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

Michel Bierlaire, Bilge Atasoy, Matteo Salani, Claudio Leonardi

Transport and mobility laboratory
EPFL

June, 2013

Outline

Outline

Flexibility

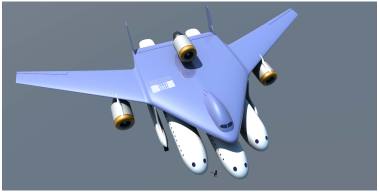
- Flexibility in transportation systems
  - Robustness
  - Demand responsiveness

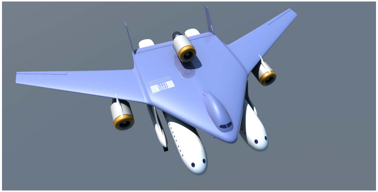
- Rail transportation ⇒ modularity in fleet
- Maritime transportation ⇒ standard unit loads, multi-modality
- Air transportation ⇒ revenue management

Flexibility of Clip-Air

Modularity

Decoupling of wing and capsules





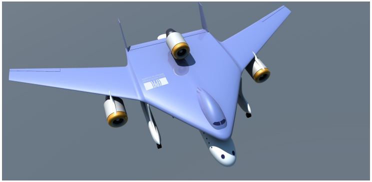


Illustration - Modularity

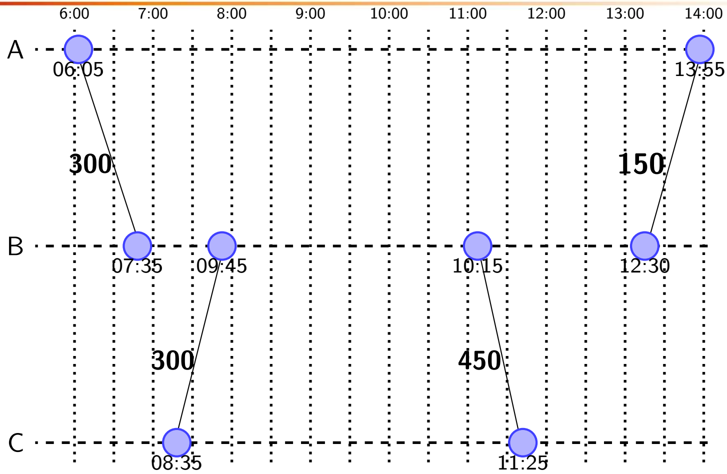
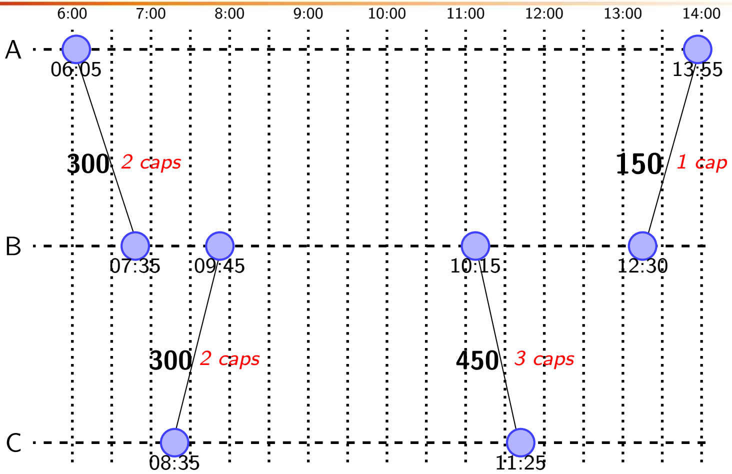
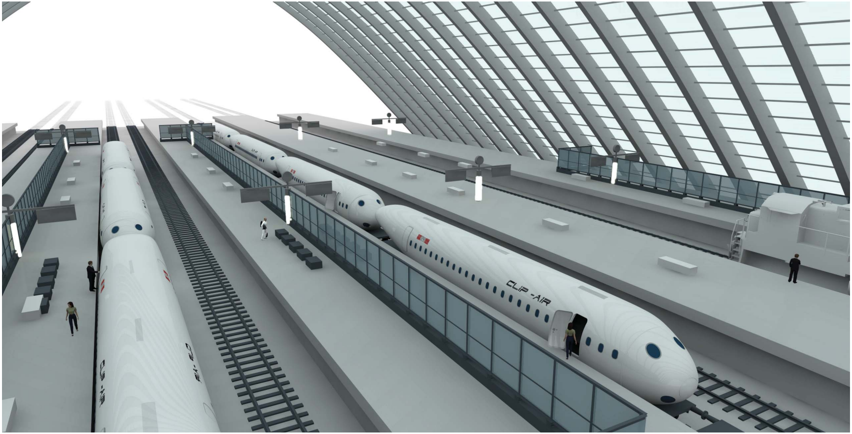


