FCTUC DEPARTAMENTO DE ENGENHARIA CIVIL
FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

MIT|Portugal

Congestion Management of Transportation Systems on the Ground and in the Air
Asilomar, California, USA
June 27-29, 2011

Optimization-based analysis of slot allocation strategies for EU airports

João P. Pita
António P. Antunes

Comments and suggestions from Profs Amedeo Odoni and Cynthia Barnhart (MIT) are thankfully acknowledge

Summary

1. Motivation
2. Problem
3. Optimization Model
4. Application
5. Conclusion
6. Future Work

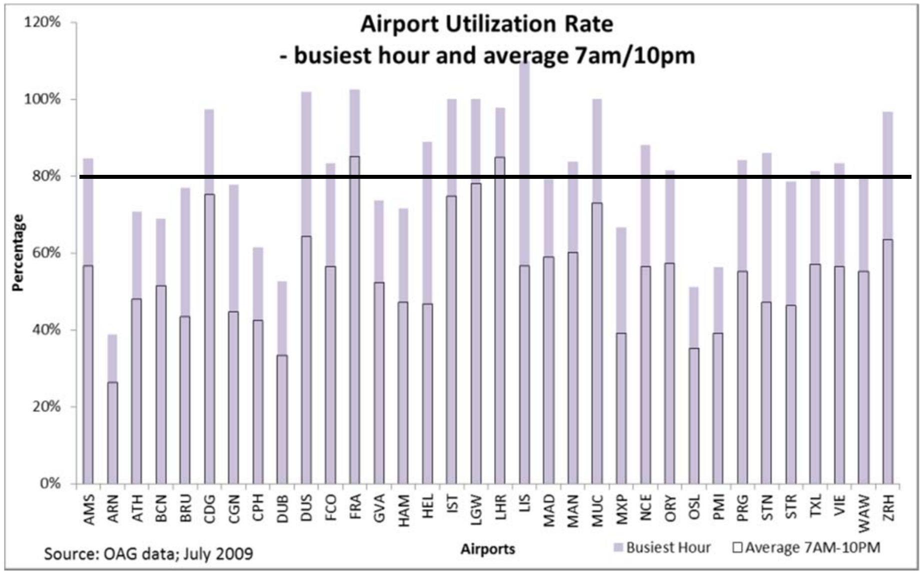
Motivation [1/2]

1. The increase in passenger demand and airport utilization has led to airport congestion
   a. 33 minutes was the average delay time per delayed flight in Europe (2010)
   b. 23% of flights in Europe (2010) were delayed > 15 min (CODA,2011)
   c. $ 28.9 billion was estimated as the direct cost of delays in the US (2007)
   d. $ 4.0 billion was estimated as the impact in the US GDP of air transportation delays (2007)

2. Airport slots are needed to control airport usage
   a. Limit airport capacity using administrative measures
   b. Slot allocation is based on grandfather rights and the lose-it-or-lose-it rule

Motivation [2/2]

3. Congestion increases exponentially when airport utilization is above 80% / 85%
   a. Several European airports operate at capacity throughout the day
   b. At peak periods a greater number of airports operate at capacity
   c. Average utilization rate is much lower than peak utilization rate



Problem [1/4]

Initial Research Questions

1. Is it possible to satisfy the current passenger demand with less cost to the air transportation system (including passengers) without compromising the airline competition and profitability?
2. Is it possible to reduce and/or reorganize the number of slots at the airports to reduce the delay time without losing a "big portion" of passenger demand?

Possible contributions of this research

1. Give insights about the use of airport capacity in congested airports
2. Help strategic decisions regarding slot allocation process

Problem [2/4]

Initial Assumptions

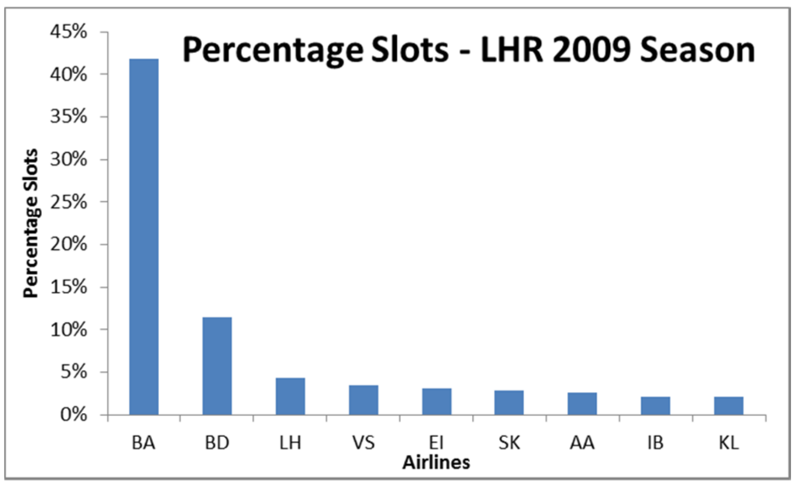
1. A set of airlines compete in an air transportation network;
2. Each airline has a given number of slots per airport (can be time-fixed or not)
3. Airport and vehicle costs per aircraft type are known
4. Unit delay costs per aircraft and passenger are known
5. Demand per leg, airline, and demand period is known
6. Demand that is not satisfied can be recaptured by other airlines
7. The expected delay time per airport and time period is known

