AIRSIDE PRODUCTIVITY
OF SELECTED EUROPEAN AIRPORTS

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ABSTRACT

Productivity and benchmarking studies on airports vary in terms of methodologies used, variables chosen and airport sample size. The usage of certain operational airport parameters on the airside, in particular the number of runways, as indicators of capacity used in previous studies is questioned. It can be shown that such indicators tend to give contradictory and unreasonable results. Instead one must take other important determinants of airport infrastructure and capacity into account, such as preferential runway(s) in use and runway configuration, apron capacity, aircraft parking positions or the daily pattern of demand.

This paper focuses on results of previous airport benchmarking studies on productivity, capacity and delay. Order-of-magnitude approximations for airport airside capacity are delivered together with data samples of European airports, which could be used for forecasts or serve as benchmarks for other airports with similar characteristics. It has been found that apart from the fundamental role of runway capacity for airports, the environmental capacity might play a larger role in the future to guarantee long-term sustainable aviation. Air transportation in Europe made a commitment to reduce fuel-burn, hence CO_2-Emissions, aircraft and engine noise and delays under its Single European Sky (SES) initiative and the inclusion of aviation in the Emission Trading System (ETS) from 2010 on.

Firstly, a distinction of the main quantitative outputs of production of airports will be made and different peer groups of airports for comparison will be established. Secondly, the relationship between demand and airside capacity will be explained, with an emphasis on runway capacity and available slots, and its utilization on an hourly and annual basis. Thirdly, externalities of production, especially delay, are analyzed in detail by simulating airside traffic in SIMMOD. The paper finishes with concluding remarks. Further research with regard to noise and CO_2-Emissions will be carried out in the future to derive benchmarks for environmental capacity.

Key words: airport productivity, runway capacity, delay, slots, SIMMOD

Introduction

Today's airports are vast and expensive infrastructures, which have considerable positive and negative impacts on population and environment. In the vicinity an airport and its (growing) traffic could seriously affect the local neighbors by decreasing air quality and increasing aircraft noise. On the other hand - regionally and globally - airports represent the most important interfaces for different transport modes and cargo transport. Especially the demand for business aviation, tourism and fresh goods make air transportation the mode of choice for the transportation and logistics industry. The consumer behavior towards air travel has also changed in the last ten years. With the rapid development of telecommunication and information technology, specifically the Internet, and the simultaneous emergence of low fare airlines, the demand for air travel has considerably increased and makes flying sought after and affordable for the broader public. Even though the September 11th incidence in New York City in 2001, the SARS epidemic in 2003 and the recent global banking crisis in 2009 caused temporary converse effects to increasing air travel demand, the trend towards further future growth is clear.

In the past we have seen almost unconstrained growth in the western world, which started in the late 1940's and continued until the early millennium. This has been largely fueled by the deregulation of air transportation in the 70s in the U.S. and in the 90s in Europe. The North-American and European markets and main routes have now matured quite considerably, therefore most of the future growth of demand for air transportation will happen in Asia and the Middle East with increasing wealth and education in those regions. China, India and the oil-rich countries on the Arabian Peninsula invest billions of Euros in airport infrastructure to boost and support their economic development. This does not imply that European air transportation demand will stagnate at the current level; it will rather grow at a lower degree of around 3-4% annually in terms of total flights and at around 4-5% annually in terms of total passengers. This would still result in a doubling of traffic or passengers in the next 16 or 20 years, respectively.

The question which arises consequently is: Does Europe have sufficient and flexible airport capacity to serve future demand?

The following sections will present recent results of benchmarking studies and approaches in estimating current demand and airside capacity, the utilization of infrastructure and the level of congestion. To support a noise cap and trade system with noise quantities and since environmental capacity can play a vital role in airport development, a method of turning noise into a tradable unit will be presented on the basis of current Quota Count Systems and Noise Certification Data.

Airport Productivity and Demand

The main output of “production” of an airport can be divided into the following streams of “products”, which must be analyses separately:

- Airside Productivity Output: Number of Aircraft Landings and Take-offs or Movements
- Landside Productivity Output: Amount of Passengers and Cargo.

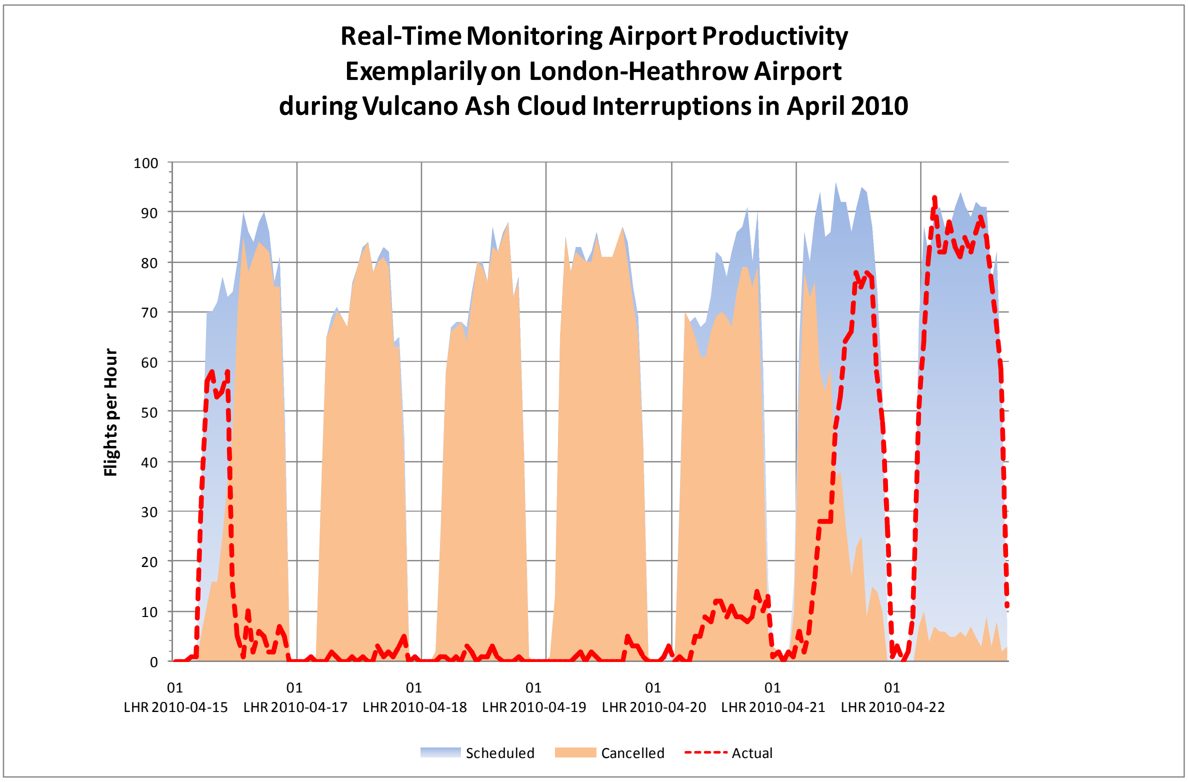
The division between airside and landside productivity is usually made between aircraft handling between the runways, apron and parking positions/gates on the airside, and passenger and cargo handling between the parked aircraft, the gates, the terminal or cargo facility and the destination on the landside. So eventually the flow of airside runway and apron movements divides into streams of passengers and cargo inside the landside facilities after parking of the aircraft. The airside, and the runway system explicitly, is a critical requirement for the operation of an airport and needs not only vast amounts of money to invest, but also a timely planning of approximately 10 years in advance, e.g. for planning, legal approval and construction.

