How close are we to the "Capacity Crunch"? - An Assessment of European Airport System Capacity, Demand and Delay

In Europe, there is a great concern among the air transport industry that we are close to the "capacity crunch" referring to the currently existing airport capacity or airport infrastructure under construction. Especially regarding runway capacity, there are worries that it will not be able to meet the projected demand for air travel from around 2020 onwards, without further investments. At the most congested European hub-airports the situation is already critical today. Some of the biggest European hubs, especially London-Heathrow (LHR) and Frankfurt am Main (FRA) airports already operate close to capacity during the core hours, between 6 am and 11 pm. The increasing demand will eventually result in crowded airport facilities and longer waiting periods and therefore in extended travel times for the traveller and lower levels of service. When demand is permanently so close to capacity, any further growth at those airports is limited and chaotic conditions are almost certain, e.g. during random weather events, like snow, winds, minor runway incursions or temporarily airspace closure due to volcanic ash clouds, as we have seen these days.

In order to allow more growth and being able to meet level-of-service standards, the only options are extending existing capacity by building new infrastructure including runways, apron area or passenger facilities. With regard to the recent volcanic ash events it is to say that airports clearly need "emergency exits" that allows trapped passengers in airport terminal buildings to leave the airport through alternative traffic modes quickly. Excellent rail and highway accesses are utterly important and constant investments in the infrastructure of such airport access modes must be politically controlled and maintained.

In the case of runway capacity, airports bridge the time until investment and construction of new infrastructure, i.e. runways, by firstly attracting increasingly bigger airplanes with more seats and high payload or secondly by the freeing of unused capacity by shifting additional traffic to periods with less traffic, so called off-peak periods. This can be steered by flexible (congestion) landing fees or other incentives.

Due to the resistance of nearby residents and environmental organisations, the airport runway approval and construction lead time has become a lengthy process, taking up to ten years time. This means long-sighted planning of such investments.

The first part of this article deals with the methodology for order-of-magnitude estimations of annual, daily and hourly capacities for a choice of airports. It will guide through the necessary steps and will present data requirements and sources, which lead to a good foundation for airport capacity analyses.

The second part looks at capacity utilization, idle capacity and delay of European airports. Based on the demand and capacity figures from the first part, this article delivers a popular deterministic delay-estimation model, which we apply exemplarily to Barcelona airport. The "model" bases on cumulative graphs of demand and delay, which give insights into the development of predictable queues and delays.

A Simple Approach to Airport Capacity and Delay

The following article presents results from a recent study of the runway capacity of 33 congested European airports on peak days in the years 2007 to 2009. The airport sample represents more than 80% of total handled passengers in Europe. "Congested airport" in this context means the airports under study are at least 75% utilized, so capacity is 25% higher than demand, over longer periods of time and demand is approaching capacity in peak times. Demand over capacity, the capacity utilization, is therefore between 75% and 100%.

Further growth of traffic at congested airports will result in increasing delays. The fundamental relationship between capacity, demand and delay we present in Fig. 1. In the presented study the *available slots* correspond to the *practical capacity* and the maximum possible flights under Instrument Flight Rules (IFR) the *IFR Capacity* (IFR CAP) corresponds to the *ultimate capacity*.

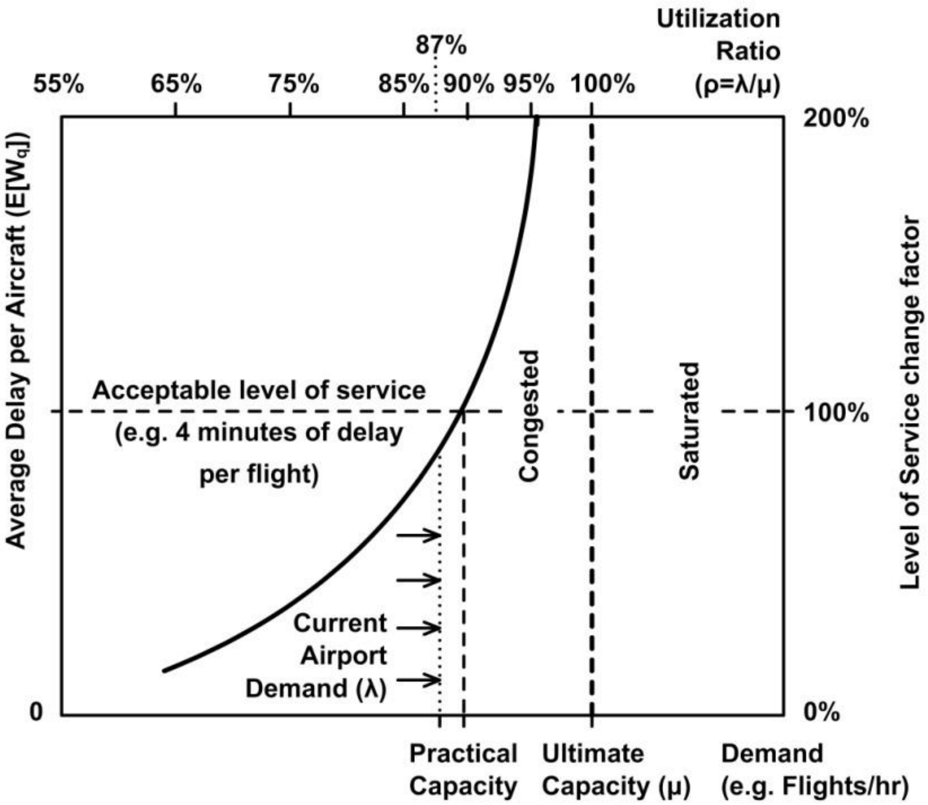


Fig. 1: Relationship between Demand, Capacity and Delay (Own Illustration based on Horonjeff 2010, p. 488)

By studying traffic capacity and demand at an airport during peak periods, it is possible to get an overview about the current minimum amount of daily available idle capacity and average delays. The relationship between demand, capacity and delay we present on an annual, daily and hourly basis.

We choose the following five different kinds of capacity measures, expressed in flight operations per year, day or hour (Table 1):

Time Frame	Capacity Description	Short Form	Method/Data Source
Annually	Annual Service Volume	ASV	FAA AC 150/5060-5
Daily	Runway Capacity under Instrumental Flight Rules during Design Peak Day	DPD IFR CAP	FAA AC 150/5060-5
Daily	Slots per Day during Core hours (from 6h to 23h)	DPD Slots	National Slot Coordination
Hourly	Runway Capacity under Instrumental Flight Rules (IFRCAP)	DPH IFR CAP	FAA AC 150/5060-5
Hourly	Slots per hour	DPH Slots	National Slot Coordination

Table 1: Capacity measurement description and Timeframes (Own illustration)

Flights under Visual Flight Rules (VFR) conditions, which would result in higher hourly ultimate capacities due to less separation between succeeding aircraft under good visibility and favourable weather conditions, we exempt from the study. In contrast to the U.S., where flights under VFR have historically bigger importance, due to a high proportion of General Aviation (GA) flights, these flights have little importance for commercial scheduled air traffic in Europe, which is largely coordinated under IFR.

For calculating airport capacity and delay, the freely available publication Advisory Circular (AC) 150/5060-5 "Airport Capacity and Delay" from the U.S. Federal Aviation Administration (FAA) has been chosen. The calculations presented in this article use the order-of-magnitude long-range planning instructions for calculating the Annual Capacity, the annual service volume (ASV), and hourly IFR CAP.

