

Airport Evolution and Capacity Forecasting

Branko Bubalo Dipl.-Wirtsch.Ing (FH)
 German Airport Performance (GAP) Project
 c/o Berlin School of Economics and Law
 Berlin, Germany
 branko.bubalo@googlemail.com

Abstract— The growth of airports is typically limited by landside or airside capacity. From a commercial perspective, large stable volumes of passengers are desired to pass through the airport facilities, but in reality demand fluctuates daily and hourly. Management at congested airports has to work under certain trade-off conditions, where runway throughput could be affected by a growing number of average passengers per flight, because Heavy aircraft (offering a large number of seats) require further separations minima between succeeding flights. Consequently the sequencing of batches from the same aircraft category must take place. Decisions and timing regarding airport expansion must be based on reviewing scenarios which consider the mix of (future) aircraft types and growth of traffic, long before certain level-of-service thresholds are exceeded. An emphasis is placed on methods of assessing baseline and future peak time traffic volumes and level-of-service through observations and simulation including the concept of simultaneous occupation of space.

Keywords— Airport Capacity, Airport Design, Delay, Forecasting

I. INTRODUCTION

In recent years it could be observed that large infrastructure investments were taking place in many countries worldwide. In developing countries and markets, infrastructure is built on a large scale. With increasing income and wealth, people and their economies develop the need for energy, goods, information and mobility. This leads to the progressive installation of domestic or continental telecommunication, energy transmission and transportation networks. Because economies and markets are strongly interlinked, in times of globalization they cannot be viewed in isolation. Therefore, as our own (e.g. European or North-American) need for new infrastructure grows and approaches some level of maturity, this is not the case for many countries, e.g. in Asia. On the other hand, the substantial growth of the economies in countries like Brazil, Russia, India and China (BRIC) will have a huge impact on national air transportation and its infrastructure (FAA 2007). Prior to the global financial crisis the Challenges of Growth report (EUROCONTROL 2008) estimated for a most-likely scenario a near doubling of 2007 traffic levels until 2030. In the future it is expected that an increasing flow of traveling passengers originating from e.g. BRIC countries will transfer or terminate at European airports (de Neufville 1995: p. 6).

Besides instant communication people in (transformed) industrialized countries demand rapid transportation for business or leisure needs. Airline profits not only in the domestic European air transport market are largely driven by frequent business travel, although tourism or personal (leisure) travel still accounts for most of the demand on many routes. In general profitability of airlines, even at times of high load factors, looks bleak at the moment, mainly as a result of low fares and continuously high fuel prices. This situation will lead to further consolidation or failures of airlines (ACRP 2010: p. 8).

II. AIR TRANSPORTATION DEREGULATION & LOW COST COMPETITION

Since the mid-seventies in the U.S. and during the 1990s in Europe, regulations concerning prices, routes and the scheduling process for air travel were gradually abandoned, allowing for more freedom for different business strategies and leading to increased competition among airlines. Low cost carriers (LCC), also called low fare airlines, entered the European short- and medium-haul market in the late 1990s with airlines like Ryanair and EasyJet, which were able to offer much lower fares than their established counterparts, and consequently captured a large share of the market. This development brought more competition and opportunities, but also at the same time huge challenges to various portions of the European air transport system. As de Neufville (2008) points out, there will be a war over prices and capacities (Table 1) not only among airlines and airline alliances, but also between major hub airports.

Choice	Before Deregulation	After Deregulation	Implications of Deregulation
Routes	Strictly controlled	Freedom to change	Loss of secure tenure
Prices	Set by formula	Freedom to change	Price wars
Frequency of flights	Controlled	Freedom to set schedules	Capacity wars
Aircraft type	Often controlled	Freedom to choose	Capacity wars

Table 1: Airlines before and after Deregulation. (Source: de Neufville 2008)

With the success of LCC, a network of secondary airports (de Neufville 2005) is evolving across Europe. Airports, which used to be operated in a safely regulated climate, under federal authority and fed with subsidies, must now learn to compete against privatized and rapidly growing secondary airports. Therefore most international European airports are going through a somewhat painful transformation process towards

becoming modern profit oriented businesses (Graham 2005: p. 99; IATA 2004: p. 109).

different layers of hub-and-spoke, point-to-point or hybrid type networks (de Neufville 2005).

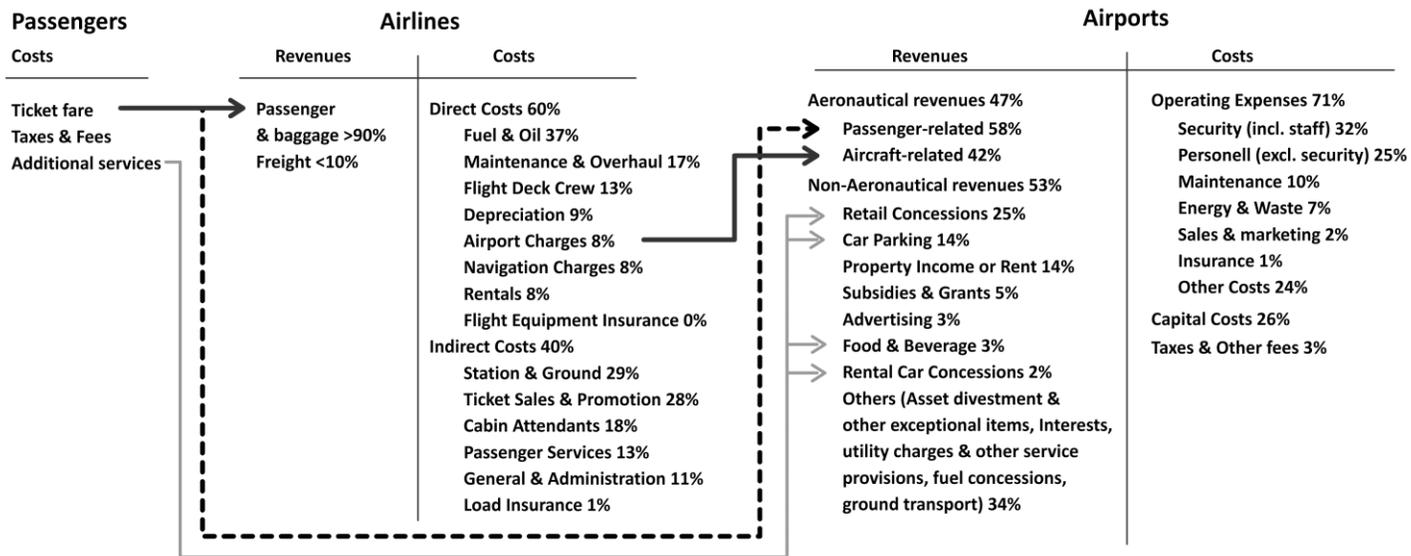


Fig. 1: Sources of Revenue and Costs in the Air Transportation Industry (compiled from AEA 2008 and ACI Europe 2010)

III. AIR TRANSPORTATION ECONOMICS

It is a great relief for the air transportation industry that the global economy is back on track and that demand for air transportation in 2010 reached previous levels of 2008. Only the price for jet fuel remains almost 3-fold higher when compared to 2000, at currently 107 US-Dollars per barrel (IATA 2011).