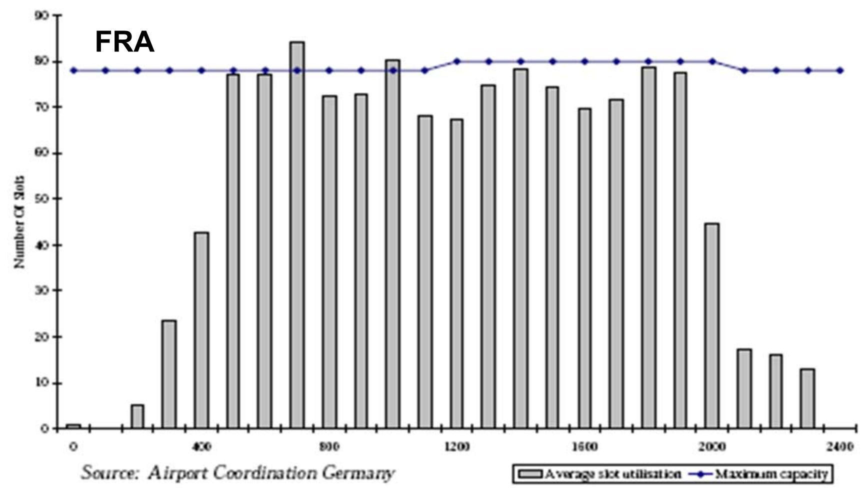
Problem [3/4]

Airport Capacity and Slot Allocation

Airport Capacity → Runway / Terminal / Air traffic control ← **Slots per Unit of Time**

Slots are used to regulate the airport capacity



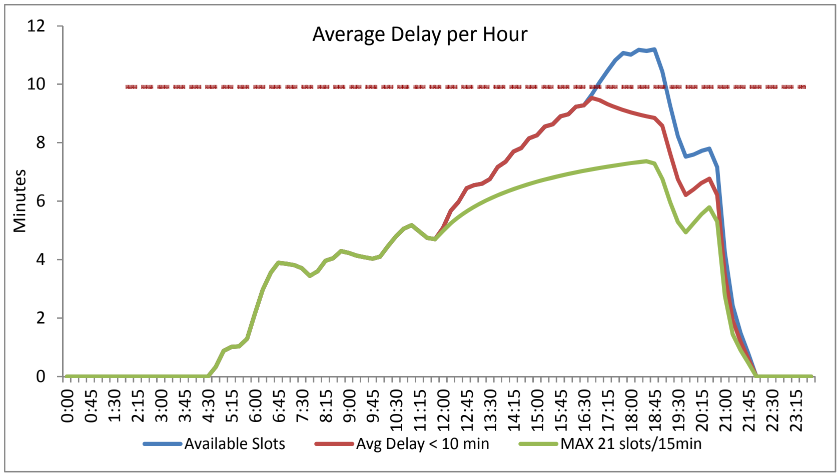


Old flag carriers still have a dominant position in “home” airports

Even when demand for slots is above capacity, airport capacity is not totally used

Problem [4/4]

Airport Utilization and Expected Delay Time



LHR Airport		Current Slots	Avg. Delay <10min		Max 21 slots/ 15 min	
Demand		1367	1362	0,37%	1352	1,10%
Capacity		2112	2112	0,00%	2112	0,00%
TotalDelay		8625,92	8044,73	6,74%	6880,25	20,24%
Maximum Delay (min)		11,29	9,57	15,23%	7,39	34,54%
Average Delay (min)		6,31	5,91	6,34%	5,09	19,33%
% flights delayed more than	5 min	614,55	585,78	4,68%	523,41	14,83%
	10 min	321	292,38	8,92%	232,01	27,72%
	15 min	153,87	132,92	13,62%	90,88	40,94%
	20 min	81,73	67,57	17,33%	40,7	50,20%

- **DELAYS©** - is a stochastic and dynamic queuing model developed at MIT (Odoni and Malone)
- Small slot reduction/reallocation can reduce significantly the delay time
- Reduction/reallocation of slots needs to be done in a “fair” way to airlines

If airport capacity was limited below current value would be possible to satisfy the current demand?

Optimization Model [1/2]

Objective Function – minimize network costs

$$\min Cost = \sum_{j,k\in A}\sum_{c\in C}\sum_{f\in F}\sum_{t\in T}\left(c_{Vjk}\times x_{jkcft} + c_{Aj}\times x_{kjcft}\right)\times s_{Vf} +$$

$$\sum_{j,k\in A}\sum_{c\varepsilon C}\sum_{f\varepsilon F}\sum_{t\varepsilon T} c_{Dj}\times d_{Tjkt}\times x_{jkcft}\times s_{Vf} +$$

$$\sum_{j,k\in A}\sum_{t\varepsilon T}\sum_{c\varepsilon C} c_{Tjk}\times\left(d_{Tjkt} - s_{Pjkc}\right)\times p_{jkct} +$$

$$\sum_{j,k\in A}\sum_{p\varepsilon P}\sum_{c\varepsilon C}\left(q_{jkcp} - \sum_{t\varepsilon T_P} p_{jkct}\right)\times a_{Fjk} +$$

$$\sum_{j,k\in A}\sum_{c\in C}\sum_{p\in P}\sum_{v\in V} c_{Sjk}\times p_{Tjkcpv}\times s_{Dv}$$