Relationship between Capacity, Demand and Delay

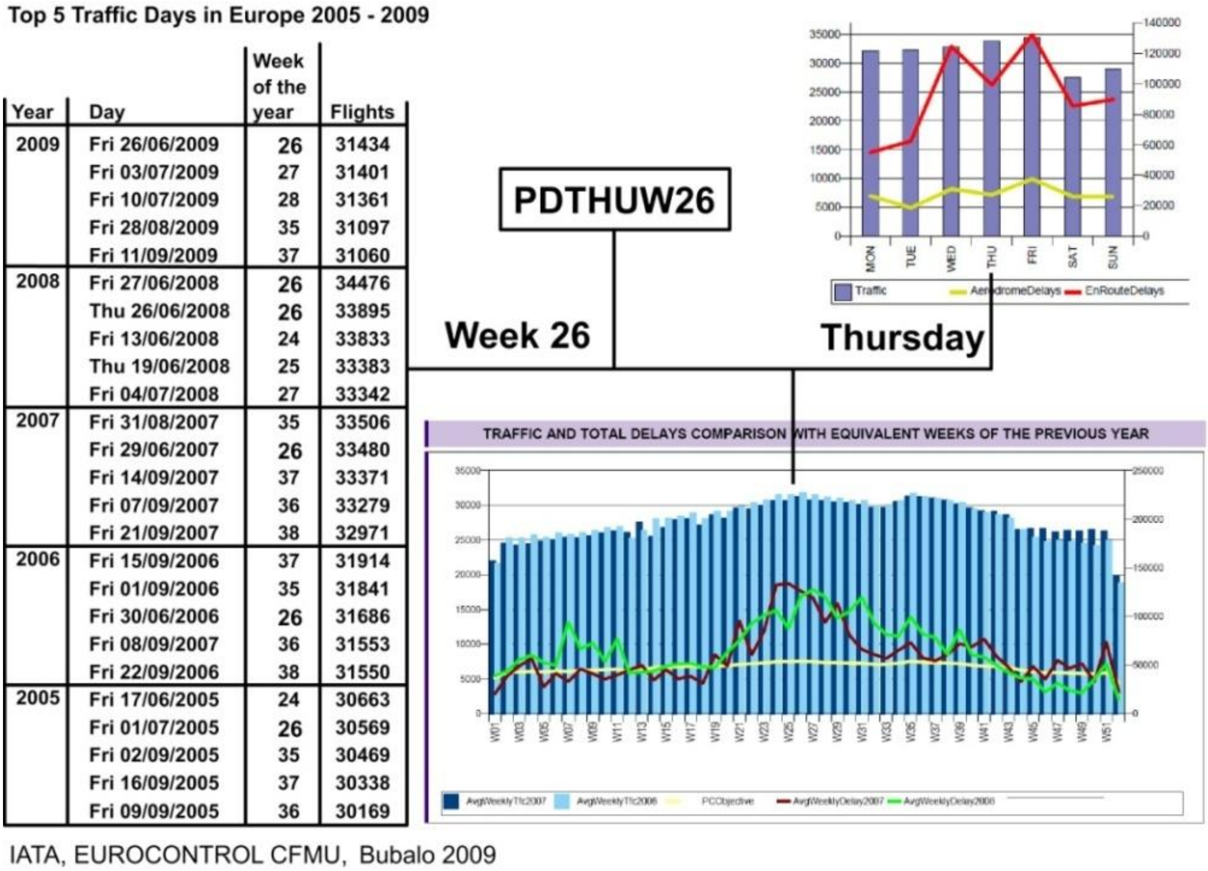
An airport should operate and serve demand below a practical capacity, where the management guarantees a level-of-service (LOS) of e.g. four minutes average delay per flight to the airport users. Demand should never exceed the practical or sustainable capacity over longer periods. As we can see in Fig. 1, the closer an airport operates towards its "physical" ultimate throughput

the stronger delays increase beyond an acceptable level of service and eventually infinity, which means the airport system breaks down and airlines need to cancel flights.
It is indeed always possible for demand to exceed capacity for shorter periods, due to fluctuations of demand at the airport. We are particularly interested in cases where capacity utilization is greater than 100% over at least one hour during the design peak day (DPD) and measurable waiting queues and therefore delays will develop.

It can make a huge difference in service quality, if an airport operates at a capacity utilization of 70%, 80%, 90% or more. Practical or sustainable capacity usually serves as declared capacity for the slot coordinator and it should never exceed 85-90% of the ultimate capacity during consecutive busy hours, otherwise, the airport system is unstable and sensitive to spontaneous changes in demand or available capacity, e.g. emergency landings or thunderstorms with unpredictable gusts and precipitation.

Design Peak Day and Design Peak Hour Assumptions

To make good assumptions for capacity analyses of airports it is vital to use a busy or design peak period for initial calculations. In its "Guidelines for Airport Capacity / Demand Management" International Air Transport Association (IATA 1981) gives a general definition for the busy period of airports: "A period that is representative of a normal busy period and not one related to peak time, such as religious festivals or some other short holiday period."
The EUROCONTROL Central Flow Management Unit (CFMU) weekly report of the last calendar week of the year shows the distribution of weekly traffic and delay over the whole preceding year. The pattern shows peaks from June to September in calendar week 25, 26, 35 and 36. Furthermore, the quality indicator "average delay per flight" has its peak with approximately 31,000 daily flights and up to 140,000 daily delay minutes, so 4.5 minutes of delay per flight, compared to the aim of 1.7 minutes (Fig. 2).
During the last consecutive years week 26 falls into the top five busiest weeks of the year. The daily pattern of week 26 reveals Friday as the busiest and Thursday as the second busiest day of the week. Assuming strong network interconnections among the airports and reducing the data requirements meeting the general IATA and other busy day definitions, as busy day we define the following representative Design Peak Day (DPD): "Peak Day is Thursday of Calendar Week 26" (PDTHUW26).
For this study, we analyze traffic data from the PDTHUW26 in 2007 to 2009, which were the following dates: Thursday, 28 June 2007, Thursday, 26 June 2008 and Thursday, 25 June 2009. The chosen Design Peak Hour (DPH) is the hour with maximum traffic during PDTHUW26.



Top 5 Traffic Days in Europe 2005 - 2009

Year	Day	Week of the year	Flights
2009	Fri 26/06/2009	26	31434
	Fri 03/07/2009	27	31401
	Fri 10/07/2009	28	31361
	Fri 28/08/2009	35	31097
	Fri 11/09/2009	37	31060
2008	Fri 27/06/2008	26	34476
	Thu 26/06/2008	26	33895
	Fri 13/06/2008	24	33833
	Thu 19/06/2008	25	33383
	Fri 04/07/2008	27	33342
2007	Fri 31/08/2007	35	33506
	Fri 29/06/2007	26	33480
	Fri 14/09/2007	37	33371
	Fri 07/09/2007	36	33279
	Fri 21/09/2007	38	32971
2006	Fri 15/09/2006	37	31914
	Fri 01/09/2006	35	31841
	Fri 30/06/2006	26	31686
	Fri 08/09/2007	36	31553
	Fri 22/09/2006	38	31550
2005	Fri 17/06/2005	24	30663
	Fri 01/07/2005	26	30569
	Fri 02/09/2005	35	30469
	Fri 16/09/2005	37	30338
	Fri 09/09/2005	36	30169

Figure 2: Design Peak Day (DPD) Simplification: Isolation of Peak Week and Peak Day

Calculation of the Mix Index

In addition to the configuration and usage of the runways the mix of operating aircraft types mainly define the runway capacity of an airport. The indicator to measure the distribution of different aircraft types is the Mix Index (MI). The mathematical expression MI = % (C+3*D) represents the traffic mix at a particular airport based on maximum take-off weight (MTOW) and corresponding aircraft or wake turbulence class (WTC) (table 2). For the calculation of the MI we need the percentages of class C and D aircraft, which correspond to WTC Large and Heavy, and a range of 7 to 136 tons and greater than 136 tons MTOW, respectively.