Secondary airports not only offer specialized services for LCC, but also for other customers, e.g. business aviation, general aviation, cargo or the military (de Neufville 2000). Typically, especially in the U.S. and in Japan, in metropolitan or general catchment areas with large populations, multi airport systems are in place (de Neufville 2003: p. 129 ff., 2005; Bonnefoy et al. 2010), which are able to serve this wide variety of airport clientele. Consequently it may be anticipated that competition will intensify on comparable routes from different airports in those same regions.

Fuel prices are not the only dark cloud on the horizon however. Additional taxes and regulations, e.g. regarding environmental issues, (mainly noise, CO2 and NOx emissions), place further financial pressure on airlines, which in turn look for opportunities to reduce costs in their balance sheets. Thus airlines try to lower the aircraft landing charges at airports, in some cases threatening to divert their traffic to alternative locations (Walters 1978: p. 132) in an effort to force airports into cooperating.

Already today, when traveling from Rome to London, the difference in time, distance and convenience is negligible, whether the route Rome-Ciampino to London-Stansted airport (served mainly by LCC) or Rome-Fiumicino to London-Heathrow airport (served mainly by flag carriers) is chosen, but the difference in ticket fare is significant. In the greater London area, there are five international airports Heathrow, Stansted, Gatwick, London-City and Luton. Furthermore the greater London region has the highest density of airports and airstrips in Europe, which may serve as additional reliever airports in the future. Paris is served by three airports, Charles-de-Gaulle, Orly und Le Bourget. In contrast the multi airport system of Berlin with Tegel, Schönefeld and Tempelhof will be fully replaced by the single-airport Berlin-Brandenburg International (BBI) in 2012 (Bubalo and Daduna 2011).

Fig. 1 shows how the main stakeholders in commercial air transportation – the passengers, airlines and airports - are connected financially. Ticket fares paid by passengers for scheduled services are the dominating source of revenue for European airlines, accounting for over 90% of the revenues. Additional revenue increasingly comes from cargo services. On the cost side, airlines have to work with very high (variable) direct operating costs, mainly due to the necessary fuel, flight crew and maintenance for their flights (Wensveen 2007: p. 304). The split between direct and indirect costs for members of the Association of European Airlines (AEA) is approximately 60% to 40%. Airport charges account for about 8% of direct operating costs, but together with air navigation charges these amounts represent 16% of the direct costs or about 10% of the total airline costs.

Although reliever airports will experience strong growth, it is the main European hubs that will dominate the air transport system and which will need adequate airport capacity. A hub is a main international airport which links the hinterland and national routes, the spokes, with international connections. We therefore speak of a hub-and-spoke network in Europe. Over time, with new routes and airports, this will transform into

The airport charges present a major source of income for the airports and feed directly into the aircraft-related and passenger-related revenues as part of general aeronautical revenues. The aircraft-related charges or revenues are paid directly by the airlines to the airports on an aircraft maximum

take-off weight (MTOW) basis and are usually subject to negotiation. Other charges are collected as published in the airport charges manuals for services such as aircraft gate stand or parking space, provision of fuel; towing, aircraft maintenance and sanitation (Walters 1978: p. 133). In the case of passenger-related charges or revenues, these are collected by the airlines for the airports on a per passenger basis for passenger services mainly inside the terminal facilities.

Data from the Airport Council International (ACI) Europe (2010) suggests a split of 47% to 53% between aeronautical and non-aeronautical revenues among its member airports in 2008. Non-aeronautical revenues result from offering additional services to airport customers. These additional services include e.g. shopping, car parking, food and beverages, and car rental facilities. The various types of customers, domestic, leisure, international and business passengers, request many additional services which are provided by airports. For many airports the terminals represent strong revenue generators. As noted earlier, around 50% of total airport revenue is generated from non-aeronautical (commercial) activities, mainly from providing space for shops, restaurants, offices, conference rooms and even hotels. Airports have become vital socio-economic centers where passengers enjoy spending time and money. Then too the close proximity to air transport is increasingly beneficial to many local and regional businesses. These factors combine as high-demand airports evolve into larger entities, which are increasingly closely linked to the immediately surrounding region. Such airports could be described as airport city, aerotropolis (John D. Kasarda) or airport region (Fig. 2).

commercially underdeveloped airports with only basic services, such as duty-free and souvenir shops or restaurants.

The operating expenditures of European airports include costs for labour (25%), airport maintenance (10%), energy and waste (7%), and adequate safety and security (32%). Operating costs account for 71% of total costs, whereas capital costs for investments in airport infrastructure accounts only for 26% of the total costs (ACI Europe 2010).

IV. AIRPORT DEMAND

Passengers rarely have a great deal of choice regarding accessible airports, and certainly most metropolitan hub airports have a virtual monopoly for serving a large densely populated area with routes to international destinations. Furthermore connecting or transfer passenger traffic is a strongly competitive market among hub airports in Europe, especially regarding intercontinental long-haul high-yield routes. It is indeed difficult to find accurate data about the amount of transfer passengers (de Neufville 2003: p. 134) shared among European airports, which would allow estimates to be made about the additional income generated by this group, e.g. by retail or food and beverage sales. By conducting surveys more information about the preferences of transfer passengers is gathered.

The data from ACI provides insight into the number of international passengers at the top global airports (Table 2), which are arguably equally interesting as a target group in their own right from a purely commercial point of view (IATA 2004). Surprisingly table 2 shows many European airports at top of the list among the largest global hubs ranked by the