The division between airside and landside can also be made with airport revenues, where a large portion of aviation (airside) revenues comes from the aircraft landing, parking, handling, and central infrastructure charges, but also noise and emission charges. Non-aviation (landside) revenues to the contrary come from passenger services and consumption, through lease and rents from shops, retail, food and beverages, and passenger parking. Many privatized airports in Europe nowadays have a 50/50 share of aviation and non-aviation revenues, which makes them less dependent on landing charges, but more dependent on a steady stream of consuming passengers. The financial term in making the deviation between airside and landside or fixed and variable revenues, respectively, is the dual till approach. To enrich the experience of spending time and money at the airport, huge investments in attractive terminal design are being made.

Perhaps the most important prerequisite for airside analysis of airports is the projected or actual flight schedule of each airport. With available flight schedule data over longer periods of time, but at least one representative day, many important observations on productivity, runway efficiency, traffic mix and traffic variability or seasonality can be made. The International Air Transport Association (IATA) suggests the first step for estimating capacity and demand of an airport should be simple busy period traffic observations (IATA 1981). Therefore the first diagram to plot would be the traffic load plot by hour of day, which gives insights about the daily peaks of demand. Peak period traffic information is required for detailed capacity planning of the airside, e.g. runways, and the landside, e.g. passenger facilities.

To illustrate the importance of the daily traffic load plots and its simplicity to read information, figure 1 shows the interruptions of airport traffic at London-Heathrow, due to the Eyjafjallajoekull volcano-ash cloud European airspace closure between April 15th and April 22nd 2010.

Just recently at the 66th IATA Annual General Meeting in Berlin, Giovanni Bisignani, CEO and Director General of IATA, commented in his speech "State of the air transport industry" on the impact of this week long airspace closure for the European and global economy: "April gave us a vivid picture of life without aviation: 10 million people stranded. Hotels and convention centers empty. Seafood and flowers rotting and just-in-time production delayed. The volcano cost the economy $5 billion, far more than the $1.8 billion of lost airline revenue. The eruption was a wake-up call. The message was clear: without air connectivity, modern life is not possible. Aviation is vital." (IATA 2010)



Source: Bubalo 2010

Figure 1: Vulcano Ash-cloud Disruption at London-Heathrow Airport in April 2010

It must be noted, that for a complete picture of overall productivity of an airport the airside and the landside must be assessed in combination, otherwise the picture will lack consistency and might result in ambivalent conclusions.

Assessment of landside productivity would include service quality measures of processes inside the terminal, which are not easy to calculate without detailed information on processing speeds of the various servers, e.g. check-in counters or baggage claim units. A slight hint on the efficient use of terminal capacity comes from the Minimum Connecting Times (MCT), which are used in the flight booking process to adequately connect transit flights. Table 1 shows the MCT for connections among and inside airports in the greater London area. It is striking that international connection flights from one terminal to the other at London Heathrow (LHR) airport can span between 45 minutes (Terminal 1 to Terminal 1) and 2 hours (Terminal 1 and Terminal 5). Therefore a large city like London with an airport system of four airports might offer more comfortable connections over the alternative airports London-Stansted (STN), London-Gatwick (LGW) or London-City (LCY).

Connection	From Terminal	To Terminal	Dom/Dom in HMM	Dom/Int in HMM	Int/Dom in HMM	Int/Int in HMM
LCY-LCY	-		30	30	30	30
LGW-LGW	N-	N	45	45	45	45
LHR-LHR	1-	1	45	45	45	45
STN-STN	-		45	45	45	45
LHR-LHR	4-	4	130	45	45	45
LGW-LGW	S-	S	40	45	100	55
LHR-LHR	2-	2	---	---	---	100
LHR-LHR	4-	1	100	100	115	100
LHR-LHR	3-	3	100	100	100	100
LHR-LHR	5-	5	100	100	100	100
LHR-LHR	1-	4	130	100	100	100
LHR-LHR	3-	2	---	115	115	115
LGW-LGW	S-	N	115	115	115	115
LHR-LHR	2-/3-	1	115	115	115	115
LHR-LHR	1-/2-/3-/4-	TN	130	130	130	130
LHR-LHR	2-/3-	4	130	130	130	130
LHR-LHR	1-/2-/3-/4-	5	200	200	200	200
LGW-LHR	-		230	230	230	230
LCY-LHR	-		300	300	300	300
STN-LGW	-		300	300	300	300
LHR-STN	-		320	320	320	320
STN-LHR	-		320	320	320	320
LHR-LTN	-		325	325	325	325
LGW-LCY	-		330	330	330	330
LHR-LCY	-		330	330	330	330
LCY-LTN	-		400	400	400	400
LCY-STN	-		400	400	400	400
STN-LTN	-		400	400	400	400

Source: Bubalo 2009 from Amadeus Selling Platform

Table 1: Minimum Connecting Times at Greater London Area Airports

Airport Peer Groups for Benchmarking

When dealing with different airports in size, location and stage of maturity it becomes obvious that comparisons among airports, e.g. benchmarking, is a difficult undertaking. This is even more so true for financial or economical comparisons, where different landing fees, accounting standards, national laws and regulations, levels of outsourcing and level of privatization frequently distort the results. Various papers point these complexities out and offer promising solutions (Graham 2008).

For an engineering perspective on airport benchmarking these difficulties exist in other ways, but it can already be concluded, that for a large portion of European airports comparisons of the airside operation are indeed possible. The main limitation for runway operations at airports result from safety separations between successive landing and departing aircrafts on the same runway and lateral separations between parallel runways, due to wake turbulences created by the wingtips of aircrafts. Encountering wake turbulences from preceding aircrafts during the critical landing and take-off phase can lead to seriously impact on the stability of an aircraft in the air. This is why air traffic control applies certain requirements in separating aircrafts of different sizes and weights. A “Small” aircraft (<7 tons) following a “Large” aircraft (7-136 tons) will experience safety distances of approximately 5 nautical miles than a “Large” aircraft following a “Small” aircraft, with a separation of approximately 3 nautical miles (NATS 2010; Horonjeff 2010). So the mix and sequencing of aircraft types obviously has a direct effect on runway capacity.