Aircraft Class	MTOW (tons)	No. of Engines	WTC
A	< 7	Single	Small (S)
B	< 7	Multi	Small (S)
C	7 – 136	Multi	Large (L)/Medium(M)
D	> 136	Multi	Heavy (H)

Table 2: Aircraft Weight and Wake Turbulence Classification

To calculate the MI for a specific airport it is necessary to analyse the flight schedule data and operating aircraft types. Flight schedule data should at least include (usually in coded form): 1.) Flight number 2. Airline name 3.) Aircraft type 4.) Departure and/or arrival times 5.) Origin and destination.

The used data set includes non-stop fights and airlines operating its own flights. Code sharing agreement flights are exempted from the sample. Table 3 shows the Mix Index during peak day for the airport sample of the top 33 European airports based on number of flights and other basic data such as operating hours, number of runways, runway configuration number from the AC 150/5060-5 and according airport peer group, annual passengers, flights and average passengers per flight.

								Annual Demand		
								2007		
Rank	Airport	Airport Name	Operating Hours	No. of Runways (<7500 ft counted as 0.5)	MI %	Rwy-use Config. No.	Group	Annual Pax in million	Annual Operations	PAX per Operation
1	CDG	Paris Charles de Gaulle	24/7	4	140	8	3	59.55	569,281	88
2	MAD	Madrid	24/7	4	118	8	3	51.40	470,315	91
3	AMS	Amsterdam	24/7	5.5	136	4 + 9	3	47.85	443,677	75
4	LHR	London Heathrow	24/7	2	170	4	2	68.28	475,786	185
5	FRA	Frankfurt	6-23	3	149	16	2	54.50	486,195	154
6	LGW	London Gatwick	24/7	2	118	2	2	35.27	258,917	124
7	MUC	Munich	6-23	2	112	4	2	34.07	409,654	108
8	FCO	Fuimicano	24/7	3	114	12	2	33.62	328,213	107
9	BCN	Barcelona	24/7	3	103	12	2	32.81	339,020	104
10	ORY	Paris Orly	6-23:30	2.5	112	12	2	26.42	238,384	84
11	IST	Istanbul	24/7	3	117	16	2	25.49	206,188	85
12	PMI	Palma de Mallorca	24/7	2	100	4	2	23.10	184,605	73
13	MAN	Manchester	24/7	2	116	2	2	22.33	206,498	78
14	CPH	Copenhagen	24/7	2.5	109	12	2	21.40	250,170	68
15	ZRH	Zurich	6-23	3	121	10	2	20.81	223,707	61
16	OSL	Oslo	24/7	2	101	4	2	19.04	226,221	60
17	ARN	Stockholm	24/7	3	106	12	2	18.01	205,251	57
18	BRU	Brussels	24/7	3	123	12	2	17.93	240,341	48
19	DUS	Dusseldorf	6-23	2	107	2	2	17.85	223,410	63
20	TXL	Berlin Tegel	6-23	2	107	2	2	13.37	145,451	47
21	HEL	Helsinki	24/7	3	107	12	2	13.10	174,751	42
22	NCE	Nice	24/7	2	55	2	2	10.38	173,584	40
23	LYS	Lyon	24/7 6-23 coord	2	102	2	2	7.19	132,076	25
24	STN	London Stansted	24/7	1	102	1	1	23.80	191,520	113
25	DUB	Dublin	24/7	3	108	14	1	23.31	200,891	104
26	VIE	Vienna	24/7	2	109	14	1	18.77	251,216	83
27	LIS	Lisbon	6-24	2	117	1	1	13.52	141,905	64
28	HAM	Hamburg	6-23	2	106	9	1	12.85	151,752	57
29	PRG	Prague	24/7	2	102	9	1	12.40	164,055	55
30	STR	Stuttgart	6-23	1	101	1	1	10.35	139,757	49
31	BHX	Birmingham	24/7	1	104	1	1	9.32	104,480	44
32	WAW	Warsaw	24/7	2	103	9	1	9.29	147,985	41
33	LCY	London City	6-22	1	100	1	1	2.91	77,274	14
		Totals		80				810.29	8,182,530	
		Mean		2	112		2	24.55	247,955	76

Table 3: Sample Airports Basic Data (ranked by Groups and Annual Passengers; AMS complex runway system has been split into two separate runway systems)

Preferential Runway Configurations

Downloading of Aeronautical Information Publications (AIP) including aerodrome charts, flight routes and airport information is possible from the EUROCONTROL European AIS Database (EAD).

The AIP for a particular airport usually point out the preferential use of runways for departures and arrivals under the preferential runway system. Other useful information, such as Cartesian coordinates and number of aircraft parking positions, noise abatement procedures and night flying restrictions are also stated.

AIP information of Frankfurt am Main airport reveals that most of the time the landing direction is from North-East (NE) to South-West (SW) direction alternately on the close space parallel runways 25R and 25L. When this landing direction is in use, the preferred take-off runways is alternately on runways 25R and 18. The parallel runways 25L/07R and 25R/07L have a separation of 1700 feet or 520 meters, therefore an independent operation is not possible. Figure 4 shows the sketch resulting from the AIP information on the preferential runway system at Frankfurt airport.

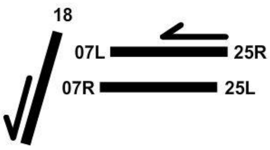


Figure 4: Simplified runway-use configuration of Frankfurt airport (Own illustration)

Applying the FAA runway schemes

With the MI calculated for all sample airports and their corresponding runway system, now we assign the closest matching runway-use configuration (which provides the greatest hourly capacity) from the 19 runway schemes found in the FAA document AC 150/5060-5 (Figure 5).

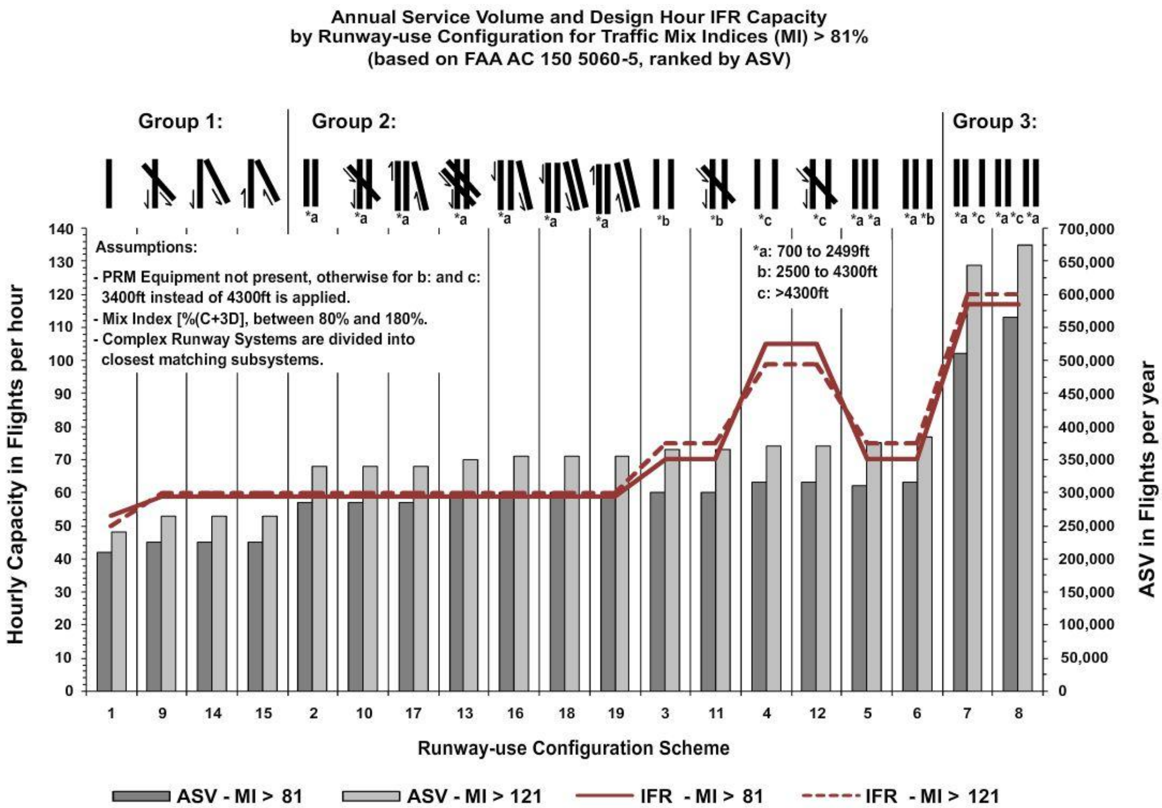


Figure 5: Peer Groups by Annual Capacity (ranked by ASV with MI greater 120%, own illustration)