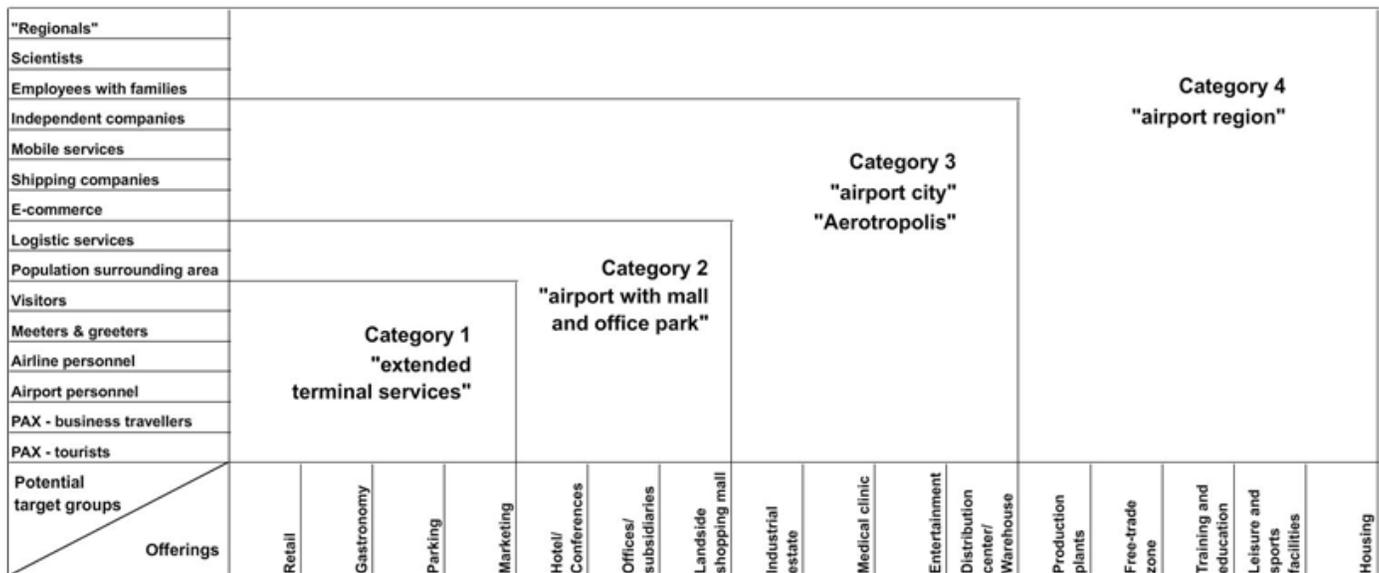


Fig. 2: Potential Target Groups and Offerings at Airports (A.T. Kearney 2008)

Airports handling a large share of freight not only need to guarantee quick transit times, but also need to provide state-of-the-art facilities for sorting, packing, storing and distributing shipments of logistic companies (A.T. Kearney 2008). However, globally we still find many examples of

number of international passengers in 2008, i.e. London-Heathrow (1.), Paris-Charles-de-Gaulle (2.), Amsterdam (3.) and Frankfurt (5.). In the U.S. we find airports serving even more total passengers and total flights than what is shown in table 2, but this market is largely driven by domestic demand, such as at Atlanta-Hartsfield, Dallas-Fort Worth or Chicago-O'Hare airports.

Even at a major internationally recognized airport like New York-John F. Kennedy international passengers make up only 47% of the total passengers at that airport. Of course when dividing the market at European airports into domestic intra-EU flights and international extra-EU flights, only three airports (Paris-Charles-de-Gaulle, London-Heathrow and Frankfurt-am-Main) can be identified as having number of flights with passengers originating or terminating outside of Europe larger than 50% (Eurostat 2008).

A. Economies of Scale through Size of Aircraft

Financially airports rely heavily on the amount of passenger traffic passing through their facilities and using their services. In the past airports were mainly concerned about convenience of service for the primary carriers stationed there, which were normally their largest clients. For this reason they were less interested in airline load factors or available seats per flight. Today, it is generally recognized that airports benefit directly from strong demand and the economies of scale which are needed by airlines to achieve profits through large volume, highly utilized and highly frequented scheduled flights (Walters 1978: p. 131; de Neufville 2000: p. 5; IATA 2004: p. 109).

However airports also share the financial risk of declining passenger demand on individual routes and flights. A superior level-of-service (LOS) at airports is a precondition for airlines to meet their turnaround times and to maximize aircraft utilization. Both airlines and airports increasingly have a keen interest for making travelling seamless and enhancing the travel experience for the passengers, which ideally leads to repeated visits or connections, by, for example, business travellers (customer retention). The trend illustrated in Fig. 3 for selected UK airports can be observed when spare capacity at airports is shrinking, but demand is rising. Since additional demand cannot be satisfied by airlines by increasing the frequency of flights at selected airports with capacity limitations, the growth of such markets is only possible by means of higher load factors or larger aircraft, resulting in more average passengers per flight (IATA 2004: p. 91).

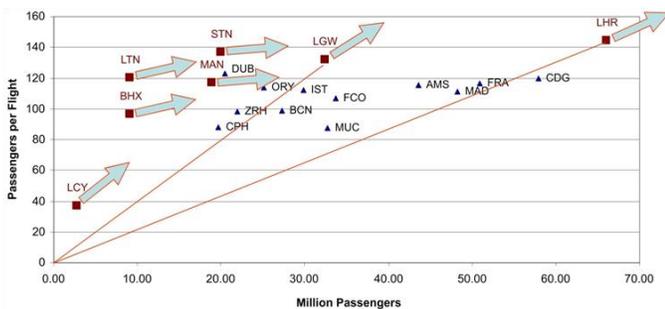


Fig. 3: Trend of Passengers per Flight as Airport Size and Utilization Increases (Source: Mott MacDonald 2010)

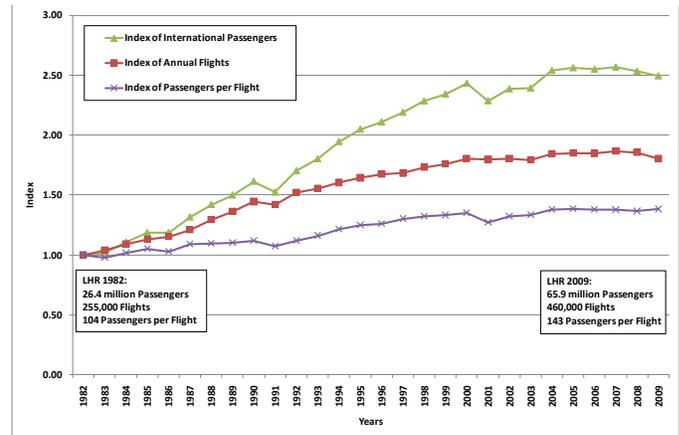


Fig. 4: London Heathrow Trend in Annual Passengers and Flights from 1982 to 2009 (Source: UK Civil Aviation Authority)

When studying the trend in passengers, movements and passengers per flight at London-Heathrow airport over the last three decades (Fig. 4), the direct effect of the number of average passengers per flight on the resulting number of annual passengers can be observed. Especially between 1991 and 2000 small continuous increases in the number of average passengers per flight, parallel to small increases in annual aircraft movements, led to a substantial boost in passenger numbers at London-Heathrow from 40 to 64 million. From 1982 to 2009, passenger numbers at Heathrow increased by 150% (from 26.4 to 65.9 million), and number of flights increased by 80% (from 255,000 to 460,000). Passengers per flight grew by a moderate 40% (from 104 to 143).

In absence of available data before 2003, the relation between available seats and passengers on board, the (seat) load factor, at London Heathrow airport is assumed to have remained constant over the last decades, at around 72-74%.

B. Estimating Capacity through Design Peak Demand

Similar to other modes of transport and especially regarding scheduled services, demand at airports fluctuates by the hour, the day, the week, the month, and the year. Therefore demand and capacity are typically expressed by these time bases, such as for example flights or passengers per hour. The capacity of an airport on the airside (runways, apron, aircraft parking space) is mainly determined by the aircraft mix and associated separation minima between aircraft types of different weight and wake turbulence categories, and runway configuration (FAA 1983). On the landside (passenger or cargo facilities and airport access) capacity is limited by the available space and processing speeds of various stations in - and outside of - the terminal. This includes not only security checks and passport control but also extends especially to baggage handling (IATA 2004).