Vehicle / Airport Costs per flight-leg

Aircraft delay cost

Passenger delay cost

Spill costs

Schedule delay costs

Capacity Constraints – airline movements per airport cannot exceed airline slots

$$\sum_{k\in A}\sum_{f\in F} x_{jkcft} + x_{kjfc,t-t_{kj}} \le s_{jct}\ ,\ \forall j\in A, c\in C, t\in T$$

Optimization Model [2/2]

Demand Equations – passengers per leg cannot exceed demand

$$\sum_{c \in C} \sum_{t \in T_P} p_{jkct} \leq \sum_{c \in C} q_{jkcp}, \forall j,k \in A, p \in P$$

$$\sum_{t \in T_P} p_{jkct} \geq q_{jkcp} \times (1 - \alpha_{jk}), \forall j,k \in A, c \in C, p \in P$$

$$\sum_{t \in T_P} p_{jkct} \leq q_{jkcp} \times (1 + \alpha_{jk}), \forall j,k \in A, c \in C, p \in P$$

α – maximum variation from current airline demand per leg

α=5% – airline can gain/lose up to 5% of passenger demand in that leg

Schedule Delay – frequency per leg is used as proxy of average schedule delay time

$$\sum_{f \in F} a_{Sjkcpf} \leq 1, \forall j,k \in A, c \in C, p \in P$$

$$p_{jkct} \leq \sum_{f \in F} a_{Sjkcpf} \times s_{Vf}, \forall j,k \in A, c \in C, p \in P, t \in T_P$$

$$x_{jkcft} \leq a_{Sjkcpf}, \forall j,k \in A, c \in C, f \in F, p \in P, t \in T_P$$

Application [1/6]

Network – 10 busy European Airports

Slots per airline and airport

Airlines	AMS	BCN	CDG	FCO	FRA	LHR	MAD	MUC	VIE	ZRH	Total
AF	14	16	126	12	16	14	20	14	8	12	252
BA	12	10	16	10	12	104	10	14	8	12	208
IB	8	84	0	10	8	22	138	8	4	6	288
KL	104	12	14	10	8	16	12	12	8	12	208
LH	28	22	36	24	132	36	16	120	20	22	456
LX	8	6	12	8	10	12	6	8	8	78	156
OS	8	4	6	4	8	8	0	8	54	8	108
U2	0	4	8	0	0	0	4	0	0	0	16
Other	31	80	22	67	20	17	65	11	38	7	358
Total	213	238	240	145	214	229	271	195	148	157	2050

Airport Demand, Capacity, and Average Delay

Indicators	AMS	BCN	CDG	FCO	FRA
Origin (pax/day)	15168	15878	16747	12511	12551
Destination (pax/day)	14149	15560	15259	13327	13226
Declared Cap. (mov/h)	106	60	112	88	80
Average Delay (min)	0.67	0.51	2.09	0.79	3.36
	LHR	MAD	MUC	VIE	ZRH
Origin (pax/day)	17670	16940	9670	8239	9401
Destination (pax/day)	18018	18111	10294	8296	9143
Declared Cap. (mov/h)	88	90	90	66	68
Average Delay (min)	4.38	0.62	2.07	1.18	2.56

- 10 airports for Friday 17th July 2009
- 8 airlines + 1 (other airlines)
- Total flights – 1025
- Total passengers – 99446
- Average seat per leg and airline – flight database
- Demand per leg – EUROSTAT data for July 2009;

The model assumes that the flights outside the network stay the same

Application [2/5]

Daily Demand (per leg)

Daily demand per leg (July 2009)

Origin	Destination									
	AMS	BCN	CDG	FCO	FRA	LHR	MAD	MUC	VIE	ZRH
AMS	0	1599	1624	813	987	1836	1315	888	748	786
BCN	1474	0	1251	1007	754	1017	4375	675	387	415
CDG	1638	1326	0	2140	1608	1678	1261	1229	1045	1154
FCO	786	1005	1458	0	774	1248	1325	520	394	432
FRA	776	721	1261	793	0	1944	1453	1364	1219	772
LHR	1682	981	1605	1301	1978	0	1582	1398	800	1494
MAD	1141	3909	1491	1261	1388	1569	0	726	205	707
MUC	809	611	1089	459	1334	1360	707	0	662	437
VIE	717	400	983	408	1217	818	222	711	0	946
ZRH	896	429	1060	495	861	1207	647	512	991	0

Passenger Delay Cost

$$c_P = 0.77 \text{ (€/min/pax)}$$

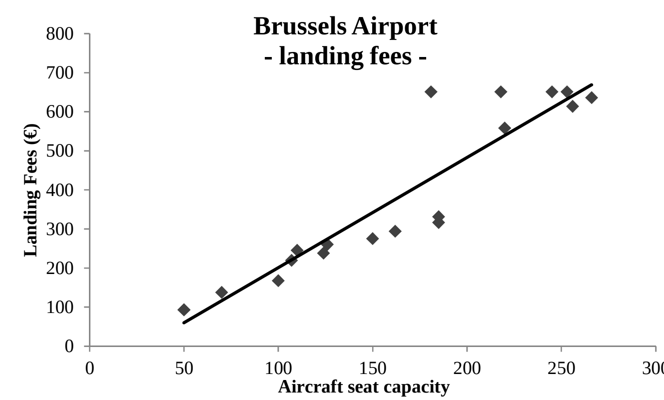
Flight Delay Cost

$$c_F = 8 + 0,75 \times (s_v - 40) \text{ (€/min/flight)}$$

Vehicle and Airport Costs

- Landing fees are used as airport costs
- Vehicle costs were addapted from literature:

$$c_V = (d_{jk} + 722) \times (s_v + 104) \times 0,019 \text{ (€/flight)}$$



Application [3/5]