From Fig. 5 we read the ASV and IFR CAP for each airport runway configuration (scheme). Table 3 reveals that an MI of 112% is the average among all studied airports and can be safely used as a first order estimate for evaluating unknown European airports with normal commercial traffic, if traffic data is unavailable.

For the example of Frankfurt the closest matching runway-use configuration is scheme number 16 and the MI is 149%. These values correspond in figure 5 to an ASV of 355.000 flights per year and an IFR CAP of maximum 60 flights per hour.
During the past two decades Frankfurt airport was able to continuously increase its hourly capacity of 60 flights with procedural and ATC enhancements. Frankfurt has increased its hourly declared capacity from 68 slots in 1993 up to currently 83 slots per hour without building extra runways (figure 6). Frankfurt airport is an extreme case, where maximum throughput in estimated IFR CAP with the FAA methodology is lower than the declared capacity. The necessity for another runway at Frankfurt am Main airport from a safety and capacity point of view is evident from the data - a fourth runway is ultimately under construction. From an environmental point of view this can be discussed and the best agreement among all stakeholders and the community must be found.

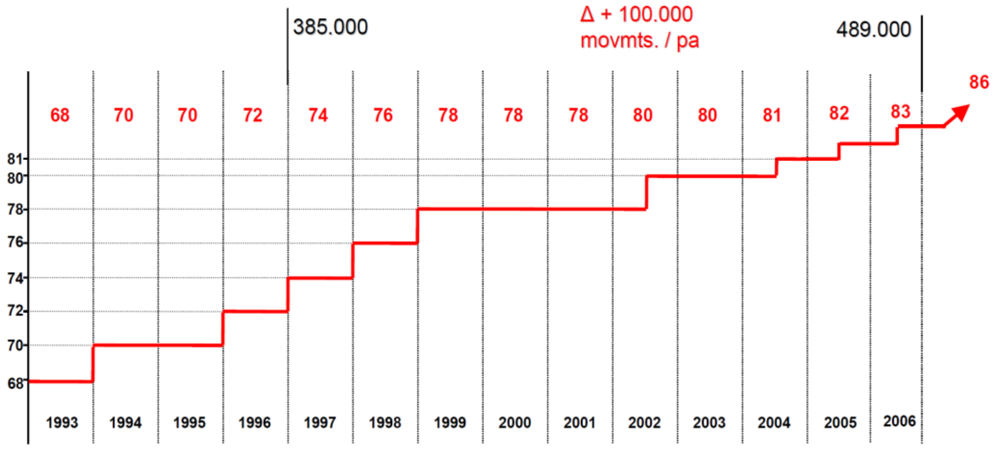


Figure 6: Development of hourly declared capacity in Frankfurt 1993-2006
Annual Service Volumes, Peak Day and Peak Hour Capacity

Under the IATA Worldwide Scheduling Guidelines airports considered Level 2 or 3 coordinated, need to declare their capacity for scheduling purposes. This is the case with all 33 sample European airports. The declared capacity is the maximum throughput of flights per period of time, usually one hour, being served at a particular airport under a predefined level-of-service. This means it is a commonly agreed minimum value, which serves as a basis for the slot allocation and scheduling process at the semi-annual IATA Schedules Conference. The terms “slots” and “declared capacity” per hour are usually interchangeable.

Slots per hour for summer season 2009 have been collected for this analysis from national slot coordination websites. The daily maximum available slots are and all other obtained capacities are included in table 4. This completes the five different calculated capacities for each studied airport. As a first approximation for the European air transport network capacity, the total ASV shows that the overall annual capacity of all sample airports is 10.3 million flights per year. The daily total capacity for the representative airport sample is 45000 IFR flights and 34000 slots.

Annual and Design Peak Day Demand

With known capacity it is time to look at existing traffic demand. The annual demand in 2007 for the airports was obtained from EUROSTAT database. The daily and hourly demand on PDTHUW26 in the years 2007 to 2009 has been extracted from the collected flight schedule data which has already been used to calculate the MI, earlier in this article

			Annual Capacity	Daily Capacity		Hourly Capacity 2009		
Rank	Airport	Group	Annual Service Volume (ASV)	DPD IFR CAP	DPD Slots Summer Season 2009	DPH IFR CAP	DPH Slots Summer Season 2009	Airport/ Runway Service Rate in seconds per Ops (reciprocal of slots per hour)
1	CDG	3	675,000	2040	1742	120	105	34
2	AMS	3	635,000	2703	1652	159	108	33
3	MAD	3	565,000	1989	1445	117	85	42
4	LHR	2	370,000	1683	1354	99	86	42
5	BRU	2	370,000	1683	1229	99	74	49
6	FRA	2	355,000	1360	1395	80	83	43
7	ZRH	2	340,000	1020	1122	60	66	55
8	MUC	2	315,000	1785	1530	105	90	40
9	BCN	2	315,000	1785	1020	105	60	60
10	FCO	2	315,000	1785	1530	105	90	40
11	CPH	2	315,000	1785	1411	105	83	43
12	ORY	2	315,000	1785	1131	105	70	51
13	OSL	2	315,000	1785	1025	105	60	60
14	ARN	2	315,000	1785	1356	105	80	45
15	PMI	2	315,000	1785	1020	105	60	60
16	HEL	2	315,000	1785	1336	105	80	45
17	IST	2	300,000	1003	680	59	40	90
18	LGW	2	285,000	1003	797	59	46	78
19	DUS	2	285,000	1003	771	59	47	77
20	MAN	2	285,000	1003	883	59	46	78
21	TXL	2	285,000	1003	884	59	52	69
22	LYS	2	285,000	1003	867	59	51	71
23	NCE	2	260,000	952	794	56	50	72
24	VIE	1	225,000	1003	1044	59	66	55
25	DUB	1	225,000	1003	703	59	46	78
26	PRG	1	225,000	1003	676	59	46	78
27	HAM	1	225,000	1003	901	59	53	68
28	WAW	1	225,000	1003	578	59	34	106
29	STN	1	210,000	901	733	53	38	95
30	LIS	1	210,000	901	612	53	36	100
31	STR	1	210,000	901	714	53	42	86
32	BHX	1	210,000	901	680	53	40	90
33	LCY	1	210,000	901	384	53	24	150
	Totals		10,305,000	45,033	33,999	2,649	2,037	
	Mean		312,273	1,365	1,030	80	62	66

Table 4: Sample Airport Capacities (ranked by Group and ASV)

To be able to compare and benchmark the sample airports, a “core hours” period from 6:00 to 23:00 has been defined for this study. Some network activity happens in off-peak times outside the core hours. The periods from 5:00 to 6:00 or from 23:00 to 24:00 usually serve for additional seasonal demand, e.g. charter or low cost carrier flights.