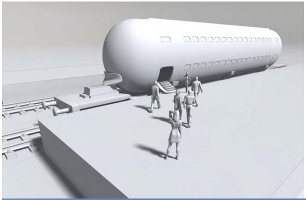
Illustration - Modularity

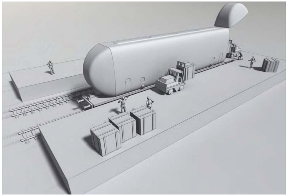


Multi-modality

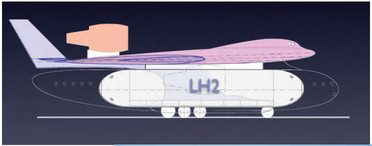


Mixed passenger and cargo





Energy



Outline

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 demand model
  - 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 demand model
  - Spill and recapture
  - Itinerary choice model

  Demand management

Integrated schedule planning model

$$Min \sum_{f \in F} (C_f^w x_f^w + \sum_{k \in K} C_{k,f} x_{k,f}) + \sum_{h \in H} \sum_{s \in S^h} \sum_{i \in (I_s \backslash I_s')} (\sum_{j \in I_s} t_{i,j} - \sum_{j \in (I_s \backslash I_s')} t_{j,i} b_{j,i}) p_i \quad (1)$$

$$s.t. \sum_{k \in K} x_{k,f} = 1 \qquad \forall f \in F^M \quad (2)$$

$$\boxed{\sum_{k \in K} x_{k,f} \leq x_f^w} \qquad \forall f \in F \quad (3)$$

$$y_{a,t^-}^w + \sum_{f \in In(a,t)} x_f^w = y_{a,t^+}^w + \sum_{f \in Out(a,t)} x_f^w \qquad \forall [a,t] \in N \quad (4)$$

$$\sum_{a \in A} y_{a,\mathrm{minE}_a^-}^w + \sum_{f \in CT} x_f^w \leq R_w \quad (5)$$

$$y_{a,minE_a^-}^w = y_{a,maxE_a^+}^w \qquad \forall a \in A \quad (6)$$

$$y_{a,t^-}^k + \sum_{\substack{f \in In(a,t) \\ k \in K}} k \ x_{k,f} = y_{a,t^+}^k + \sum_{\substack{f \in Out(a,t) \\ k \in K}} k \ x_{k,f} \qquad \forall [a,t] \in N \quad (7)$$

$$\sum_{a \in A} y_{a,\mathrm{minE}_a^-}^k + \sum_{\substack{f \in CT \\ k \in K}} k \ x_{k,f} \leq R_k \quad (8)$$

$$y_{a,minE_a^-}^k = y_{a,maxE_a^+}^k \qquad \forall a \in A \quad (9)$$

Integrated schedule planning model

$$Min \sum_{f\in F}(C_f^w x_f^w + \sum_{k\in K} C_{k,f}x_{k,f}) + \sum_{h\in H}\sum_{s\in S^h}\sum_{i\in(I_s\setminus I_s')}(\sum_{j\in I_s} t_{i,j} - \sum_{j\in(I_s\setminus I_s')} t_{j,i}b_{j,i})p_i \quad \text{op. costs + loss of pax.} \qquad (1)$$

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

$$\boxed{\sum_{k\in K} x_{k,f} \le x_f^w} \quad \text{wing-capsule relation} \qquad \forall f\in F \qquad (3)$$

$$y^w_{a,t^-} + \sum_{f\in In(a,t)} x_f^w = y^w_{a,t^+} + \sum_{f\in Out(a,t)} x_f^w \quad \text{flow cons. wings} \qquad \forall [a,t]\in N \qquad (4)$$

$$\sum_{a\in A} y^w_{a,\mathrm{minE}_a^-} + \sum_{f\in CT} x_f^w \le R_w \quad \text{available wings} \qquad (5)$$