If capacity or service rate is not sufficient and cannot meet the fluctuating demand, then excess demand results in the

build-up of waiting queues and delays, and consequently lower LOS (Fig. 5). Normally queues dissolve in quieter periods, especially during midday hours (firebreaks), and therefore do not continue to increase indefinitely. When the demand rate is higher than the service rate over consecutive hours, the whole airport system is operating in an unsustainable manner and enters a region of poor LOS. Under these conditions queues tend to increase exponentially.

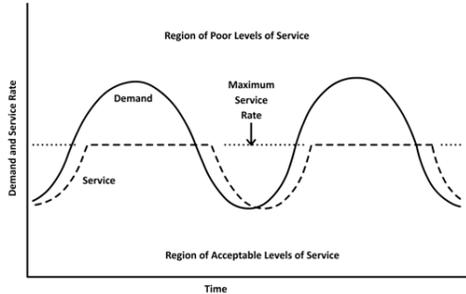


Fig. 5: Rate of Demand and Service (Source: TRB 1975)

An assessment of capacity for a particular airport is commonly based on a design day schedule and involves a (design) peak hour analysis, often separately for arriving and departing traffic or flows of terminating, originating and transferring passengers. For European airports a separate analysis of international intra- and extra-EU, Schengen, and domestic passenger flows should be made.

Finding the number of flights and the passenger volume in the design peak hour at a particular airport can certainly be a data intensive task, especially depending on the chosen definition for the design peak hour, which has been variously defined by various international transport-related institutions and ministries as the standard busy rate, the typical peak hour, the busy hour, etc. (de Neufville 2003: p. 851 ff.). However, the design peak hour should be understood to satisfy only one precondition: that it should not represent an absolute peak, but rather a busy period which recurs during 10 to 30 days (de Neufville 2003: p. 853) throughout the year. Therefore the design day and the design peak hour can be estimated in the following straight-forward way.

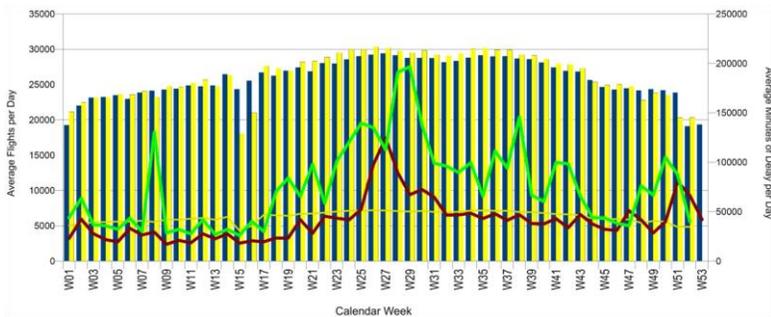


Fig. 6: Pattern of Average Weekly European Flights (Source: EUROCONTROL CFMU 2010)

C. Design Peak Period Assumptions

The Central Flow Management Unit (CFMU) of EUROCONTROL publishes weekly reports with the demand pattern of average weekly flights in European airspace for the running year (Fig. 6), with data from 2009 (dark columns) and 2010 (light columns). It shows the seasonal variation between the demand in autumn/winter, and spring/summer.

With the demand pattern displayed in Fig. 6, it is possible to select a given week having average traffic above or below a given threshold. Observations have shown that this pattern does not significantly change over the years. Therefore it is plausible to assume, at least for the larger European hub airports, that the design peak day or hour can be isolated from selected traffic data samples especially for weeks 24 to 27 (usually mid-June to the beginning of July) and for weeks 34 to 38 (usually in September) (Table 3), these being the two most important busy periods.

By narrowing the candidate weeks needed for eventually isolating a design (peak) day or hour for peak period analysis, the time and data effort needed to find the proper schedule for an airport analysis is significantly reduced.

Year	Date	Calendar Week	Flights in Europe
2010	Fri 02/07/2010	26	32,575
	Fri 10/09/2010	36	32,341
	Fri 09/07/2010	27	32,334
	Fri 18/06/2010	24	32,247
	Thu 01/07/2010	26	32,198
2009	Fri 26/06/2009	26	34,476
	Fri 03/07/2009	27	33,895
	Fri 10/07/2009	28	33,833
	Fri 28/08/2009	35	33,383
	Fri 11/09/2009	37	33,342
2008	Fri 27/06/2008	26	34,476
	Thu 26/06/2008	26	33,895
	Fri 13/06/2008	24	33,833
	Thu 19/06/2008	25	33,383
	Fri 04/07/2008	27	33,342
2007	Fri 31/08/2007	35	33,506
	Fri 29/06/2007	26	33,480
	Fri 14/09/2007	37	33,371
	Fri 07/09/2007	36	33,279
	Fri 21/09/2007	38	32,971
2006	Fri 15/09/2006	37	31,914
	Fri 01/09/2006	35	31,841
	Fri 30/06/2006	26	31,686
	Fri 08/09/2006	36	31,553
	Fri 22/09/2006	38	31,550
2005	Fri 17/06/2005	24	30,663
	Fri 01/07/2005	26	30,569
	Fri 02/09/2005	35	30,469
	Fri 16/09/2005	37	30,338
	Fri 09/09/2005	36	30,169

Table 3: Peak Days and Peak Daily Flights in European Airspace (modified from: EUROCONTROL CFMU 2011)

As Table 3 also shows, the busiest day of the week is frequently a Friday. However, as general peak period characteristics are desired, absolute peaks should be avoided. Accordingly, a design day other than a Friday is chosen. This could be a Monday or Thursday (which tend to be the second busiest days), but it also depends on the day-to-day variation of traffic throughout the week. Hence it would make little sense to choose a Thursday as design day for an airport under

investigation, when it is known that peak demand and congestion can only be found on Saturdays (ACRP 2010: p. 91).

A collection of actually operated airport schedules for different representative days of the week, the month or the year, is certainly an important prerequisite for capacity analyses and especially for detailed demand pattern analyses, e.g. regarding seasonal variations. Design day flight schedules also serve as main input for airport simulations.

V. AIRPORT CONGESTION AND LEVEL-OF-SERVICE

When looking at actually operated design day schedules from airports, we can gain insight into the characteristic peaking of the demand pattern at an airport (de Neufville 2003: p. 856 f.). These transportation system demand patterns are plotted over time, by the hour of the day, where the information about individual peaks is used to dimension and design the related server or part of the infrastructure. In this article only the most critical parts of the airport system will be examined: The airport terminal, the runway system and the immediate airspace.