Type of results to compare from current situation

- Number of flights (leg and airline)
- Delay time and cost
- Demand transfer between airlines
- Airport costs
- Passenger schedule delay

Several situations will be tested

Base Scenario:

- Fixed number of slots (current situation) → Limited pax demand transfers → Variable avg seat

Alternatives:

- Changes in the number of slots ("pick the best")
- Free pax demand transfers
- Fixed avg seat

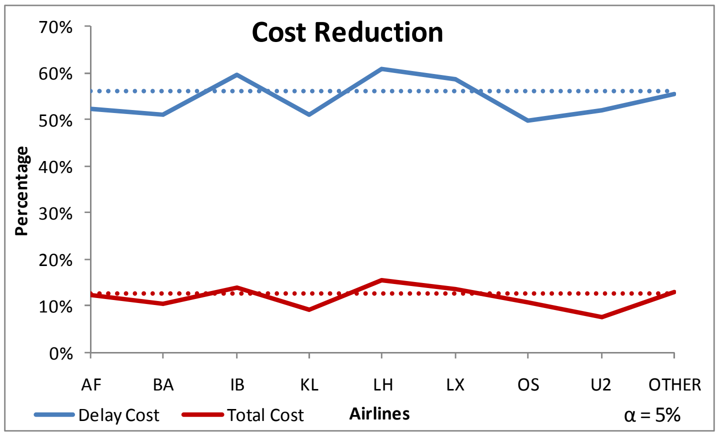
**LOWER DELAY LEVEL
INCREASE AVG SEATS**

**AIRLINE EQUITY
AIRLINE COMPETITION**

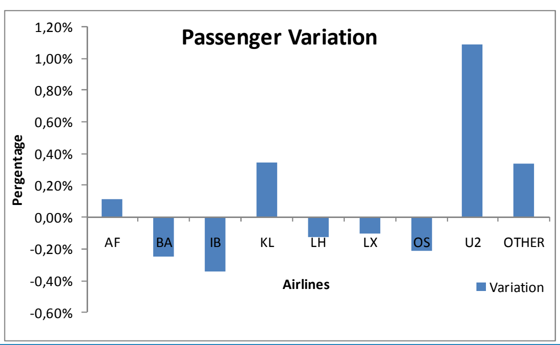
**LOAD FACTOR
DECREASE FREQUENCY**

Application [4/5]

Results – base scenario [α = 5% ; fixed slots]



975 flights -4,88%
101,32 seats/flight +4,01%



Total cost decreases 13,12%

LH – 16,59% (biggest)

U2 – 7,52% (lowest)

Delay cost decreases 56,36%

LH – 61,85% (biggest)

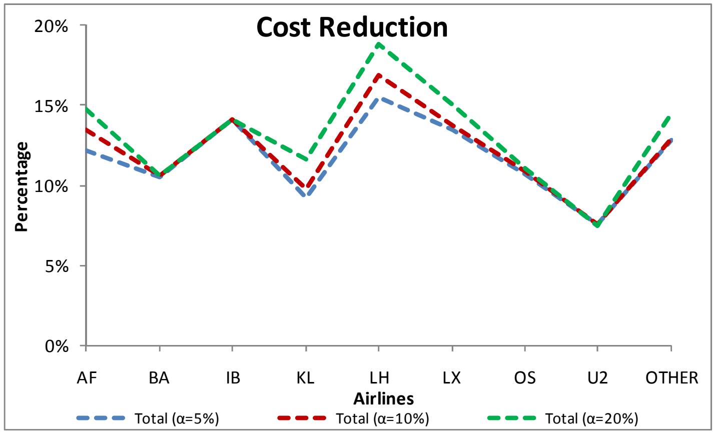
OS – 50,32% (lowest)

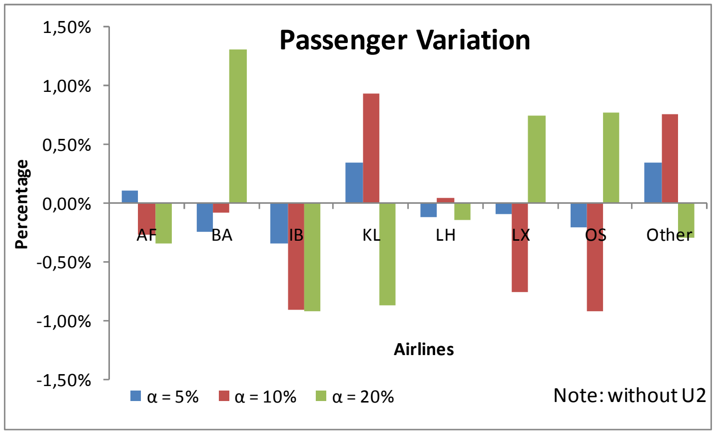
Passenger variation is nil (all demand must be satisfied)