$$y^w_{a,minE_a^-} = y^w_{a,maxE_a^+} \quad \text{cyclic wings} \qquad \forall a\in A \qquad (6)$$

$$y^k_{a,t^-} + \sum_{\substack{f\in In(a,t)\\ k\in K}} k\ x_{k,f} = y^k_{a,t^+} + \sum_{\substack{f\in Out(a,t)\\ k\in K}} k\ x_{k,f} \quad \text{flow cons. capsules} \qquad \forall [a,t]\in N \qquad (7)$$

$$\sum_{a\in A} y^k_{a,\mathrm{minE}_a^-} + \sum_{\substack{f\in CT\\ k\in K}} k\ x_{k,f} \le R_k \quad \text{available capsules} \qquad (8)$$

$$y^k_{a,minE_a^-} = y^k_{a,maxE_a^+} \quad \text{cyclic capsules} \qquad \forall a\in A \qquad (9)$$

Integrated schedule planning model

$$\sum_{s \in S^h} \sum_{i \in (I_s \setminus I_s^{'})} \delta_f^i D_i - \sum_{j \in I_s} \delta_f^i t_{i,j} + \sum_{j \in (I_s \setminus I_s^{'})} \delta_f^i t_{j,i} b_{j,i} \leq \pi_{f,h} \qquad \forall f \in F, h \in H \qquad (10)$$

$$\boxed{\sum_{h \in H} \pi_{f,h} \leq \sum_{k \in K} Q \; k \; x_{k,f}} \qquad \forall f \in F \qquad (11)$$

$$\sum_{j \in I_s} t_{i,j} \leq D_i \qquad \forall h \in H, s \in S^h, i \in (I_s \setminus I_s^{'}) \qquad (12)$$

$$x_f^w \in \{0,1\} \qquad \forall f \in F \qquad (13)$$

$$x_{k,f} \in \{0,1\} \qquad \forall k \in K, f \in F \qquad (14)$$

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

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

$$\pi_{f,h} \geq 0 \qquad \forall f \in F, h \in H \qquad (17)$$

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

Integrated schedule planning model

$$\sum_{s \in S^h} \sum_{i \in (I_s \setminus I_s^{'})} \delta_f^i D_i - \sum_{j \in I_s} \delta_f^i t_{i,j} + \sum_{j \in (I_s \setminus I_s^{'})} \delta_f^i t_{j,i} b_{j,i} \leq \pi_{f,h} \quad \textit{demand-supply} \qquad \forall f \in F, h \in H \qquad (10)$$

$$\boxed{\sum_{h \in H} \pi_{f,h} \leq \sum_{k \in K} Q \ k \ x_{k,f}} \quad \textit{k capsules up to 3} \qquad \forall f \in F \qquad (11)$$

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

$$x_f^w \in \{0,1\} \qquad \forall f \in F \qquad (13)$$

$$x_{k,f} \in \{0,1\} \qquad \forall k \in K, f \in F \qquad (14)$$

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

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

$$\pi_{f,h} \geq 0 \qquad \forall f \in F, h \in H \qquad (17)$$

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

Outline

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

Configuration - Comparison with Airbus A320

		A320	**Clip-Air**
Maximum Capacity		150 seats	3x150(450 seats)
Engines		**2** engines	**3** engines
Maximum Aircraft Weight	1 (plane/capsule)	78t	139t (+78%)
	2 (planes/capsules)	2x78t (156t)	173.5t (+11%)
	3 (planes/capsules)	3x78t (234t)	208t (-11%)

Operating costs for *Clip-Air*

- Based on standard flight operating costs
- Adjustment based on weight differences:
  - Fuel costs [1] (25.3% of the total op. cost)
  - 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

[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
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size
- Operating cost of Clip-Air is higher

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 empty capsules 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 empty capsules is ignored
- We ignore potential savings related to 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 empty capsules is ignored
- We ignore potential savings related to 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 empty capsules is ignored
- We ignore potential savings related to maintenance, number of engines
- Only passenger transportation
- Total fleet investment cost is ignored

Conservative Assumptions

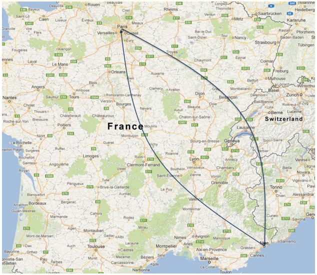
- Fleet composition
  - Standard fleet optimizes the fleet composition
  - Clip-Air capsules are of same size
- Operating cost of Clip-Air is higher
- The repositioning of empty capsules is ignored
- We ignore potential savings related to maintenance, number of engines
- Only passenger transportation
- Total fleet investment cost is ignored
- The schedule and the demand is assumed to remain the same