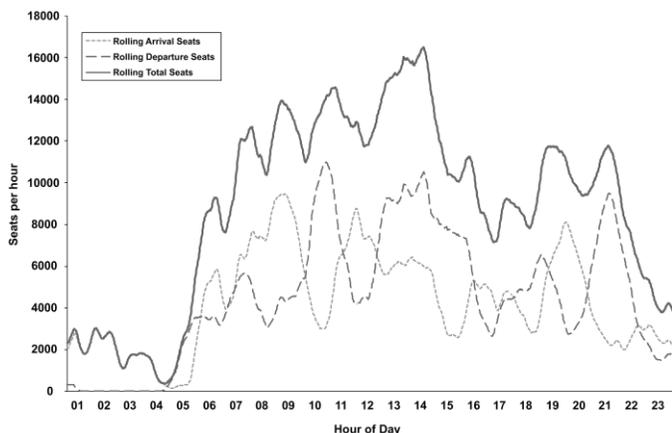


Fig. 7: Hourly Seat Distribution at Amsterdam-Schiphol Airport on Design Day 2008

A. Terminal demand, capacity and LOS

The pattern of distributed hourly seats by actually flown aircraft at Amsterdam-Schiphol airport is exemplarily presented in Fig. 7. Over the course of the day, the pattern of demand at Schiphol airport fluctuating between arriving seats and departing seats is clearly recognizable. It is equally clear that resources need to be shifted within the same terminal space. Indeed strong arrival peaks with up to 9,500 seats per hour, between say 08:00 and 09:00, and departure peaks with up to 11,000 seats per hour, between say 10:00 and 11:00 can be observed. At around 14:00 both patterns form the

highest simultaneous peak in seat volume, approximately 16,000 seats per hour.

What has hitherto not been recognized are the actual load factors on these flights (ACRP 2010: p. 88), but first order approximations for the design (peak) day can be made by applying seat load factors of between 75% and 85%, resulting in total peak passenger volumes of between 12,000 and 13,500 passengers per hour. It is important to note, that the actual dwell time (de Neufville 2003: p. 639 ff.) of passengers using the airport facilities at the same time should be factored into this result. Thus the terminal space should be dimensioned and designed according to the number of passengers simultaneously occupying the volume of space by using the formula: Design passenger volume (per hour) x dwell time (in hours).

The dwell time of passengers is, however, obviously not easy to assess without large-scale observations of passenger flows. Given the difficulties in obtaining data on arriving and departing passenger dwell time, the minimum connecting time (MCT) for transfer passenger could be used as an approximation (minimum) dwell time in the airport terminal buildings, but keeping in mind that not all processes required for originating and terminating passengers are included in this figure. For example Schiphol airport has a high rate of international passengers, of which many might be connecting, and also it serves as a connecting hub for KLM airline. Schiphol achieves an MCT of between 40 minutes (international-domestic connections) and 1 hour and 20 minutes (international-international connections), or say 1 hour on average. These MCT include all the processing times needed for passengers and their luggage to transfer from an arrival gate to the departure gate. Since in our example at Schiphol airport the average MCT and approximated average dwell time is about 1 hour per passenger, the passenger volume in the terminal facilities during the design hour is equal to the volume of passengers simultaneously present.

Furthermore space is dimensioned and provided accordingly to a predefined LOS for each terminal facility, which includes check-in, security, passport control, departure gates, etc. (IATA 2004: p. 179 ff.). Thus space standards vary between 1.0 and 2.5 square meters per passenger, depending on the desired LOS for the specific facility (de Neufville and Odoni 1992; IATA 2004: p. 179 ff.).

Level of Service and Maximum Waiting Time Guidelines (in minutes)	Check-In	Check-In	Passport	Passport	Baggage	Security
	Economy	Business class	Control Inbound	Control Outbound	Claim	
A An excellent level-of-service. Conditions of free flow, no delays and excellent levels of comfort						
B High level-of-service. Conditions of stable flow, very few delays and high levels of comfort	0-12	0-3	0-7	0-5	0-12	0-3
C Good level-of-service. Conditions of stable flow, acceptable delays and good levels of comfort						
D Adequate level-of-service. Conditions of unstable flow, acceptable delays for short periods of time and adequate levels of comfort						
E Inadequate level-of-service. Conditions of unstable flow, unacceptable delays and inadequate levels of comfort	12-30	3-5	7-15	5-10	12-18	3-7
F Unacceptable level-of-service. Conditions of cross-flows, system breakdowns and unacceptable delays; an unacceptable level of comfort.						

Table 4: Level-of-Service Maximum Waiting Time Guidelines (modified from IATA 2004)

An excellent (A) or high (B) LOS should be targeted for stable flows, few delays and high levels of comfort. What is even more interesting for the individual passenger is not only the available space in a particular queue or departure/arrival hall, but rather how long he or she will have to wait.

In Table 4 desired maximum waiting times suggested for different airport terminal facilities are noted (IATA 2004: p. 189). Nowadays the development is such that electronic advance ticketing over the internet and carry-on luggage are making facilities like the check-in counter or baggage conveyor systems gradually obsolete.

When airport management has a desire to translate design hourly passenger volume into anticipated annual figures at airports certain design hour factors come into use (Kanafani 1981; de Neufville 2003: p. 851 ff.; Janić 2007: p. 61). The design hour factor is the percentage share of design hour volume to annual volume. It is important to realize that with the increasing annual volume of traffic or passengers the trend of design hour factor to annual volume is strongly decreasing (Fig. 8). This effect is largely due to the strong peaking of low volume and underutilized airports, in contrast to airports with high volume and constant traffic flow.

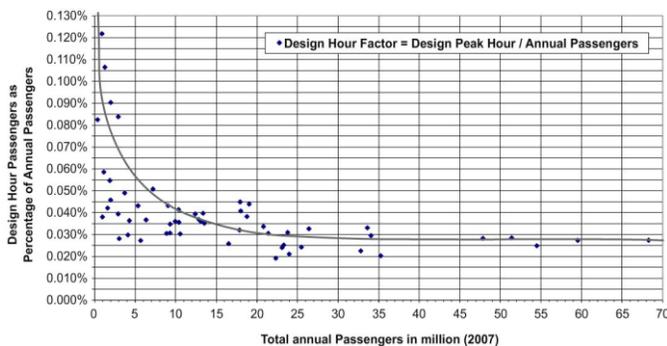


Fig. 8: Trend of Design Hour Factor to Annual Passengers at European Airports (Data from Eurostat, Official Airline Guide, Flightstats.com)

Checking for the consistency of these conversion factors is critical when assuming future volumes of traffic or passengers in airport expansion planning (Kanafani 1981; de Neufville 2003: p. 859). For example an airport currently serving 10 million passengers might have a volume of 4,000 passengers on the design peak hour, resulting in a conversion factor of 0.04%. Now the forecast ten years into the future predicts an annual volume of 15 million passengers, thus resulting in a decreasing design hour factor of 0.035% (Fig. 8) and in an hourly volume of 5,250 passengers per hour.