U2 – 1,08% (biggest) / IB – - 0,34% (lowest)

Application [5/5]

Results – different maximum passenger variation





Total cost decreases with the increase in α

- Cost drops 10% from α = 0% to α = 5%
- But only 2,5% from α = 5% to α = 20%

Delay cost decreases 6,7 % (α=0% to α=20%)

- α = 0% – 50,56% decrease
- α = 20% – 57,33% decrease

Average seat per flight increases 4% - 5%

- Except for α = 20% – + 7,08%

Passenger variation between airlines always below 1,5% except for U2 – very small number of passengers

- U2 – 1,08% (α = 5%) ; 4,73% (α = 10%) ; 9,21% (α = 20%)

"Free variation" gives the same results that α=20%

Conclusions

Total cost in the system can be reduced mainly by decreasing delay costs

a. Delay cost can be reduced to 6% of total costs (from 9%)
b. This reduction is achieved without passenger spilling
c. Delay cost decrease is well-distributed between the airlines

Reduction in flights is much lower than reduction in total cost

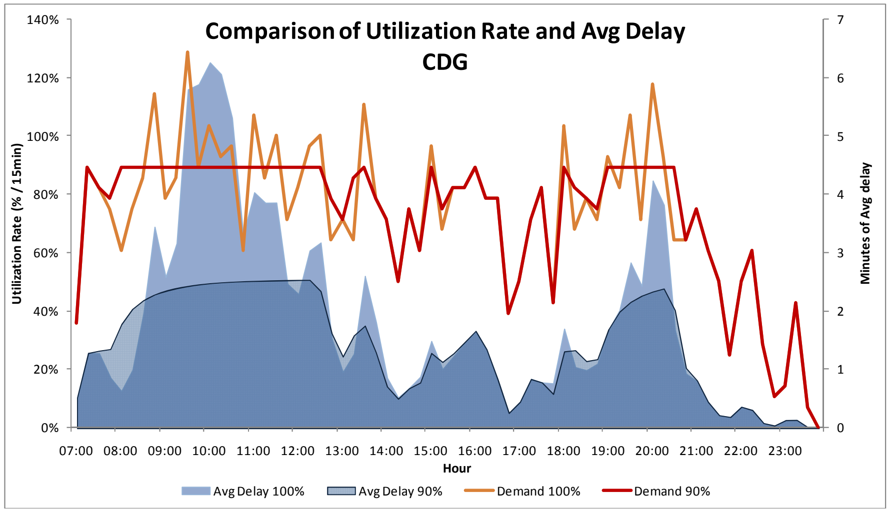
a. Flight reduction is higher in busiest periods and at the busiest airports
b. Passenger transfer between airlines is small – not compromising airline market power
c. Average seat per flight increases, in most of cases, by margin up to 5%;

Biggest airlines have biggest reduction in delay costs

a. More slots in each airport, more capacity to change flight time;
b. Influence of delay cost is higher for the biggest airlines – thus greater reduction in delay cost
c. Passenger variation is negative to the biggest airline – better to promote competition

Future Work

Changing Slots – limiting max utilization to 90% current slots



Slots per airline and airport											
Parameters		Airports									
		AMS	BCN	CDG	FCO	FRA	LHR	MAD	MUC	VIE	ZRH
Capacity (slot/15m)	100%	28	23	28	23	21	22	30	23	18	15
	90%	25	20	25	20	18	19	27	20	16	13
Periods > 90%		5	1	16	4	29	31	3	19	1	17
Reassigned Slots		11	3	65	7	96	135	12	71	1	35
Avg Delay	100%	0,67	0,51	2,09	0,79	3,36	4,38	0,62	2,07	1,18	2,56
	90%	0,63	0,5	1,57	0,56	2,29	2,47	0,57	1,59	1,18	1,95
Max Delay	100%	2,67	2,23	6,32	2,43	7,65	8,8	2,57	6,86	2,83	8,01
	90%	1,9	1,57	2,54	2,09	2,45	2,47	1,61	2,44	2,83	3,57

1. Slots are changed by minimizing the total changing time in each airport;
2. Modification in the optimization model:

$$\sum_{c \in C} s_{jct} \leq S_{jt}^{MAX} + \Delta s_{jct}, \forall j \in A, t \in T$$
$$\Delta s_{jct} \ is\_free$$

3. Each airline retains the same number of slots ;
4. Demand still needs to be satisfied in the corresponding demand period;
5. Expected delay times are updated to the new values;

FCTUC DEPARTAMENTO DE ENGENHARIA CIVIL
FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

MIT|Portugal

Congestion Management of Transportation Systems on the Ground and in the Air
Asilomar, California, USA
June 27-29, 2011

