- Solution methods for the resulting mixed integer nonlinear problem
  - A Lagrangian relaxation based heuristic is already developed
  - Performance of the method should be tested
- Clip-Air
  - There is a clear potential
  - Multi-modality aspect will be further investigated

Thank you for your attention!

Discrete choice analysis

- Finite and discrete set of alternatives
  - Choice of transportation mode: car, bus, etc.
  - Choice of brand: Leonidas, Lindt, Suchard, Toblerone, etc.
  - Choice of flight: GVA-NCE 10:00, GVA-NCE 06:30, etc.
- Individual n associates a utility to alternative i
- Represented by a random function

$$U_{in} = V_{in} + \varepsilon_{in} = \sum_k \beta_k x_{ink} + \varepsilon_{in}$$

Discrete choice analysis

▸ Choice Model

- Individual n chooses alternative i if $U_{in} \geq U_{jn}$, for all j.
- Utility is random, so we have a probabilistic model

$$P_n(i|C_n) = Pr(U_{in} \geq U_{jn}) = Pr(V_{in} + \varepsilon_{in} \geq V_{jn} + \varepsilon_{jn})$$

- Concrete models require
  - specification of V_{in}
  - assumptions about ε_{in}
  - estimation of the parameters from data