B. Runway demand, capacity and LOS

The most critical issue with runways and the expansion of runway capacity is the long lead time for approval, planning and constructing such a fundamental piece of infrastructure.

Additionally, expansion projects at existing airports are strongly opposed by environmental groups and local residents in the vicinity of an airport. Narita international airport presents a good example of a failed airport expansion project, due to successful local opposition. Located 60 kilometers east of Tokyo this airport was initially planned to serve the city's international flights, but local opposition forced the government to reduce its plans from three runways to eventually one runway. It took over three decades of negotiation for a second short runway to go into operation in 2002.

Since runways are depreciated over up to 40 years (see annual reports of Fraport and Schiphol Group), the construction costs for building a new runway should certainly not pose an insurmountable obstacle for airports with a critical mass of demand. Compared to some observed costs for airport terminals, which can easily reach billions of Euros (e.g. London-Heathrow Terminal 5, 3 and 1) (IATA 2003: p. 359), costs for building new runways seem reasonably low at up to approximately 300 million Euro (e.g. Schiphol airport's fifth runway Polderbaan) (IATA 2003: p. 185).

Although runways may be viewed as lumpy investments (Walters 1978: p. 136), since you cannot adjust capacity (supply) to demand very easily, there are still certain steps of progression. Runways can evolve from simple greenfield airstrips for gliders and small propeller planes, to medium-sized 3-kilometer long 45-meter wide runways for most commercial aircraft, and on to full-length 4-kilometer long 60-meter wide asphalt runways for very large aircraft such as the Airbus A380. Furthermore the navigational and surveillance equipment installed at an airport and at a particular runway end, ranges from none installed, to the typical instrument landing system (ILS), to the high-end, state-of-the-art, precision runway monitor (PRM) equipment installed to allow independent landings on close-spaced parallel runways (< 210 meters lateral separation). Therefore construction costs to expand current capacity can vary quite substantially for different types of runways and their configuration (Butler 2008: p. 5).

Runway demand and capacity is, analogous to terminal demand and capacity, measured in arrivals, departures or total flights per unit of time (usually [rolling] 15 minutes or one hour) (Janić 2007: p. 268). When regarding a runway system as a queueing system, it is well known that the reciprocal of the demand rate is the interarrival time (de Neufville 2003: p. 822 ff.), which is the weighted average interval between all arriving and departing flights demanding service at the runway(s). Consequently the inverse of the runway occupancy time (ROT) (for a single runway) (Horonjeff 2010: p. 497 ff.) or minimum interarrival time (for a runway system), which is the weighted average minimum physically possible interval between peak demands in a near saturated queueing system, is the throughput capacity or service rate. One of the main differences between demand and service rate is the distribution of flights, where the former is characterized by an incoming fluctuating Poisson distribution above and below capacity and the latter is characterized by an outgoing organized flow (see Fig. 5). Graphically these flows can be shown with cumulative diagrams (de Neufville 2003: p. 819 ff.). As explained in

Section 4.2, ideally demand is sufficiently lower than capacity and can be served at all times, but if demand cannot be served immediately, for example due to other aircraft blocking the runway, waiting queues and delays develop.

For example an airport with a single runway has a peak demand of 40 flights per hour, resulting in an average interarrival time of one aircraft every 90 seconds. Since field observations reveal that mixed takeoffs and landings (of mostly medium sized aircraft) occupy a given runway only for a minimum of 70 seconds, resulting in a capacity of about 51 flights per hour, a demand rate of 40 flights per hour could be served. If future peak hour demand at that airport is estimated at 65 flights per hour and the average interarrival time is 55 seconds and thus less than the capacity threshold of 70 seconds, this demand can only be accommodated on a two- runway system (such as two independent parallel runways). Small aircraft require as little as 40 seconds or less ROT, so capacity and thus requirements for additional infrastructure can vary substantially with the aircraft type mix.

Obviously runway capacity is determined by either ROT, the amount of landings compared to departures, separation minima due to wake turbulences, aircraft type mix, and prevailing weather conditions at an airport (Horonjeff 2010: p. 489). Means to minimize ROT and to increase runway capacity at an airport with regard to the predominant aircraft mix include optimized arrival and departure aircraft sequencing, adequate locating of runway exits, such as 30 degree angle rapid exits, and optimized distances from runway thresholds to the runway exits.



Fig. 9: Bottleneck Situation at Departure Queue for Runway 17R at Denver airport (Source: Google 2010)

As one can see in the aerial photograph of the runway departure queue at Denver airport on June 16, 2010 (Fig. 9), at least eight aircraft are visible waiting for departure at runway 17R. Calculating roughly up to two minutes between following departures, the last aircraft will have to wait at least 16 minutes for takeoff clearance. Because this waiting time in the queue is effectively wasted time and costs airlines huge amounts of money (for schedule deterioration, passenger compensation, additional fuel and crew costs), this kind of operational bottleneck must be avoided or at the very least minimized by airport and air traffic flow management.

When the demand for runway service is greater than the throughput capacity, departing aircraft have to wait in the departure queue and arriving aircraft have to wait in the airspace holding stack. Delays can build up very rapidly in periods of congestion (de Neufville 2003: p. 444 ff.). In Fig. 10 the evolution of daily demand to LOS, measured in average delay per flight, is presented for far spaced independent parallel runways (> 1,310 meters lateral separation). This theoretical relationship (Horonjeff 2010: p. 488) is reproduced using data from SIMMOD simulations, based on the original design schedules of London Heathrow and BBI airports, of various traffic mixes, types of operation (segregated mode and segregated mode plus mixed mode during the peaks), conservative and less conservative separation minima (e.g. 2.5 nautical miles on final approach) and stepwise increasing levels of demand (Bubalo and Daduna 2011). Such simulations are used to predict the ultimate capacity of a runway system and to forecast the impacts of future demands (Horonjeff 2010: p. 152).

As it can be seen, when daily demand increases on the parallel runways, the average delay per flight increases exponentially. For example London-Heathrow airport operates under a LOS of 10 minutes of average delay per flight (NATS 2007: p. 5), whereas Munich airport operates under a level of service of about 4 to 5 minutes of average delay per flight. The practical implication is, significantly more flights are available at Heathrow on each day (Fig. 10). While Heathrow airport could offer between 1,150 and 1,400 slots per day, or 1,250 slots on average, on its independent parallel runways, Munich could only offer between 950 and 1,200 slots, or 1,050 slots on average. It is therefore the airport management's judgment call to decide on how many slots the airport wants to offer under the trade-off which LOS it wants to maintain for its customers (de Neufville 2003: p. 847 ff.).