Table 5 gives an overview of annual, daily and hourly demand at the 33 sample airports and is another important prerequisite to calculate idle capacity, capacity utilization or delay later in this article.

			Annual Demand	Weekly Demand	Daily Demand					Hourly Demand		
			2007	2007	2007	2007	2007	2008	2009	2007	2008	2009
Rank	Airport	Group	Annual Operations	Average Weekly Ops	Average Daily Ops	Average Day to DPD Factor	Design Peak Day (DPD) Operations	DPD Ops	DPD Ops	DPH Ops	DPH Ops	DPH Ops
1	MAD	3	470,315	9,045	1,289	1.10	1,412	1,478	1,370	96	112	112
2	CDG	3	569,281	10,948	1,560	1.04	1,624	1,657	1,424	114	126	107
3	AMS	3	443,677	8,532	1,216	1.09	1,321	1,392	1,188	109	111	106
4	FCO	2	328,213	6,312	899	1.20	1,076	1,338	1,110	109	103	100
5	MUC	2	409,654	7,878	1,122	1.12	1,258	1,277	1,144	99	93	92
6	LHR	2	475,786	9,150	1,304	1.17	1,530	1,530	1,386	103	103	90
7	FRA	2	486,195	9,350	1,332	1.03	1,373	1,342	1,274	92	89	87
8	BCN	2	339,020	6,520	929	1.15	1,071	940	866	86	80	74
9	BRU	2	240,341	4,622	658	1.19	784	800	736	77	71	67
10	CPH	2	250,170	4,811	685	1.18	811	776	712	67	70	62
11	ORY	2	238,384	4,584	653	1.17	765	749	710	62	63	60
12	DUS	2	223,410	4,296	612	1.16	713	718	701	58	51	58
13	ZRH	2	223,707	4,302	613	1.23	754	681	654	69	57	57
14	MAN	2	206,498	3,971	566	1.19	671	669	499	60	69	51
15	ARN	2	205,251	3,947	562	1.18	666	727	528	61	61	50
16	LGW	2	258,917	4,979	709	1.07	757	802	678	55	56	49
17	OSL	2	226,221	4,350	620	1.09	678	693	577	66	60	49
18	NCE	2	173,584	3,338	476	1.08	515	610	469	47	52	48
19	IST	2	206,188	3,965	565	1.05	593	607	663	42	44	47
20	PMI	2	184,605	3,550	506	1.05	529	551	502	50	44	45
21	HEL	2	174,751	3,361	479	1.04	497	496	434	47	41	44
22	LYS	2	132,076	2,540	362	1.14	411	351	376	47	44	43
23	TXL	2	145,451	2,797	398	1.24	496	531	482	43	42	42
24	VIE	1	251,216	4,831	688	1.15	794	795	726	66	67	59
25	DUB	1	200,891	3,863	550	0.99	545	560	467	42	44	43
26	PRG	1	164,055	3,155	449	1.18	529	573	445	48	57	39
27	STN	1	191,520	3,683	525	1.05	549	516	408	51	47	38
28	HAM	1	151,752	2,918	416	1.24	516	509	458	46	44	38
29	LCY	1	77,274	1,486	212	1.41	298	332	239	34	36	36
30	STR	1	139,757	2,688	383	1.71	656	427	370	54	41	35
31	LIS	1	141,905	2,729	389	1.04	405	350	326	38	37	34
32	BHX	1	104,480	2,009	286	1.19	340	348	307	32	29	28
33	WAW	1	147,985	2,846	405	1.04	422	425	322	35	32	26
	Totals		8,182,530	157,356	22,418	1.13	25,359	25,550	22,551	2,105	2,076	1,916
	Mean		247,955	4,768	679	1.15	768	774	683	64	63	58

Table 5: Sample Airport Demand (ranked by Group and 2009 DPH Ops)

From the small time series of DPD flights of three consecutive years it is observable how strong the global financial crisis has impacted the air traffic demand. Daily and hourly demand has peaked in 2007 and 2008 and has dropped considerably by around 10% in 2009 (Figure 6). Recent signs of an ending of the crisis will also translate in an increasing demand in 2010.

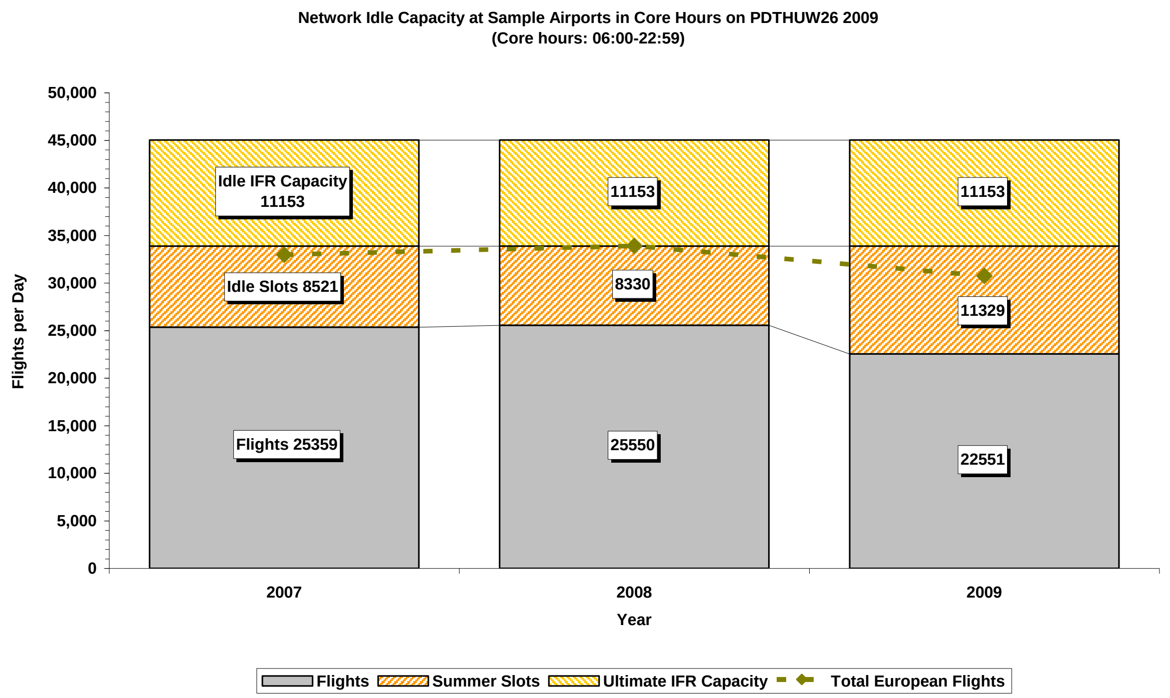


Figure 6: Network Idle Capacity and Total Daily European Flights

If traffic and data is unavailable, order of magnitude peak hour values for DPH flights and passengers from the total number of annual flights can be found accordingly to the trends shown in figure 7.