Traffic Mix expressed in Weight and Turbulence Class Shares and Mix Index per selected European Airport March 2008

Airport	Airport Code	Small	Large	Heavy	Mix Index
Amsterdam	AMS	0%	83%	17%	135%
Athens	ATH	0%	95%	5%	110%
Birmingham	BHX	0%	98%	2%	103%
Brussels	BRU	0%	90%	10%	121%
Cologne	CGN	0%	98%	2%	103%
Copenhagen	CPH	0%	96%	4%	107%
Dusseldorf	DUS	0%	97%	3%	106%
Frankfurt	FRA	0%	76%	24%	147%
Hannover	HAJ	0%	100%	0%	100%
London-City	LCY	0%	100%	0%	100%
London-Gatwick	LGW	0%	91%	9%	118%
London-Heathrow	LHR	0%	66%	34%	168%
London-Luton	LTN	0%	99%	1%	102%
Munich	MUC	0%	94%	6%	111%
Nice	NCE	46%	54%	1%	56%
Oslo	OSL	0%	100%	0%	100%
Palma de Mallorca	PMO	0%	100%	0%	100%
London-Stansted	STN	0%	99%	1%	102%
Stuttgart	STR	0%	99%	1%	101%
Vienna	VIE	0%	96%	4%	108%
Zurich	ZRH	0%	90%	10%	120%

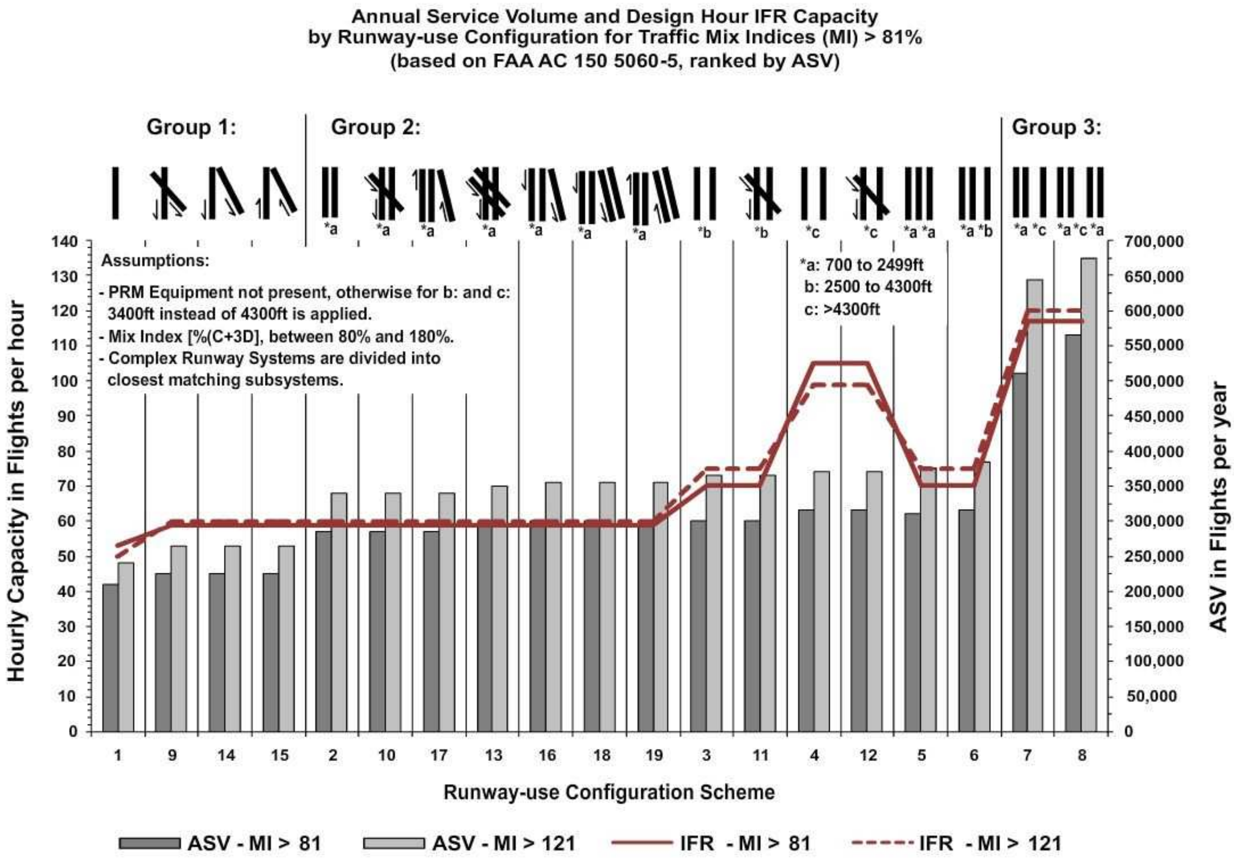
Source: Bubalo 2009

Table 2: Traffic Mix and Mix Index of selected European Airports

Table 2 shows the mix of different aircraft classes at some European airports. Since “Heavy” aircrafts (>136 tons) in the mix of an airport influence its overall throughput strongly, a mathematical expression, the Mix Index, has been adopted from the U.S. Federal Aviation Administration, which comprises the importance of the ”Heavy” class. The Mix Index (MI) adds to the (usually predominant) percentage share of "Large" aircrafts in the mix, the three-fold percentage share of "Heavy" aircrafts, therefore:

$$Mix\ Index = \ (\%\ class\ \text{"}Large\text{"}\ aircrafts) + \ 3x\ (\%\ class\ \text{"}Heavy\text{"}\ aircrafts).$$

Tretheway (2006) and Forsyth (2004) give the advice to isolate potential peer groups of airports, where among its peers a benchmarking analysis can be made. Earlier work (Bubalo 2008) isolates such peer groups according to the primarily used runway system and configuration and its according airport runway capacity. The underlying analysis of the capacity of runway systems at US airports has been conducted by the FAA and is documented in the Advisory Circular "Airport Capacity and Delay" (FAA 1995). The results presented in that document are used to isolate peer groups based on similar traffic mix and maximum productivity of runway operations, namely the annual and hourly capacity of an airport.