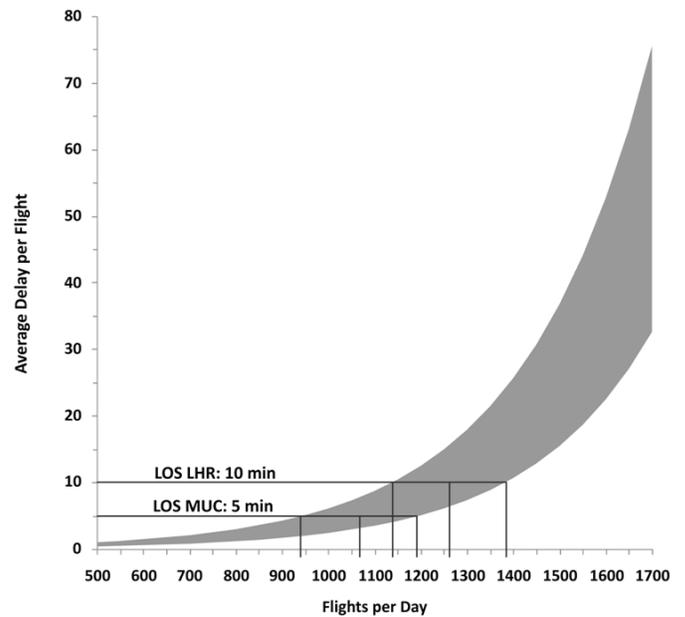


Fig. 10: Relationship between Daily Demand and LOS for Far Parallel Runways

In general, a working airport system is driven mainly by sheer growing demand. Changes in the current aircraft mix towards a more desired split of shares with regard to capacity (or environmental) benefits can mainly be influenced by airport management by the use of incentives such as aircraft landing charges. These incentives should ultimately result in airline schedule changes. Otherwise airport management may advance operational procedures by flow optimization methods in cooperation with local air traffic control (ATC) (by sequencing similar aircraft types to minimize average separation minima between aircraft) or may expand infrastructure to minimize ROT, for example by building sufficient rapid runway exits or by installing different departure queue locations for different aircraft types.

C. Airspace demand, capacity and LOS

As noted earlier, if runway capacity is not sufficient, arriving aircraft have to queue in airspace holding stacks or lock into the holding pattern, until they are granted a landing slot by ATC. Therefore coordination and collaborative decision making (CDM) between airport and local ATC is vital to expand airport capacity without resorting to costly measures like the outright construction of additional infrastructure (Butler 2008).

The role of ATC is mainly to direct air traffic safely to and from an airport through airspace. Here the rules are mainly determined by international standards from the International Civil Aviation Organization (ICAO) published in Doc 4444, the Procedures for Air Navigation Service – Rules of the Air and Air Traffic Services (PANS-RAC) (ICAO 2001). The main task should be to organize the fluctuating flows of arriving aircraft at the arrival fixes and to convert these flights into a continuous concentrated flow of landing aircraft towards the runway. This should be manageable in all weather conditions (snow, wind, rain, fog, etc.), but certainly under instrument flight rules (IFR) that allow instrument landings under inclement weather conditions with a minimum visibility of one nautical mile (1.85 kilometres) and a cloud ceiling of 245 meters.

In the immediate airspace of London Heathrow airport, four main holding stacks are in place, where the aircraft circle (and descend) until they get clearance to land (Fig. 11). The flight tracks in Fig. 11, constructed by signals from Automatic Dependent Surveillance Broadcast (ADS-B) transmitters on board modern aircraft, show clearly how the airspace around London-Heathrow is operated. Although tracks from an afternoon winter schedule are displayed in the figure, large queuing can be observed even in off-peak periods at Heathrow airport, suggesting that this airport is operating well above a stable long-term sustainable capacity and is highly congested throughout the year.

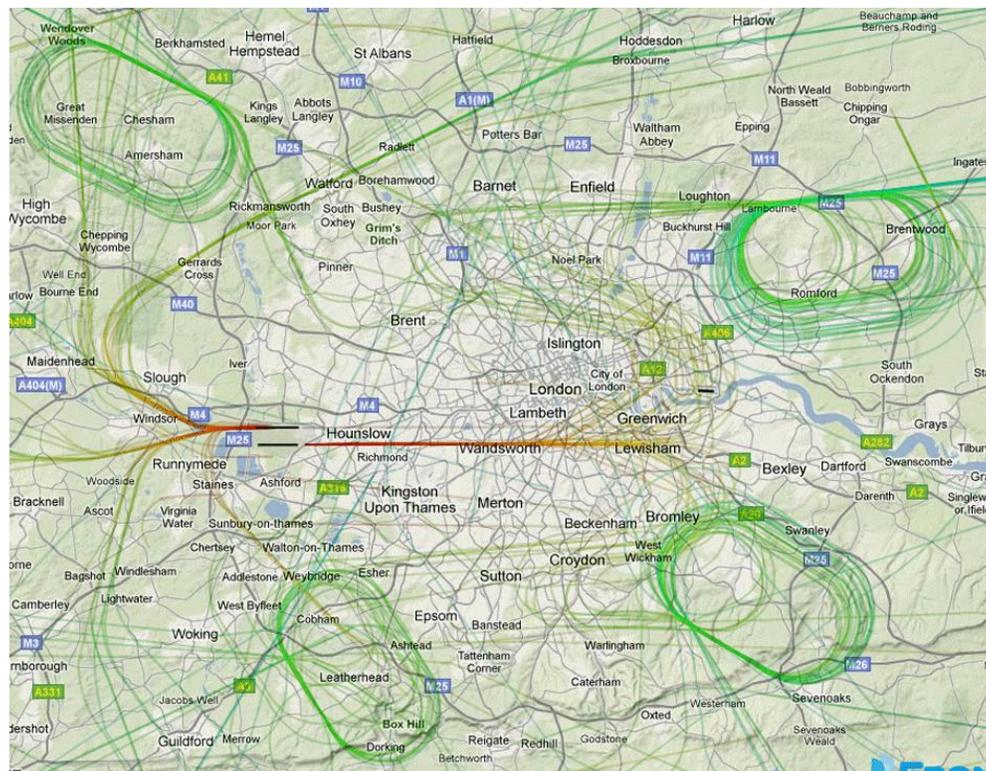


Fig. 11: Airspace and flight tracks around London Heathrow airport on January 7th, 2011 between 16:00 and 17:00 (Source: Frontier 2011)

VI. AIRPORT EVOLUTION AND FUTURE CHALLENGES

It will be interesting to see in which direction air transportation evolves in the future. All imaginable scenarios are possible, the timeframes for investments are thereby highly uncertain (Button 2004: p. 23 ff.). Current research projects within the Single European Sky (SES) Air Traffic Management (ATM) Research Programme (SESAR), which is initiated and coordinated by the European Commission and EUROCONTROL, try to identify performance determinants and bottlenecks in the flow of European air traffic (EUROCONTROL 2009). State-of-the-art technology is expected to be reviewed for implementation in air transportation. Surveillance and positioning of air traffic through satellites, like the Global Positioning System (GPS), or through advanced radar technology has only just begun to reveal its full potential.