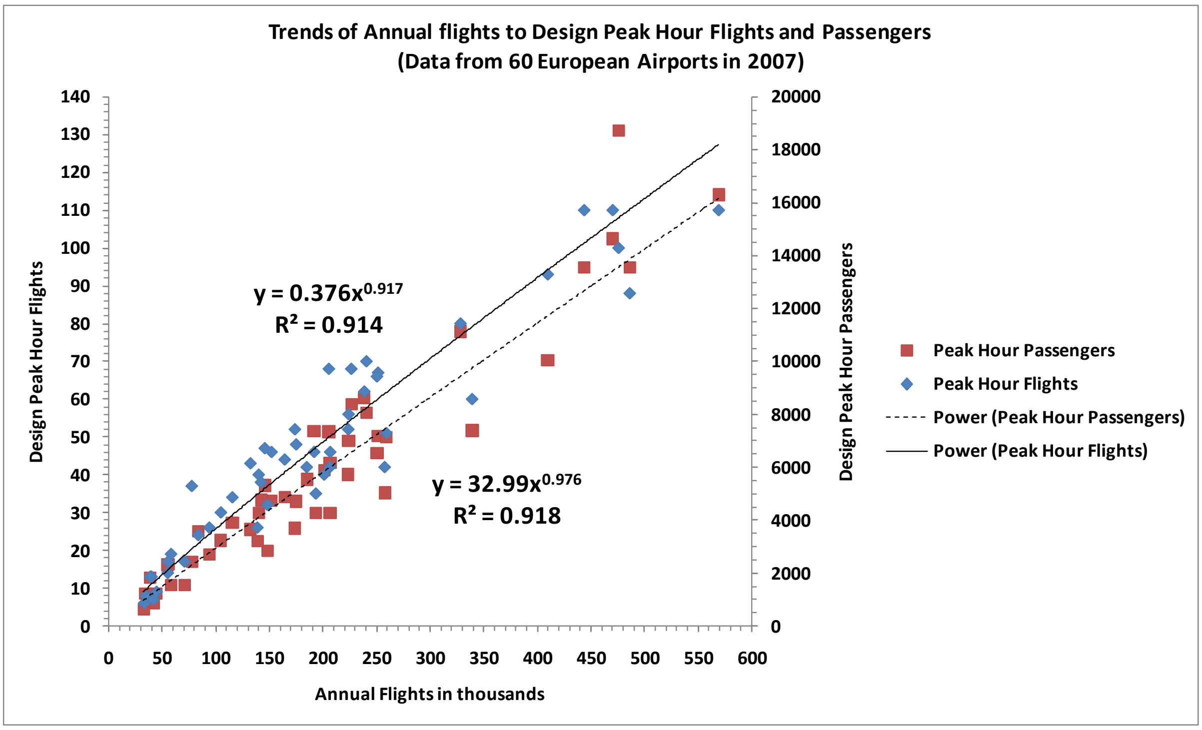


Figure 7: Trends of Annual Flights to Design Peak Hour Flights and Passengers

Combining Capacity and Demand Data

Finally the collected values for capacity and demand from the first part of this article can be combined for analysis and further calculations like idle capacity, capacity utilization and delay can be made. Capacity Utilization is the fraction of demand and capacity. Idle capacity results from the difference of capacity and demand. Table 5 shows results for the sample of 33 airports for the year 2009.

Airport	Group	DPD Idle Slots	DPD Slot Utilization	DPH Slot Utilization	Aircraft Delay Hours	DPD Delayed Flights	max Delayed Aircraft	Delay per delayed Aircraft in min	Delay per Aircraft in min
MAD	3	149	95%	132%	612.00	1283	67	28.62	26.80
CDG	3	318	82%	102%	0.00	0	0	0.00	0.00
AMS	3	504	72%	98%	85.00	260	40	19.62	4.29
LHR	2	37	102%	105%	239.50	1316	49	10.92	10.37
IST	2	46	98%	118%	31.10	473	7	3.94	2.81
FRA	2	128	91%	105%	6.53	259	4	1.51	0.31
DUS	2	93	91%	123%	41.21	456	11	5.42	3.53
BCN	2	181	85%	123%	75.14	466	23	9.68	5.21
MUC	2	388	75%	102%	1.12	101	2	0.67	0.06
FCO	2	434	73%	111%	22.44	250	14	5.39	1.21
ORY	2	421	63%	86%	0.00	0	0	0.00	0.00
BRU	2	493	60%	91%	0.00	0	0	0.00	0.00
NCE	2	325	59%	96%	0.00	0	0	0.00	0.00
ZRH	2	468	58%	86%	0.00	0	0	0.00	0.00
MAN	2	384	57%	111%	0.00	0	0	0.00	0.00
OSL	2	448	56%	82%	0.00	0	0	0.00	0.00
TXL	2	402	55%	81%	0.00	0	0	0.00	0.00
CPH	2	699	50%	75%	0.00	0	0	0.00	0.00
PMI	2	518	49%	75%	0.00	0	0	0.00	0.00
LYS	2	491	43%	84%	0.00	0	0	0.00	0.00
ARN	2	828	39%	63%	0.00	0	0	0.00	0.00
HEL	2	902	32%	55%	0.00	0	0	0.00	0.00
LGW	1	119	85%	107%	0.00	0	0	0.00	0.00
VIE	1	325	70%	89%	1.14	55	2	1.25	0.09
DUB	1	236	66%	93%	0.00	0	0	0.00	0.00
PRG	1	274	66%	85%	80.50	75	43	64.40	10.85
LCY	1	167	62%	150%	34.36	122	13	16.85	8.63
WAW	1	256	56%	76%	0.00	0	0	0.00	0.00
STN	1	325	56%	100%	0.00	0	0	0.00	0.00
LIS	1	286	53%	94%	0.00	0	0	0.00	0.00
STR	1	344	52%	83%	0.00	0	0	0.00	0.00
HAM	1	443	51%	72%	0.00	0	0	0.00	0.00
BHX	1	373	45%	70%	0.00	0	0	0.00	0.00
Mean	2	358	65%	95%	37	155	8	5.10	2.25

Table 6: Exemplary Calculation Examples from Demand and Capacity Data from 2009

Figure 8 shows each core hour demand and capacity - available slots or IFR CAP - over time of day for Barcelona airport (BCN) as an example. Due to the unavailability of recent information on declared capacities or slots of Spanish airports, a reasonable hourly capacity of 60 slots per hour has been estimated for Barcelona airport from older data.

At Barcelona airport total daily operations on DPD during core hours add up to 866 flights compared to 1020 total available slots, which means under current conditions Barcelona has a daily slot utilization of 85% and 181 idle slots available during 6:00 and 23:00 on design peak day for further growth in demand. Peak hour demand between 9:00 and 10:00 at Barcelona airport accounts for 74 flights and its slot capacity is therefore exceeded by 14 flights, which are delayed into the next hour. Figure 8 especially gives an indication of the demand in 2007 where the slot capacity is over utilized almost the whole day, from 8:00 to 22:00.