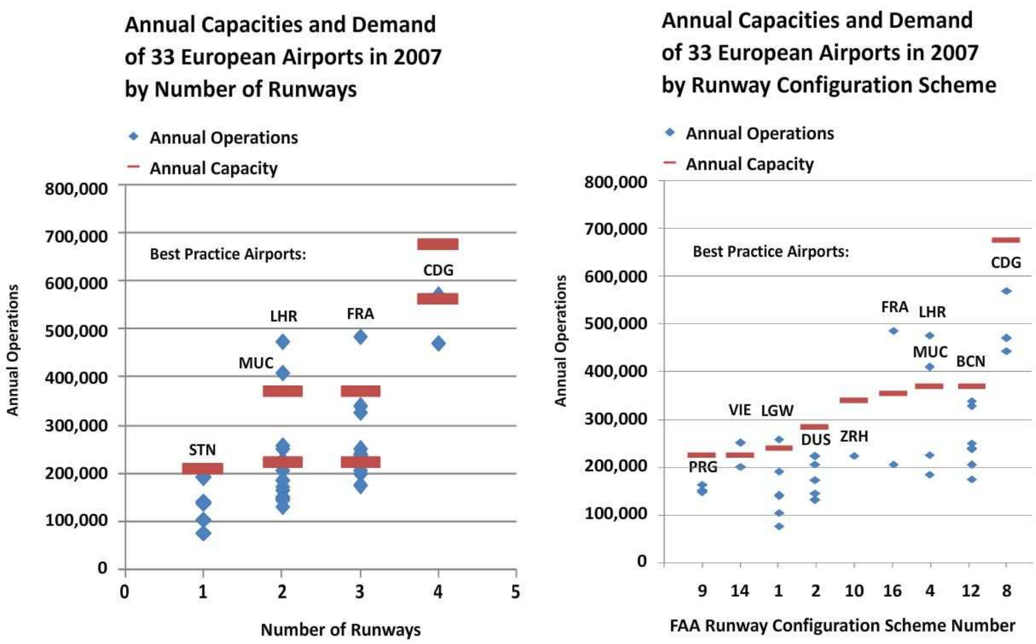
Source: FAA 1995; Bubalo 2008

Figure 2: Peer Groups of Airports based on Annual and Hourly Capacity

The Federal Aviation Administration (FAA) in the U.S. developed a simple technique to estimate order-of-magnitude annual and hourly capacity (FAA 1995; Horonjeff 2010, p. 532). As figure 2 shows, three main groups with approximately similar annual capacity have been isolated. Group 1 represents airports with a single runway, which might have an additional crosswind runway for changing wind directions. The extra crosswind runway will therefore not increase the overall runway capacity. Group 2 represents airports with parallel runways, which are less than 4300 feet/1.3 kilometers apart from each other. Most of the airports with separation indication *a (700-2500 feet separation) and *b (2500-4300 feet separation) in figure 2 can only be operated dependently due to safety regulations. Wake turbulences caused by aircrafts on one of the dependent runways can be shifted by winds into lateral direction and possibly impact aircraft at the parallel runway. Exceptions are configuration 4 and 12 with indication *c (>4300 feet separation), which allow independent operation of the runways and therefore have higher hourly capacities than its peers.

Group 3 includes all runway systems with complex configurations. This group's configurations have a minimum of two independent parallel runways and one additional closed parallel runway on one side (configuration 7).

When looking at the annual capacities from the FAA methodology and the annual operations of different European airports plotted by number of runways s shown in figure 3a), we find proof, that the sole usage of number of runways as an input parameter for productivity analyses with linear equations solving (e.g. Data Envelopment Analysis) leaves too much variation for upper and lower bounds of capacity to deliver adequate results. For example a doubling of number of runways would not necessarily result in a linear behavior and provide a doubling of capacity.



Source: Bubalo 2010

Figure 3a) and 3b): Comparison Annual Capacity and Demand by FAA Runway Scheme Number and by Number of Runways.

London Gatwick airport (LGW) is such an example, where this drawback of earlier analyses can be nicely shown. In a strict sense London Gatwick has two runways, but the Aeronautical Information Publication (AIP) of the airport states that the airport only operates one runway under its preferential runway-use system and uses the other one for taxiing aircrafts and emergencies. So only the FAA methodology would return the true capacity result by applying the runway-use configuration 1 for London Gatwick airport (Figures 2 and 3b). The FAA methodology requires the study of more detailed information of the operational characteristics of the airports chosen for the study. AIP information can be downloaded from the European AIS Database (EAD) from EUROCONTROL for any European airport.

Figure 3b gives a more diverse picture of different groups and subgroups of airports and its configurations and capacities. The direct effect on capacity of additional runways added to an airport could be estimated by either capacity approximations with the FAA methodology or the isolation of best practices. Figure 3b highlights the best practice airports in Europe for each runway configuration, which can alternatively be used as a benchmark. Frankfurt and London Heathrow are extreme examples of airports, which operate much over the approximated capacities, but those are the same airports that experience most of the annual delays (Table 3), which suggests that operations reach capacity quite frequently. London Gatwick (LGW) airport is a prominent example for a highly productive, but severely congested, single-runway airport. Even globally the 260,000 flights per year in 2007 are without comparison. On busy days this extraordinary performance of London-Gatwick can be observed even better. As a comparison the biggest single-runway airport in the U.S., San-Diego airport (SAN), reaches a far lower number of hourly operations, than its European counterpart. As it can be seen in the hourly arrival and departure plot of busy day traffic (the Gilbo Diagrams (Gilbo 1993)) of San-Diego and London-Gatwick airports in figures 4a) and 4b), San-Diego airport can only serve 34 hourly operations (17 arrivals and 27 departures simultaneously per hour, which are obtained by constructing or imagining a 45 degree line from the origin to the identical maxima of the identical scale of x and y), whereas London-Gatwick reaches an impressive maximum of 61 actual served flights (29 arrivals and 32 departures) during the peak day.

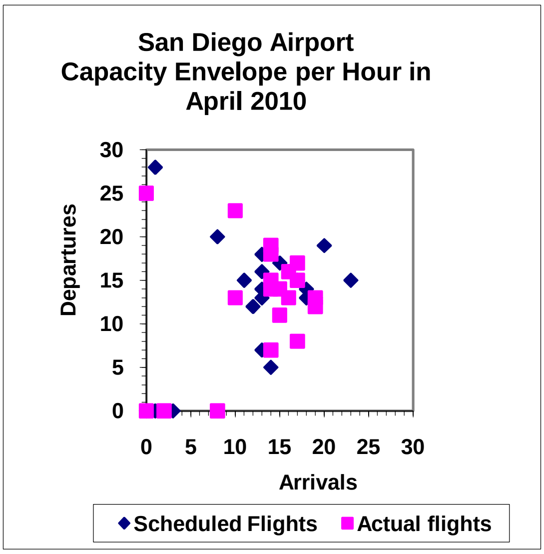
Of course Table 3 reveals that this high productivity comes at the expense of delay, which in the case of London-Gatwick resulted in ca. 80,000 delay minutes in 2006. Using the "cost per minute of delay" estimations from the Eurocontrol document "Standard-Inputs for Cost-Benefit Analysis" (Eurocontrol 2009) it is possible to derive annual delay costs for the top 21 congested airports in Europe (Table 3). Value of time estimated at 42 Euro per minute of delay results in an approximate total of 3.3 million Euros at London-Gatwick in 2006 (network knock-on effects not included).