Towards results

- Input: data from Air France (ROADEF Challenge 2009)
  - 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		
Airports		2
Flights		38
Density (Flights/route)		19
Passengers		13,965
Itineraries		45
Standard fleet types		A320(150), A330(293), B747-200(452)
Results		
	Standard fleet	Clip-Air
Operating cost	1,607,166	1,725,228
Spill costs	604,053	448,140
Revenue	2,419,306	2,575,219
Profit	**812,140**	**849,991 (+4.66 %)**
Transported pax.	**10,276**	**11,035 (+7.39 %)**
Flight count	38	38
Total flight duration	3135 min	3135 min
Used fleet	2 A320 5 A330	7 wings 12 capsules
Used aircraft	7	7
Used seats	1765	1800
ASK	78,388,063	79,942,500
TPASK ($\times 10^-5$)	13.11	13.80



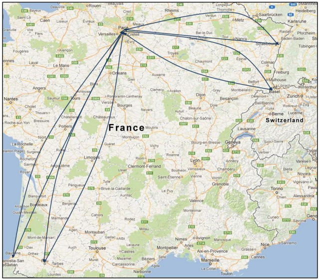
- Aircraft sizes are almost equivalent to 1, 2, 3 capsules
  ⇒ same usage of capacity
- High flight density
  ⇒ improved profit

TRANSP-OR

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Network effects - Hub and spoke

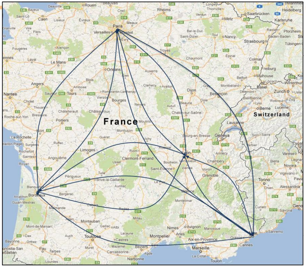
Data		
Airports		5
Flights		26
Density (Flights/route)		3.25
Passengers		9,573
Itineraries		37
Standard fleet types		A320(150), A330(293), B747-200(452)
Results		
	Standard fleet	Clip-Air
Operating cost	817,489	938,007
Spill costs	484,950	393,677
Revenue	1,247,719	1,338,992
Profit	**430,230**	**400,985 (- 6.80 %)**
Transported pax.	**5,031**	**5,721 (+ 13.71 %)**
Flight count	**24**	**22**
Total flight duration	**1850 min**	**1700 min**
Used fleet	5 A320 2 A330 1 B747	6 wings 12 capsules
Used aircraft	**8**	**6**
Used seats	1788	1800
ASK	**46,860,500**	**43,350,000**
TPASK ($\times 10^{-}5$)	**10.74**	**13.20**



- Low flight density
  - ⇒ less potential
  - ⇒ lower profit

Network effects - Peer-to-peer network

Data		
Airports		4
Flights		98
Density (Flights/route)		8.17
Passengers		28,465
Itineraries		150
Standard fleet types		A320(150), A330(293), B747-200(452)
Results		
	Standard fleet	Clip-Air
Operating cost	3,189,763	3,117,109
Spill costs	982,556	978,683
Revenue	5,056,909	5,060,782
Profit	**1,867,146**	**1,943,673 (+ 4.1 %)**
Transported pax.	**20,840**	**21,424 (+ 2.8 %)**
Flight count	91	84
Total flight duration	6650 min	6160 min
Used fleet	7 A320 10 A330 3 B747	13 wings 28 capsules
Used aircraft	20	13
Used seats	**5336**	**4200 (- 21.3 %)**
ASK	**502,695,667**	**366,520,000**
TPASK ($\times 10^{-5}$)	**4.15**	**5.85**



- High flight density
- Better connected network
  - ⇒ increased potential
  - ⇒ higher profit
  - ⇒ less allocated capacity
  - ⇒ significantly less aircraft

TRANSP-OR

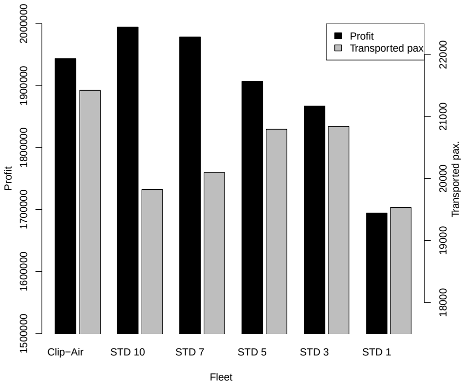
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Network effects