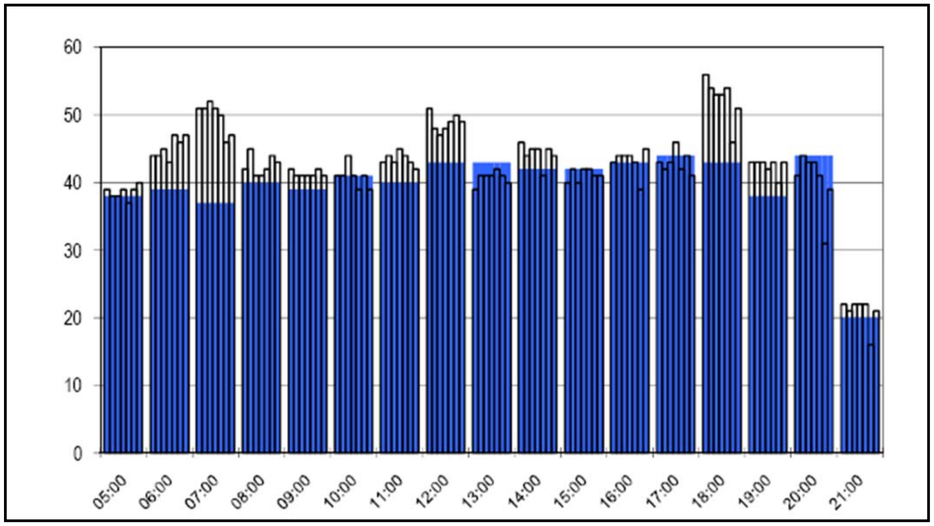
Optimization-based analysis of slot allocation strategies for EU airports

João P. Pita
António P. Antunes

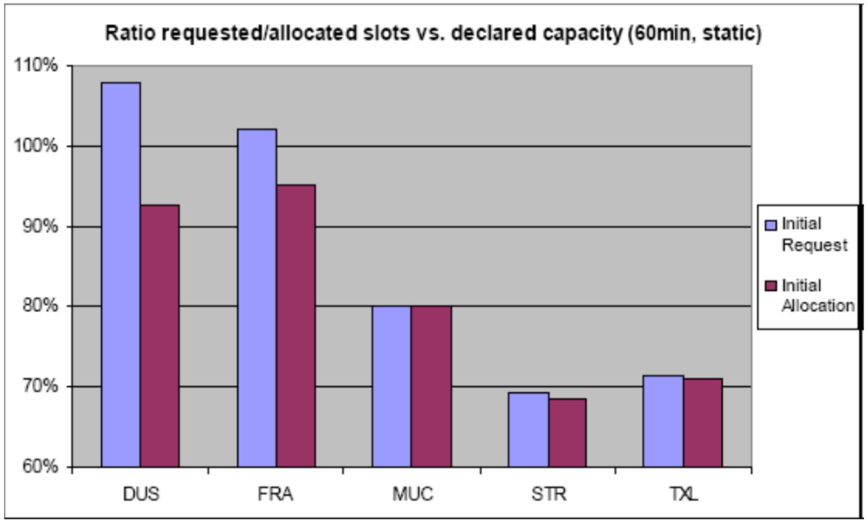
Financial support from Fundação para a Ciência e Tecnologia through the MIT-Portugal Project - *AirNets* Project - and scholarship SFRH/BD/43060/2008

Motivation []

5. Demand is higher than capacity in the busiest airports
    a. Requests for slots are above capacity at peak periods
    b. In those cases, assigned slots do not correspond to airline requests
    c. Airport capacity is “lost” even in airports where demand is higher than capacity



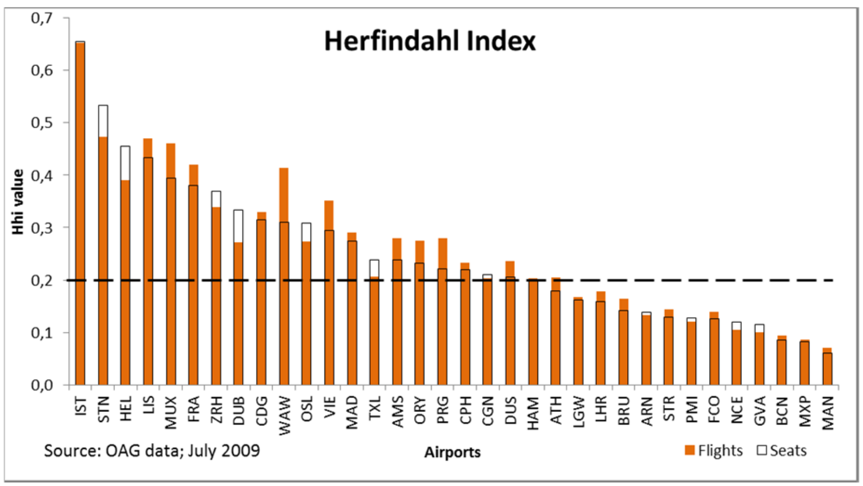
ACL, 2009



Aachen University, 2007

Motivation []

6. Market concentration is very strong in most of the busiest airports in Europe
   a. More than half (20) of the 34 biggest airports in Europe can be seen as "market-concentrated"
   b. Top-5 airlines have more than 70% of slots in all airports
   c. Biggest airline in 30 of the 34 airports is a country-based airline
   d. In those 4 airports the leading carrier is a low-cost carrier



Problem [5/5]