It is not surprising that London-Heathrow airport tops Table 3, causing an enormous 9-fold delay of London-Gatwick (Rank 16th) of 715,761 minutes of delay, resulting in an approximate annual delay cost of 30 million Euros.

	Airport Name	IATA	ICAO	Experienced Delay 2006 in Minutes	Annual Delay Costs at 42€ per Minute (Eurocontrol 2009)
1.	LONDON HEATHROW	LHR	EGLL	715761	30,061,962
2.	FRANKFURT MAIN	FRA	EDDF	671693	28,211,106
3.	MILANO MALPENSA	MXP	LIMC	626853	26,327,826
4.	WIEN	VIE	LOWW	534717	22,458,114
5.	ROMA FIUMICINO	FCO	LIRF	464088	19,491,696
6.	MADRID BARAJAS	MAD	LEMD	388094	16,299,948
7.	MUENCHEN	MUC	EDDM	343938	14,445,396
8.	ZURICH	ZRH	LSZH	248709	10,445,778
9.	PARIS ORLY	ORY	LFPO	242897	10,201,674
10.	ISTANBUL - ATATUERK	IST	LTBA	216167	9,079,014
11.	SCHIPHOL	AMS	EHAM	151918	6,380,556
12.	COPENHAGEN/KASTRUP	CPH	EKCH	124148	5,214,216
13.	LONDON CITY	LCY	EGLC	111567	4,685,814
14.	PRAHA RUZYNE	PRG	LKPR	105861	4,446,162
15.	PARIS CH DE GAULLE	CDG	LFPG	81062	3,404,604
16.	LONDON GATWICK	LGW	EGKK	79190	3,325,980
17.	ROMA CIAMPINO	CIA	LIRA	60362	2,535,204
18.	MANCHESTER	MAN	EGCC	59495	2,498,790
19.	TEGEL-BERLIN	TXL	EDDT	55816	2,344,272
20.	LONDON STANSTED	STN	EGSS	53408	2,243,136
21.	PALMA DE MALLORCA	PMI	LEPA	44508	1,869,336
	Total			**5,380,252**	**225,970,584**

Source: Eurocontrol CFMU 2009,

Table 3: Annual delays and calculated delay costs of European airports in 2006



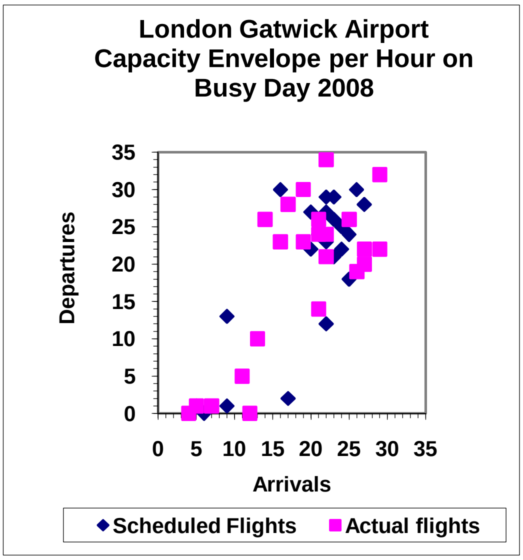


Figure 4 a) and 4b): Gilbo Diagram of Single Runway Airports San Diego, USA and London Gatwick

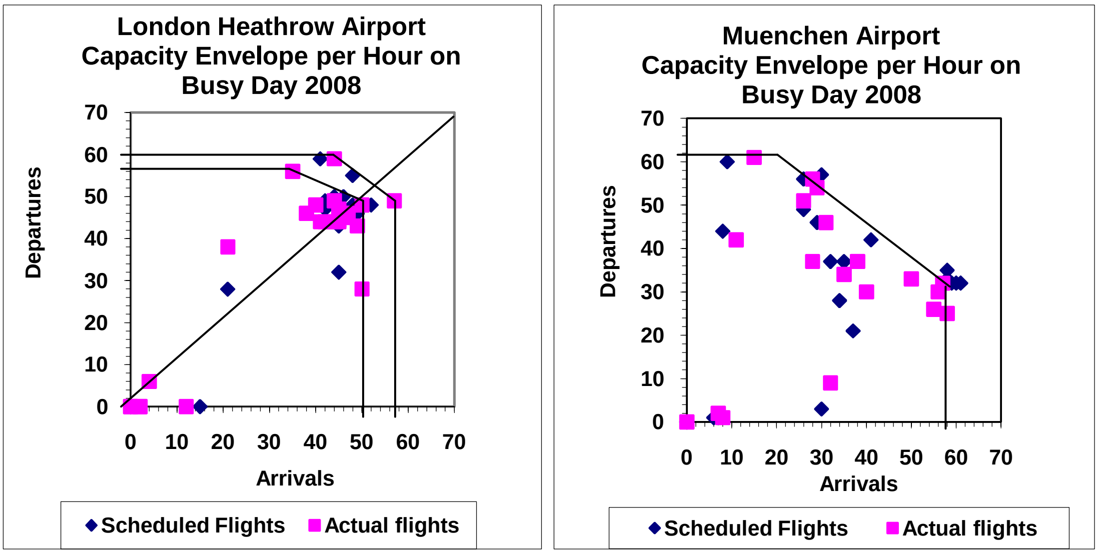


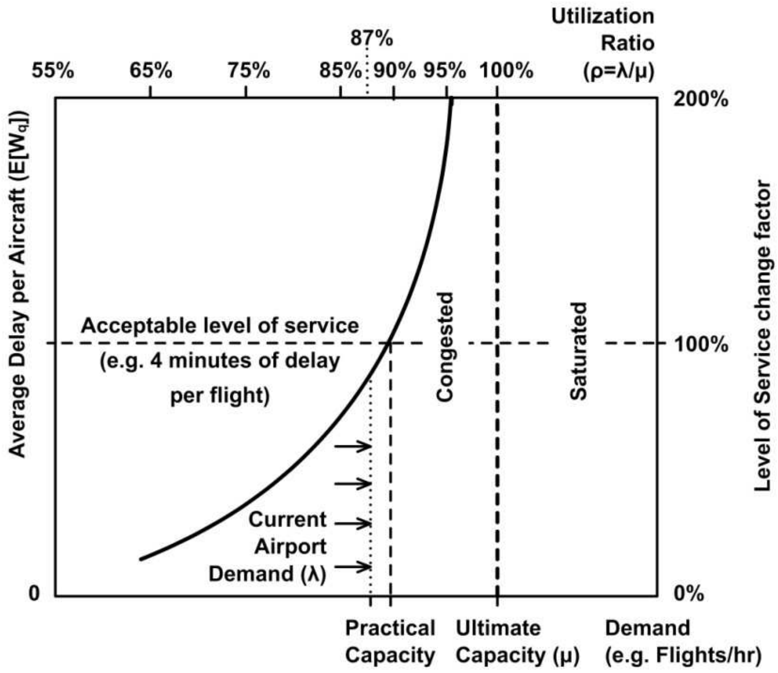
Figure 4c) and 4d): Gilbo diagram for Parallel Runway Airport London Heathrow and Munich