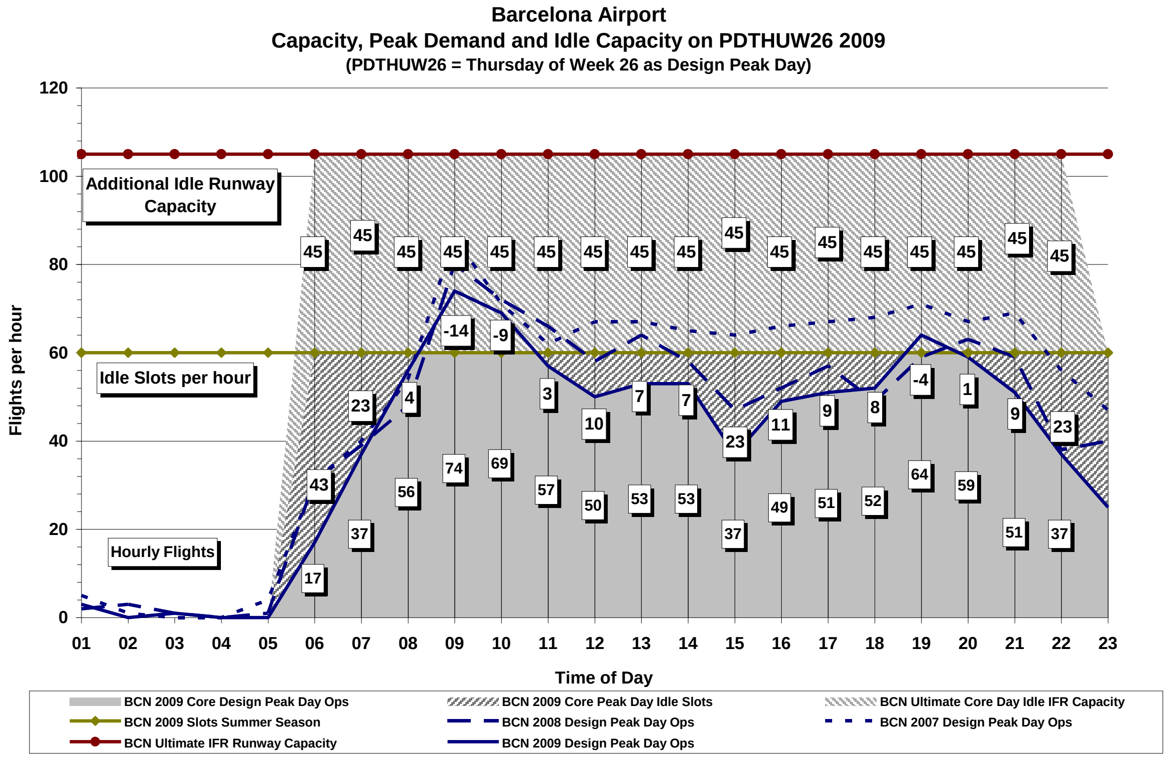


Figure 8: Design Peak Day Capacity and Demand over Time of Day at Barcelona Airport

The runway configuration of Barcelona airport has enough spare or idle capacity to serve the current demand. The maximum daily IFR CAP is roughly twice as high as the current peak daily demand of 866 flights per day, although demand dropped 8% from a total of 940 flights on peak day in 2008. The estimations from the FAA runway-use schemes for the parallel runways plus one crossing runway at Barcelona airport reveal an IFR CAP of 105 operations per hour, which translates into 1785 total and 765 additional flights that could possibly be served each core day operating at full capacity. Table 6 provides the calculation steps for this example.

		Airport	Time of day (T)																		
Step	Year	Barcelona (BCN)	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	TOTALS on DESIGN PEAK DAY (DPD)	
a	2009	IFR CAPACITY	105	105	105	105	105	105	105	105	105	105	105	105	105	105	105	105	105	1785	DPD IFR CAP
b	2009	SLOTS	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	1020	DPD SLOTS
c	2009	DEMAND	17	37	56	74	69	57	50	53	53	37	49	51	52	64	59	51	37	866	DPD TOTAL FLIGHTS
d	2009	IDLE CAPACITY	43	23	4			3	10	7	7	23	11	9	8		1	9	23	181	DPD IDLE SLOT CAPACITY
e	2009	DEMAND - SLOTS	-43	-23	-4	14	9	-3	-10	-7	-7	-23	-11	-9	-8	4	-1	-9	-23		
f	2009	OVERLOAD				14	9									4					
g	2009	CUMULATIVE DEMAND - SLOTS				14	23	20	10	3	-4					4	3	-6			
h	2009	AIRCRAFT HOURS OF DELAY				7.0	18.5	21.5	15.0	6.5	0.6					2.0	3.5	0.5		75.14	DPD HOURS OF DELAY
i	2009	DELAYED AIRCRAFT				74	69	57	50	53	23					64	59	17		466	DPD DELAYED FLIGHTS
j	2009	DELAY PER DELAYED FLIGHT				5.68	16.1	22.6	18	7.36	1.7					1.88	3.56	1.76		9.68	DELAY MINUTES PER DELAYED FLIGHT
k	2009																			5.21	DELAY MINUTES PER FLIGHT

Table 7: Breakdown of Calculation Steps for Barcelona airport

Delay and delayed aircraft on Design Peak Day

The capacity and demand diagram in figure 8 of Barcelona airport shows slight over utilization of slot capacity with 14 and 9 landings or departures without an available slot between 8:00 and 11:00, and with 4 slots lacking between 18:00 to 20:00.

In our example the slots per hour represent the airport service rate, which is the maximum throughput of the runway system, and the demand or flights in each hour represents the demand rate. Queued and delayed aircraft are shifted into the next hour (Figure 9).

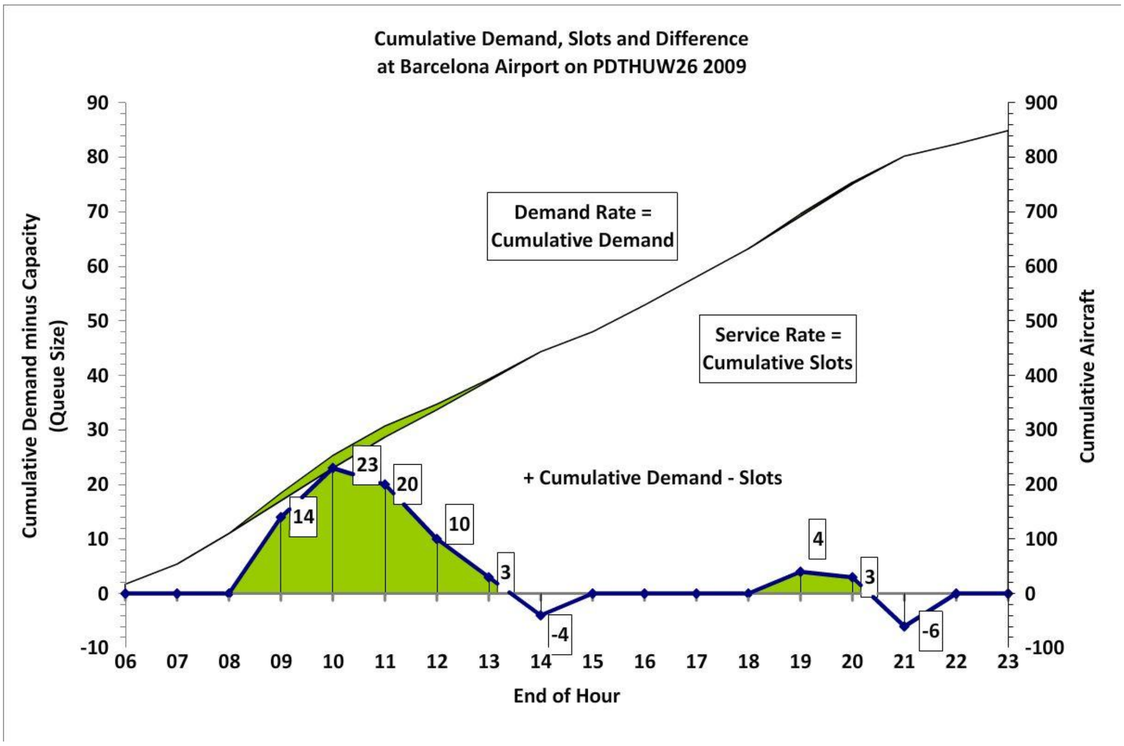


Figure 9: Cumulative Chart for Barcelona Airport

A good and clear representation is the cumulative demand minus capacity chart, which allows a more accurate estimation of delay and delayed aircraft and shows the cumulative and resolving effect of the waiting queue over time of the day. Please refer to Figure 9 for more details.

The positive area or integral of the cumulative demand-capacity chart shown in figure 10 are delayed aircraft-hours. In the case of Barcelona airport on PDTHUW26 in 2009 this amounts to a maximum of 23 aircraft being delayed between 8:00 and 10:59. The total daily delayed aircraft-hours amount to 75.14 hours.

At Barcelona airport even short over utilization periods of two hours as seen in figure 8 cumulate very fast to longer periods of congestion of 5 hours as seen in figure 9 and 10, until the queues are finally reduced. With a runway service time of 60 seconds or 1 minute per flight, taken from table 3 from above, the longest delay for the last and 23rd user in the waiting queue at 10:59 will be exactly 23 minutes.