Possible contributions of this research

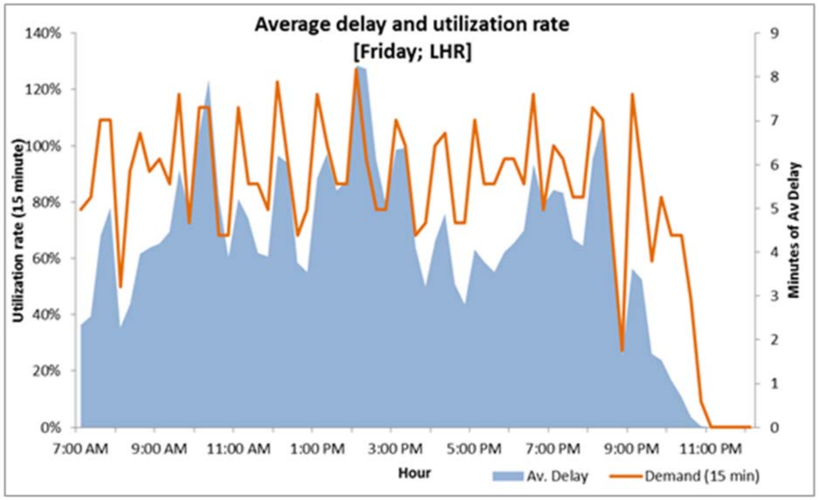
1. Give insights about the use of airport capacity in congested airports

2. Help strategic decisions regarding slot allocation process

3. Analyze the impact of a change in the landing fee scheme

Application []

Delay time and cost



Airport Demand, Capacity, and Average Delay

Indicators	Airports				
	AMS	BCN	CDG	FCO	FRA
Origin (pax/day)	15168	15878	16747	12511	12551
Destination (pax/day)	14149	15560	15259	13327	13226
Declared Cap. (mov/h)	106	60	112	88	80
Average Delay (min)	0.67	0.51	2.09	0.79	3.36
	LHR	MAD	MUC	VIE	ZRH
Origin (pax/day)	17670	16940	9670	8239	9401
Destination (pax/day)	18018	18111	10294	8296	9143
Declared Cap. (mov/h)	88	90	90	66	68
Average Delay (min)	4.38	0.62	2.07	1.18	2.56

- DELAYS© was used to get the average primary delay per flight and airport in each 15-minute time period
- Average primary delay is used as input to the optimization model
- To account for delay propagation we use multipliers
- Delay cost values were adapted from Cook et al. (2011):

Passenger Delay Cost

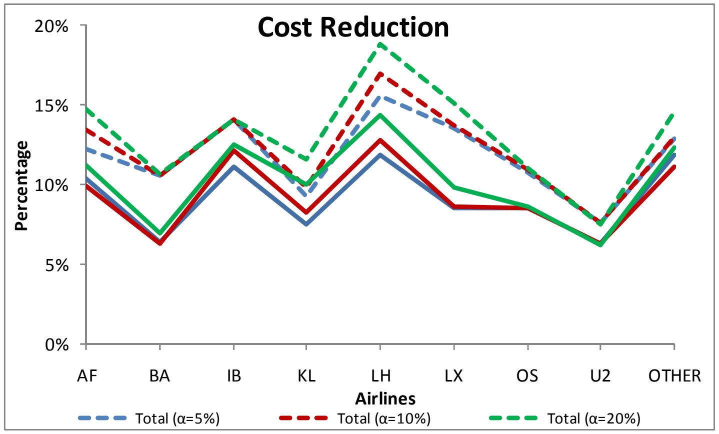
$$c_P = 0.77 \text{ (€/min/pax)}$$

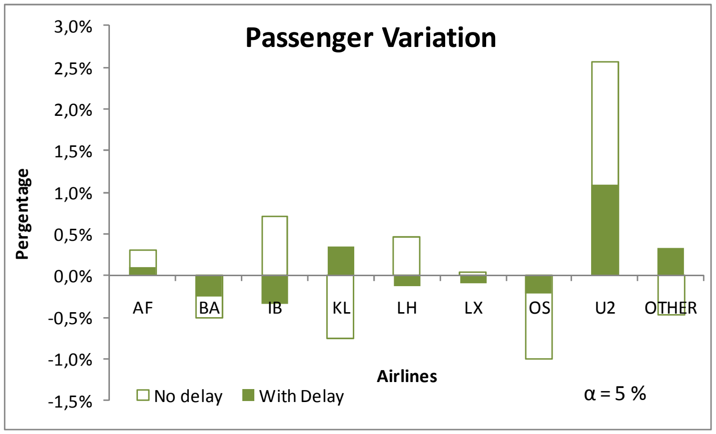
Flight Delay Cost

$$c_F = 8 + 0{,}75 \times (s_v - 40) \text{ (€/min/flight)}$$

Application []

Results – optimization without delay cost





Total cost decreases <u>but less</u> than when optimizing considering delay costs

- average decrease is 4,67% lower than with delay costs
- highest difference is with α = 20% (5,20%)