Airport Capacity and Delay

But what exactly is the importance of airport capacity? Airport capacity represents the limit of productivity under current conditions in a specific time, usually per hour, per day, per month or per year. An airport operator should make clear that the airport operates and serves demand below a practical capacity, where an acceptable level-of-service of e.g. four minutes average delay per daily flight, is guaranteed for the airport users. The practical or sustainable capacity should never be exceeded for longer periods. As it can be seen in figure 5), the closer an airport operates towards its ultimate or “physical” throughput capacity, the stronger delays increase beyond an acceptable level of service, and eventually delays reach infinity, which means flights never leave the gate or wait an infinite time in the holding pattern in the airspace. Therefore the arriving and landing aircraft have priority over departing aircraft, due to limited fuel reserves which allow waiting in the holding stack in the airspace only for a certain period of maybe 20-30 minutes maximum.

At congested airports, which are slot coordinated, the amount of hourly capacity must be declared by the airport operator (IATA 2010b). The declared capacity is the common denominator of all processes at an airport involved in serving passengers, aircrafts or cargo. Ideally the declared capacity is close to the practical capacity

Temporary collapsing of the airport system can be seen already during weather events like snow, fog, heavy rain and winds, when an airport’s airside (runway) capacity could largely be reduced due to poor visibility and lateral winds, which exceed the safety limit. This can happen quite frequently in some regions of Europe.



Modified from: Horonjeff 2010, p. 488

Figure 5: Fundamental relationship between Demand, Capacity and Delay

It is indeed always possible for demand to exceed capacity for short periods of time, due to fluctuations of demand at the airport. The situation becomes more critical when capacity us utilized more than 100% over a minimum of one hour and measurable waiting queues and delay will develop (Horonjeff 2010).

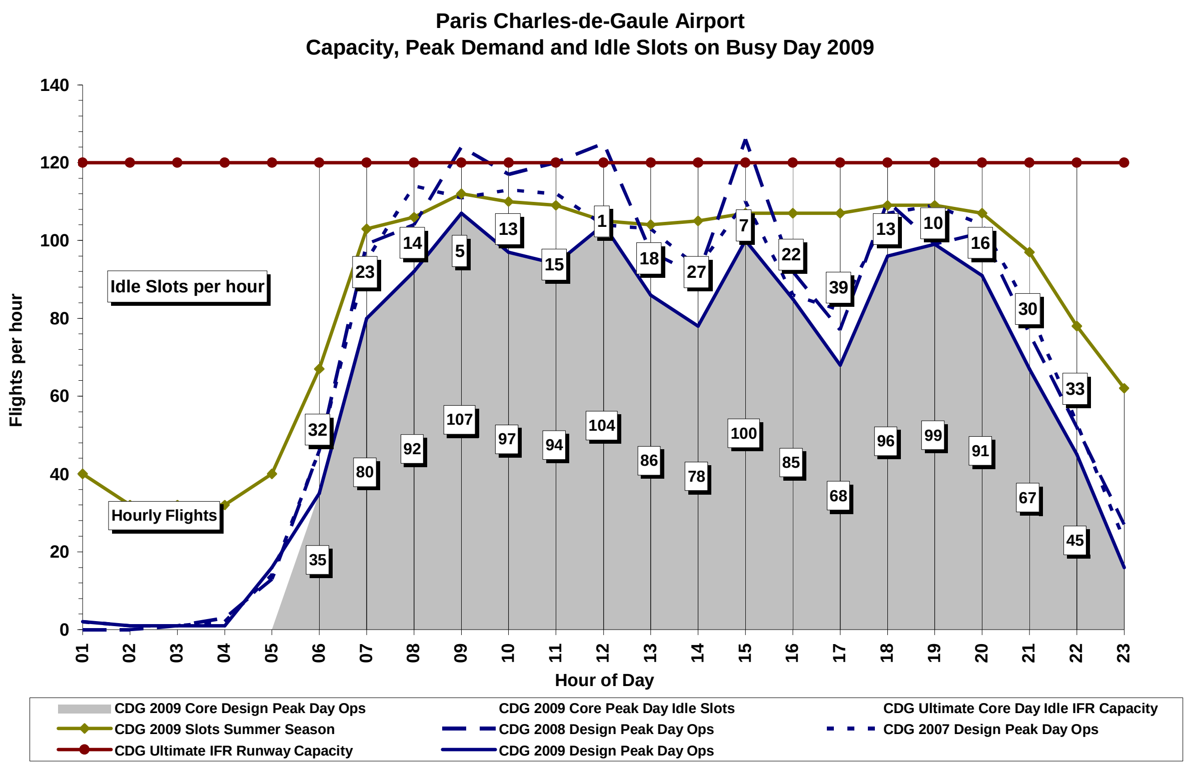
As we can see from figure 5 it can make a huge difference in service quality, e.g. average delay per flight, if an airport operates at a capacity utilization of 65%, 75%, 85% or more. Practical capacity usually serves as declared capacity for the slot coordinator and should never exceed 85-90% of the ultimate capacity during consecutive busy hours, otherwise the airport system is unstable and sensitive to changes in demand or available capacity, e.g. due to unscheduled flights, runway incursions or weather.

The practical capacity for the maximum sustainable landing and departures at a particular airport can be estimated constructing the Capacity Envelop in the Gilbo Diagram of a specific airport of interest (figure 4c) and 4d)). With data of many operating hours these kind of diagrams deliver a precise picture of how many arrivals and departures are maximum possible under current conditions. In the case of the Gilbo diagrams of London-Heathrow 4c) and Munich 4d) airports the practical capacity is 100 flights per hour (50 arrivals and 50 departures simultaneously per hour) for London and 82 flights per hour (41 arrivals and 41 departures simultaneously per hour) for Munich. Actually the Gilbo diagram for Munich reveals that the airport achieves its best operational performance with a 64% (57 arrivals per hour) and 36% (32 departures per hour) share of arrivals to departures, resulting in a total of 89 hourly flights.