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

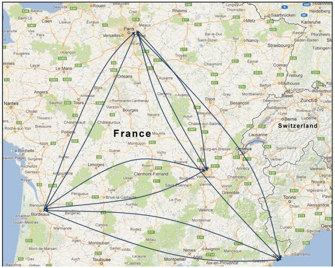
Fleet composition

The same data as peer-to-peer network
Clip-Air always carries more passengers
Standard fleet has more profit when the fleet is highly heterogeneous



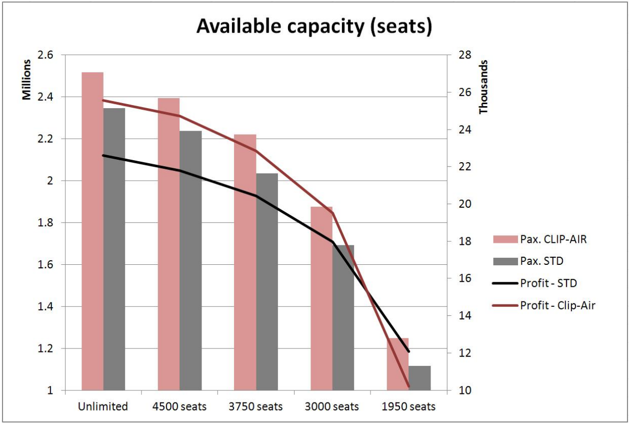
Available capacity

Airports	5
Flights	100
Density (Flights/route)	6.25
Passengers	35,510
Itineraries	140
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)



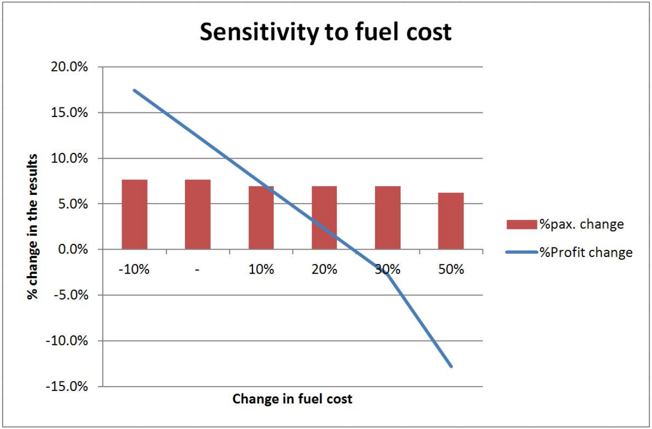
Available capacity

Constraint on the total number of seats for the assigned fleet



Sensitivity analysis on the cost of Clip-Air

The same data used for the test on the available capacity



Outline

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
- 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
- Results are robust to the cost values of Clip-Air
- Atasoy, B., Salani, M., Bierlaire, M., and Leonardi, C. (2013). Impact analysis of a flexible air transportation system, European Journal of Transport and Infrastructure Research 13(2): 123-146.

Outline

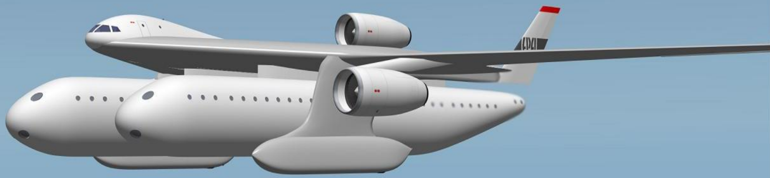
Different wing and capsule sizes

- 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 transfered 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

Model

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

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

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

TRANSP-OR

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Spill and recapture

	class	nonstop	morning	time	price	V
A-B_1	E	0	1	250	300	-2.67
A-B_2	E	0	0	250	300	-2.70
A-B_3	E	1	0	80	200	-1.68
A-B_4	E	1	1	80	200	-1.65
A-B'	E	1	1	80	225	-1.92

	A-B_1	A-B_2	A-B_3	A-B_4	A-B'
A-B_1	-	0.113	0.314	0.323	0.250
A-B_2	0.116	-	0.314	0.322	0.248
A-B_3	0.146	0.141	-	0.403	0.310
A-B_4	0.147	0.143	0.396	-	0.314