Delay cost decreases up to 10 % comparing with > 50%

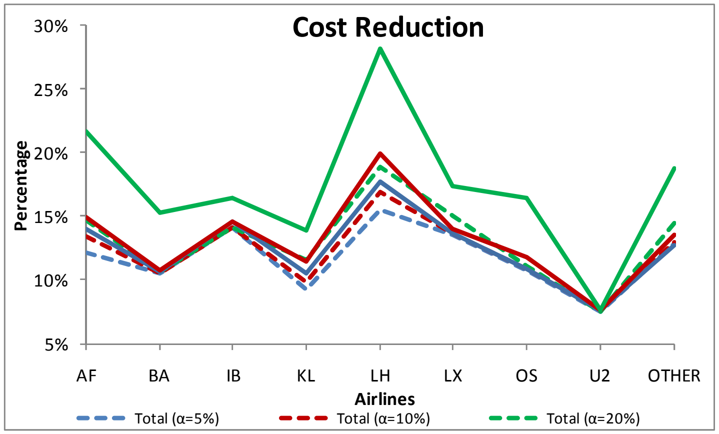
- very close to total cost decrease
- related with the decrease in flights (same decrease)

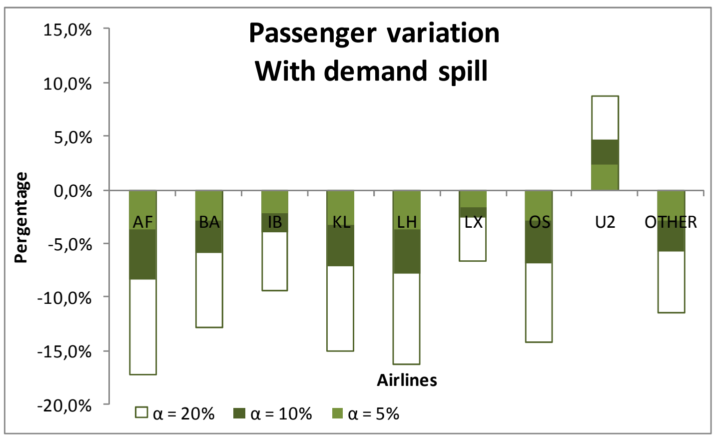
Passenger (flight) variation between airlines is higher

- α = 5% average variation 0,76% (0,32%)
- α = 10% average variation 1,26% (1,04%)
- α =20% average variation 2,54% (1,62%)

Application []

Results – demand can be spilled up to a limit [5% ; 10% ; 20%]





Total cost is reduced between 13.67% and 19.46%

- Highest difference is with α = 20%
- Decrease from base scenario is only 0,54% [α = 5%]

Demand spill is much lower than the limit value [α]

- 2,95% with 5,85% flight reduction (α = 5%)
- 6,13% with 7,02% flight reduction (α = 10%)
- 12,98% with 13,05% flight reduction (α = 20%)

Delay cost decreases between 57,68% and 63,83%

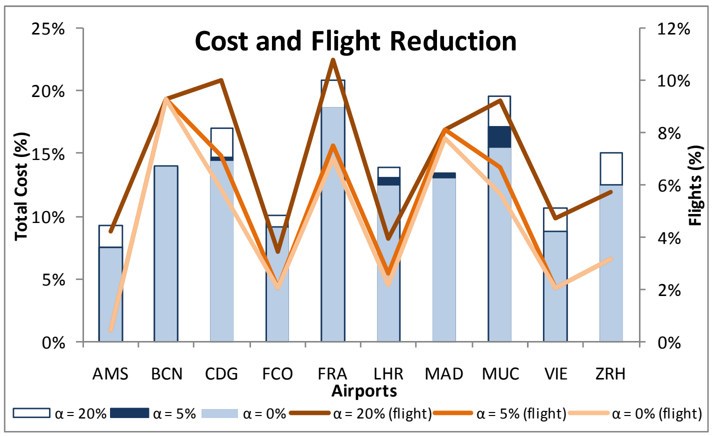
- Average decrease is 7% higher than in the base scenario (for equal α)

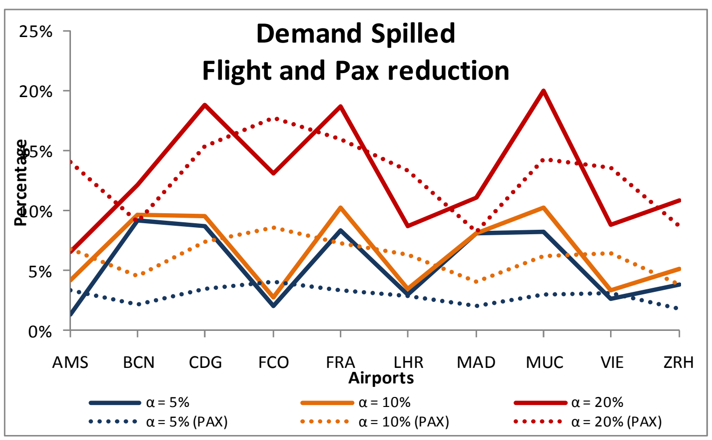
Passenger variation is negative for all airlines except U2

- Highest drops for the biggest airlines [AF, LH, and KL]

Application []

Results – overview of the impact to the airports





Decrease in cost is higher in the busiest airports

- Highest drop is with α = 20% – FRA (20,75%)
- BCN and MUC – cost decrease are related with flight reduction (high frequency is internal legs)

Delay cost can represent more than 10% of airport costs

- Values vary very significantly between airports
- Lowest values for BCN, AMS, and FCO;
- Highest values for LHR, FRA, ZRH, and CGD;

When demand can be spilled:

- Busiest airports with higher losses in flights and passengers;
- Flight reduction with α = 20% is very significant;