The Gilbo diagrams can be modified to include the frequency of occurrence of each plotted point. This has been done by Kellner (2009) to derive so-called “density plots”. The density plots can then be used to isolate outliers and to establish frequency thresholds, e.g. occurrences 95% of the time.

Traffic Load Diagrams

For a general overview over demand and capacity the traffic load diagrams over time of day are very interesting. The hourly demand can be monitored and quantified with these plots. Certainly the diagrams offer even more information by including hourly capacity data, e.g. hourly capacity under Instrument Flight Rules (IFR) from the FAA methodology, declared capacity or available slots. Figure 6 gives an example of such a diagram for Paris Charles-de-Gaule (CDG) airport on a design peak day 2009, where it can be observed that this airport has a high productivity of about 100 flights per hour and uses its slot capacity of about 110 Slots per hour very efficiently. In contrast the traffic at Charles-de-Gaule airport in 2008 was much higher with exceeding the slot capacity and even exceeding the IFR capacity of 120 flights per hour.



Source: Bubalo 2010 with data from Flightstats.com

Figure 6: Traffic Load and Capacity Diagram

The expression for the amount of used slots and/or IFR capacity is the Capacity Utilization, which is generally speaking the quotient of demand divided by capacity. In particular the annual capacity utilization is the annual operations divided by the annual service volume, and the hourly capacity utilization is the design peak hour demand divided by the available slots per hour or estimated IFR capacity. For a selection of capacity utilization figures please refer to the basic airport data Table 4 in the appendix.

Conclusions

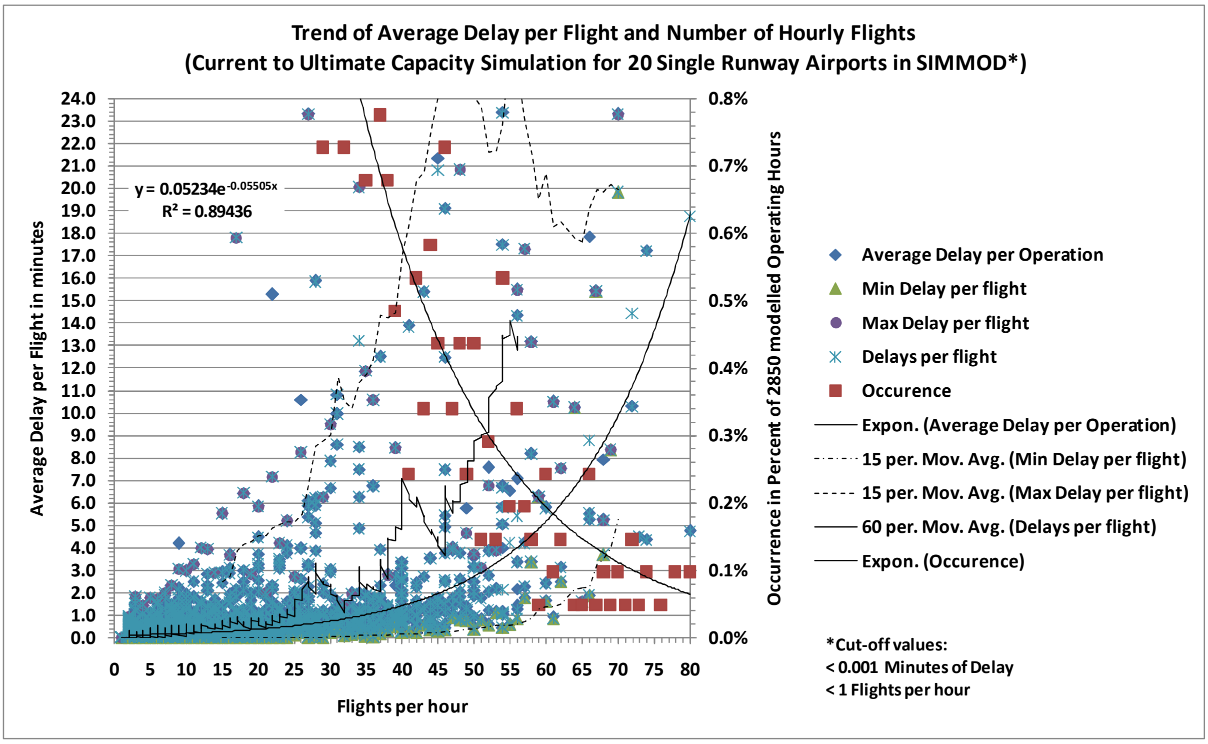
As it could be shown for London-Heathrow and Gatwick airports, the high productivity of both airports results in huge amounts of experienced delay and delay costs for the airport users. It is ongoing research of how this externality of highly productive airports can be included in productivity and efficiency analysis to be able to make fair assumptions and comparisons of airports with regard to service quality and externalities.

Another crucial externality of air transportation is annoyance caused by aircraft noise on the community in the vicinity of airports. Cumulative long-term aircraft noise is made responsible for all kinds of stress symptoms, which could even lead to decreased life expectancy, due to cardiovascular diseases (Greiser 2007). Aircraft noise and community annoyance and resulting health effects are currently being studied at the EU level. Another important research project (MIME-Market-based Impact Mitigation for the Environment) is currently looking into the feasibility of transforming noise/annoyance into tradable noise permits for a market based approach to reducing aircraft noise.

The difficulty for including these externalities into recent econometric analyses for calculating airport productivity has been the non-linear relationship between number of operations and delay or noise. The second issue is the maximization of output (e.g. annual operations) and the simultaneous minimizing of “unwanted” output (e.g. noise and delays) in input/output analysis.

The taken approach to airport productivity analysis concentrates more on the fundamental understanding of externalities of air transportation than on actually conducting a holistic analysis.

An earlier capacity study of 20 European single-runway airports, which simulated airside airport operations and increasing growth of demand in SIMMOD (A popular simulation and modeling software developed by the FAA), gave great insights into queuing problems at airports in general. In the SIMMOD study the relationship between capacity, demand and delay could be clearly observed (Figure 7).



Source: Bubalo 2009

Figure 7: Trend of Average Delay per Flight for European Single-runway airports

Figure 7 shows the trend of delay per flight from the results of all 20 simulated airports. To get an impression of the spread of simulated delays in each of the modeled 2850 operating flight-hours, an upper and lower boundary in addition to the moving average and exponential trend for delays has been plotted. Although heteroscedasticity can be observed in the plotted data, the trend lines provide enough evidence for an over-proportional increase of delays with an increasing number of operations per hour at single runway airports as it has been presumed earlier from the theoretical relationship between demand, capacity and delay depicted in figure 5.