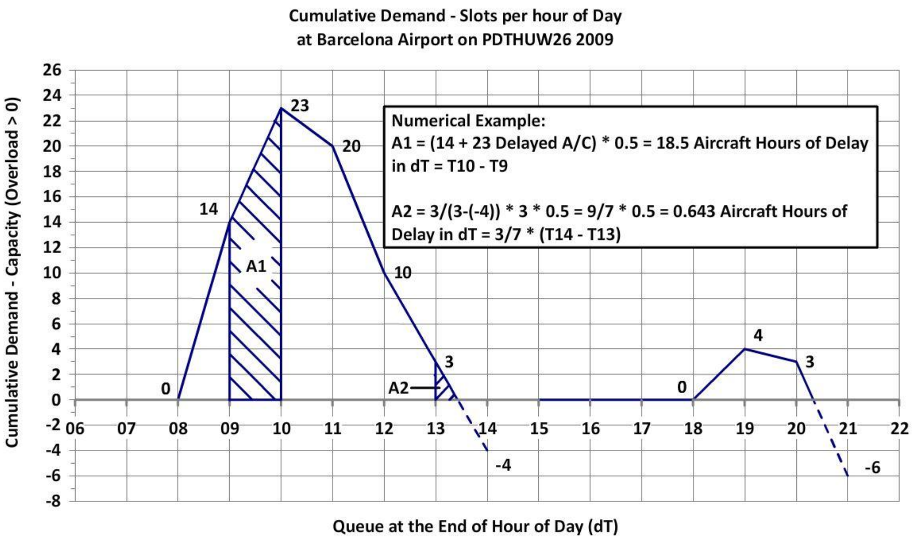


Figure 10: Deterministic Delay Hours for Barcelona Airport

Rank in 2008	Airport	Name	Country	Delay per delayed Aircraft in minutes on DPD			Delay per Aircraft in minutes on DPD		
				2007	2008	2009	2007	2008	2009
1	LHR	London Heathrow	UK	66.3	65.9	11.8	63.2	62.6	11.2
2	MAD	Madrid*	ES	16.5	54.4	28.7	15.3	50.7	26.8
3	LCY	London City	UK	26.4	39.5	17.3	20	31.2	8.9
4	PRG	Prag	CZ	73.7	57	99.6	19.2	20.2	16.8
5	BCN	Barcelona	ES	63.7	20.7	9.7	56.3	17.4	5.2
6	CDG	Paris Charles de Gaule	FR	4.3	14.5	-	2.3	9.8	-
7	LGW	London Gatwick	UK	7.2	8.6	-	3.9	8.1	-
8	FCO	Rom Fiumicino	IT	6.3	9.4	5.4	2.1	6.6	1.2
9	AMS	Amsterdam	NL	21.7	11.1	20.1	6.6	4.1	4.4
10	DUB	Dublin	IE	17.1	-	-	1.4	1.5	1.5
11	DUS	Duesseldorf	DE	4.7	2.9	5.7	2.6	1.5	3.7
12	FRA	Frankfurt Main	DE	6.9	2.5	2.7	6.6	1.4	0.5
13	MAN	Manchester	UK	1.1	6.4	-	0.2	1	-
14	IST	Istanbul	TK	1.2	2.3	3.9	0.2	0.5	2.8
15	STR	Stuttgart	DE	16.8	-	-	10.8	0.4	0.6
16	NCE	Nizza	FR	-	1.3	-	-	0.4	-
17	MUC	Muenchen	DE	1.6	1.4	2.8	0.8	0.3	0.2
18	HAM	Hamburg	DE	-	-	-	0.1	0.1	0.1
19	LIS	Lisbon	PT	1.7	0.8	-	0.4	0.1	-
20	STN	London Stansted	UK	2	0.7	-	0.4	0.1	-
21	VIE	Wien	AT	9.5	0.7	1.3	0.7	0.1	0.1
22	ARN	Arlanda	SE	-	-	-	-	-	-
23	BHX	Birmingham	UK	-	-	-	-	-	-
24	BRU	Bruessel	BE	1.2	-	-	0.1	-	-
25	CPH	Kopenhagen	DK	-	-	-	-	-	-
26	HEL	Helsinki	FI	-	-	-	-	-	-
27	LYS	Lyon	FR	-	-	-	-	-	-
28	ORY	Paris Orly	FR	-	-	-	-	-	-
29	OSL	Oslo	NO	0.5	-	-	0.1	-	-
30	PMI	Palma Mallorca	ES	-	-	-	-	-	-
31	TXL	Berlin Tegel	DE	-	-	-	0.1	-	-
32	WAW	Warschau	PL	0.9	-	-	0.1	-	-
33	ZRH	Zuerich	CH	1.4	-	-	0.1	-	-
		MEAN		15.3	16.7	17.4	8.5	10.4	5.6

*A declared capacity of 85 has been estimated, 100 Movements per hour seem more likely

Table 8: Congested European airports and calculated delays ranked by delays per aircraft in 2008 (Source: Bubalo 2010)

The average delay per delayed aircraft on design peak day at Barcelona airport is 75.14 aircraft-hours divided by 466 operations = 0.16 hours or 9.68 minutes. Average delay per aircraft is 75.14 aircraft-hours divided by 866 operations = 0.087h or 5.21 minutes (table 8).
All information regarding delays at Europe's most congested airports during the peak days in 2007 to 2009 is presented entirely in table 8.

Conclusions

The presented assessment and necessary calculations give a suggestion about the state of delay and capacity utilization at European airports over different time periods. The traffic situation and clear slot over utilization during the busy days and hours in summer 2007 and 2008 should make the stakeholders in the industry aware. Delays are very costly and must be minimized to maximize productivity and welfare. So it must be in greatest common interest that delays do not occur because there are not enough slots available to serve the demand at anytime.
If enough capacity cannot be guaranteed during the busy periods it should certainly be enhanced. For example London Heathrow offers 86 and Munich airport offers 90 slots per hour with a parallel runway layout, in contrast Oslo and Palma de Mallorca airports offer only 60 slots per hour with the same basic runway layout. So the possible capacity for the latter two airports could most likely be much higher.
Deterministic delays in the analysed network of 33 congested airports decreased from 10.4 minutes per flight in 2008 to 5.6 minutes per flight in 2009, essentially due to decreasing scheduled flights as a result from the economic crisis, which clearly affected travel demand.
To redefine the calculations, better capacity values can be used as they become available. Capacity values for flights under instrumental flight rules (IFR CAP) as defined by the FAA have been presented. At most airports the IFR CAP has not been exceeded, so there could be considerable spare capacity in the network, which can be freed by overcoming other than runway related airport limitations.

References

Bubalo (2009), “Benchmarking Airport Productivity and the Role of Capacity Utilization – A Study of selected European Airports”, Diploma Thesis, Berlin School of Economics and Law, 2009

FAA (1995), “Airport Capacity and Delay”, December 1995, Advisory Circular (AC No: 150/5060-5), initiated by AAS-100, Department of Transportation, 1983 and 1995.

Graham, A. (2008), “Managing Airports”, 3rd ed. Oxford: Elsevier Ltd., 2008.

Horonjeff, R., McKelvey, F. X. (2010), “Planning and Design of Airports”, 5th ed. New York: McGraw-Hill, 2010.

International Air Transport Association (IATA) (1981), “Guidelines for Airport Capacity / Demand Management”, Airport Associations Coordinating Council (AACC) and TRAP WG, November 1981, Montreal – Geneva.

De Neufville, R., Odoni, A. (2003), “Airport Systems: Planning, Design, and Management”, The McGraw-Hill Companies, Inc., 2003.