The observed simulation data includes traffic data of congested and soon-to-be-congested single-runway airports, like London-Gatwick, London-City, London-Stansted, Birmingham or Stuttgart airport (Bubalo 2009). By steadily increasing traffic in the simulations from a baseline scenario to an ultimate growth scenario, the goal was to reveal the ultimate capacity of each modeled airport. The results shown in figure 7 give an indication of the maximum throughput of single-runway airports in Europe. It is interesting to note that from a relatively low level of demand of between 35 to 40 flights per hour, delays and random effects start increasing strongly. At 40 Flights per hour the lower boundary reveals 0.3 minute of average delay per flight, the moving average over a constant period of 60 data points reveals 6 minutes per flight and the upper boundary reveals 14 minutes per flight. At 50 flights per hour the situation is more critical, when .5 minutes of delay at the lower limit, 8 minutes of delay on average and over 24 minutes of delay at the upper limit can be observed.

It should be noted that the discontinuity of the trend curves could be due to airports being excluded from the simulation at high growth scenarios due to occurring grid locks from lack of apron capacity.

Ultimately it can safely be concluded, that 60 flights per hour represent the ultimate capacity of single-runway airports in Europe, above which unpredictability is predominant. It is quite remarkable that an airport like London-Gatwick has a peak throughput of 61 flights per hour in 2008, where there just could be no margin-of-safety or latent capacity for further growth under those circumstances. One can only imagine the high workload for air traffic control (ATC) staff and tight sequencing of aircrafts for arrivals and departures at London-Gatwick airport.

Since the (hourly) practical capacity is about 85-90% of the ultimate capacity of 60 flights per hour, we derive a practical capacity of between 51 and 54 flights per hour on average for European single-runway airports. This figure is almost identical with the order-of-magnitude figures from the FAA methodology.

Further research will deliver more insights in simulating and modeling of more complex airport systems with more than one runway. A study on parallel-runway airports is currently in progress.

Noise and CO2-emissions will be included in future capacity studies, as soon as new results and legislation in these fields is being published. A promising approach for quantifying noise can be found by the “Enhanced Quota Count System” (Figlar 2009), which enables the transformation of noise into tradable permits with a continuous function adopted from the Quota Count System, which is already in place at some of the congested European hub airports.

Evaluation of mitigation of carbon emissions with the ETS must be analyzed further as information becomes available after the first trading round.

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Appendix:

					Annual Demand		Annual Capacity	Annual Capacity Utilization		Peak Hourly Demand		Hourly Capacity Utilization	
					2007	2007	2007	2007	2009	2008	2009	2008	2009
Group	**Airport**	**IATA**	**No of Runways**	**FAA Runway config. No.**	**Annual Passengers (in million)**	**Annual Flights**	**Annual Service Volume**	**Annual Capacity Utilization**	**Slots per hour Summer Season**	**Flights per hour**	**Flights per hour**	**Slot Utilization**	**Slot Utilization**
3	Paris Charles-de-Gaule	CDG	4	8	59.55	569,281	675,000	84%	105	126	107	120%	102%
3	Madrid-Barajas	MAD	4	8	51.40	470,315	565,000	83%	100	112	112	112%	112%
3	Amsterdam	AMS	6	8	47.85	443,677	635,000	70%	108	111	106	103%	98%
2	Frankfurt/Main	FRA	3	16	54.50	486,195	355,000	137%	83	89	87	107%	105%
2	London-Heathrow	LHR	2	4	68.28	475,786	370,000	129%	86	103	90	120%	105%
2	Munich	MUC	2	4	34.07	409,654	315,000	130%	90	93	92	103%	102%
2	Barcelona	BCN	3	12	32.81	339,020	315,000	108%	60	80	74	133%	123%
2	Rome-Fiumiciano	FCO	3	12	33.62	328,213	315,000	104%	90	103	100	114%	111%
2	Copenhagen	CPH	3	12	21.40	250,170	315,000	79%	83	70	62	84%	75%
2	Brussels	BRU	3	12	17.93	240,341	370,000	65%	74	71	67	96%	91%
2	Paris-Orly	ORY	3	12	26.42	238,384	315,000	76%	70	63	60	90%	86%
2	Oslo	OSL	2	4	19.04	226,221	315,000	72%	60	60	49	100%	82%
2	Zurich	ZRH	3	10	20.81	223,707	340,000	66%	66	57	57	86%	86%
2	Dusseldorf	DUS	2	2	17.85	223,410	285,000	78%	47	51	58	109%	123%
2	Manchester	MAN	2	2	22.33	206,498	285,000	72%	46	69	51	150%	111%
2	Istanbul	IST	3	16	25.49	206,188	300,000	69%	40	44	47	110%	118%
2	Stockholm-Arlanda	ARN	3	12	18.01	205,251	315,000	65%	80	61	50	76%	63%
2	Palma de Mallorca	PMI	2	4	23.10	184,605	315,000	59%	60	44	45	73%	75%
2	Helsinki	HEL	3	12	13.10	174,751	315,000	55%	80	41	44	51%	55%
2	Nice	NCE	2	2	10.38	173,584	260,000	67%	50	52	48	104%	96%
2	Berlin-Tegel	TXL	2	2	13.37	145,451	285,000	51%	52	42	42	81%	81%
2	Lyon	LYS	2	2	7.19	132,076	285,000	46%	51	44	43	86%	84%
1	London-Gatwick	LGW	2	1	35.27	258,917	240,000	108%	46	56	49	122%	107%
1	Vienna	VIE	2	14	18.77	251,216	225,000	112%	66	67	59	102%	89%
1	Dublin	DUB	3	14	23.31	200,891	225,000	89%	46	44	43	96%	93%
1	London-Stansted	STN	1	1	23.80	191,520	210,000	91%	38	47	38	124%	100%
1	Prague	PRG	2	9	12.40	164,055	225,000	73%	46	57	39	124%	85%
1	Hamburg	HAM	2	9	12.85	151,752	225,000	67%	53	44	38	83%	72%
1	Warsaw	WAW	2	9	9.29	147,985	225,000	66%	34	32	26	94%	76%
1	Lisbon	LIS	1	1	13.52	141,905	210,000	68%	36	37	34	103%	94%
1	Stuttgart	STR	1	1	10.35	139,757	210,000	67%	42	41	35	98%	83%
1	Birmingham	BHX	1	1	9.32	104,480	210,000	50%	40	29	28	73%	70%
1	London-City	LCY	1	1	2.91	77,274	210,000	37%	24	36	36	150%	150%
	Mean		2		24.55	247,955	310,909	79%	62	63	58	102%	94%

Table 4: Basic Data of selected European Airports