Opposition and legal action by environmental groups against building of such large infrastructures as airports and particularly runways will increase, further extending the

planning horizons. The discussion about extending the largest hub in Europe – London-Heathrow – has dragged on for years. Heathrow airport has been experiencing congestion for the last two decades. That privatized Heathrow belongs to the Spanish infrastructure managing company Ferrovial has not helped to gain support for an airport extension. Just recently further plans to support and expand Heathrow with a third runway or by mixed-mode operations were scrapped by the government. Fig. 12 depicts how the development of Heathrow was anticipated just a few years ago. Between 2000 and 2005, extended operating hours were to have been implemented, then in 2007 mixed-mode operations were to be introduced and finally in 2015 a new third runway would go into operation (Janić 2007: p. 14 f.)(Fig. 12).

Unfortunately not a single measure has been started so far, leaving Heathrow just as saturated as it was before with a capacity of about 90 to 95 flights per hour. To ease some congestion during peak periods at Heathrow parallel approaches on both runways are operated under the Tactically Enhanced Arrival Measures (TEAM) (BAA 2009: p. 17)

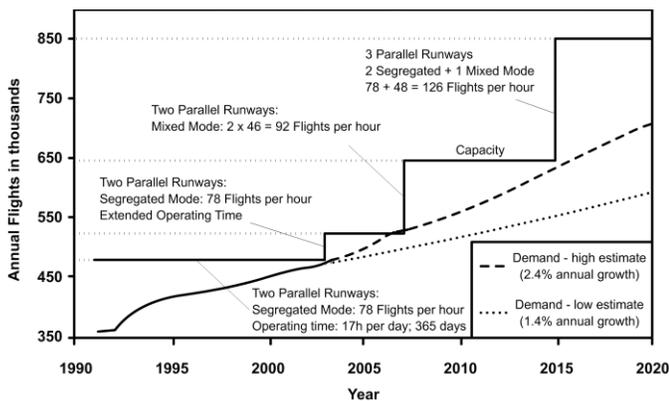


Fig. 12: Possible long-term Scenarios for London Heathrow Airport by Adjusting Capacity to Demand (Source: Janić 2007)

Heathrow is an extreme example of an airport lacking adequate expansion of capacity. But in Europe there are other hubs that are taking the opportunity to develop themselves much faster, commonly many years ahead of demand. Paris’ Charles-de-Gaulle airport has undergone major investments in the last two decades, pushing the capacity from 72 flights per hour on a far parallel runway system in 1990 (SRI International 1990: p. 72 ff.) to currently 120 flights per hour on a four parallel runway system. Madrid’s Barajas airport has expanded even further since the mid 1980s. Before 1990 Madrid-Barajas had a peak hour capacity of 30 flights per hour, serving a demand of 13.2 million passengers with 139,000 flights on a crossing runway system (SRI International 1990: p. 46 ff.) (Fig. 13). By 1998 when another runway was added, Barajas airport had already improved peak hour capacity to 50 flights per hour (IATA 1998). With this third runway in place from 1998, parallel operations started at Barajas, pushing peak hour capacity to 74 operations per hour, for a demand of 28 million passengers and 306,000 flights (IATA 2003). Finally in 2006 the master plan was completed with the addition of two further

runways and the closing of an older one Madrid-Barajas has currently two pairs of far spaced parallel runways, which achieve well beyond 100 movements per hour for a demand surpassing 45 million passengers and 450,000 flights.

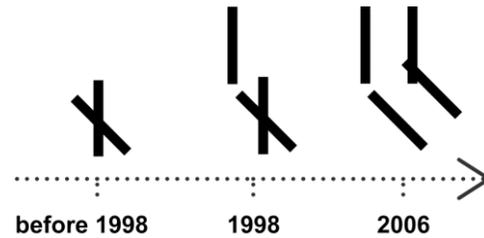


Fig. 13: Evolution Path of Madrid Barajas Airport

Comparing developments in the U.S. to the development of airports in Europe, much more could be on the horizon. For example in Europe there is only one airport which could manage triple independent parallel IFR landings - that is Amsterdam’s Schiphol airport. Although triple and even quadruple simultaneous IFR landings are still being under study by the FAA (McNerney and Hargrove 2007), U.S. airports especially are pushing development in that direction in order to be able to attain further capacity benefits. Currently the maximum hourly capacity can be observed at Atlanta’s Hartsfield airport with 200 peak hour flight and over 20,000 distributed seats per hour.

Sophisticated runway operations depend largely on the type of equipment in place and on the skills of the air traffic controllers. Currently radar screens are updated about every 5 seconds, which leads to delayed reaction times and imprecise aircraft localization. In the future aircraft will be equipped with Global Positioning System (GPS) signal receivers allowing them to be located by transmitted ADS-B signals in 3-dimensional space over time. Radar screen update frequency may improve to one second or less between images. Furthermore wake turbulence may be accurately predicted, which would allow a dynamic separation between succeeding landing or departing aircraft on the same (or close parallel) runway under different wind conditions. Separations of 2.5 nautical miles or less at any time between aircraft may seem reasonable to achieve (certainly in a harmonic sequence of aircraft of the same wake turbulence categories).

VII. CONCLUSION

It is a long way to reach the goals for seamless travelling. Large scale initiatives like NextGen in the U.S. or SES in Europe aim to accelerate the provision of capacity ahead of the increase of demand (EUROCONTROL 2003). Operational performance and bottlenecks on the ground and in the airspace need to be determined and resolved (EUROCONTROL 2009). In the near term many international airports and especially the main hubs will experience peak congestion, leading to aircraft delays which propagate through the air transport network. In Europe the most prominent examples of congested and near saturated airports like London Heathrow, Frankfurt am Main and London Gatwick take all technical measures to raise

capacity at its current airport system. Therefore traffic levels and capacity enhancement procedures at those airports can serve as a benchmark for airports with similar configurations. Frankfurt airport is expected to have a new fourth runway in place by Winter 2011/2012. On the contrary London Heathrow can only grow through increasing load factors and seat capacities offered by airlines. Internationally Tokyo Haneda airport is comparable to the configuration of London Heathrow, however, the airport achieves the same level of passengers of almost 70 million, but with significantly less daily flights, but up to 200 passengers per flight on average. As it was explained in this article, the trend towards increasing load factors, aircraft size and eventually passengers per flight can only be influenced by airport management through incentives in the airport charges schemes aiming at discriminating certain aircraft types. Ideally a multi-airport system could be established around metropolitan areas, which would allow the provision of services for specific airlines and aircraft types and would create a win-win situation for stronger and weaker players regarding market split and traffic relief. Nevertheless, airports continue to grow commercially mainly through income from retail concessions and other non-aeronautical revenue, such as parking fees. This development is driven by the average spending per passenger at the airport.

Moreover this article presented critical requirements in planning future capacity and demand levels. In the terminals the concept of dwell time and the underlying trends when converting annual figures to peak hourly volumes should be integrated for consistent airport capacity expansion planning. Order-of-magnitude assumptions on peak volumes can be conducted with the presented guideline material.

Further research should head towards finding the best practice airport, regarding sustainable capacity and LOS, through airport benchmarking of similar airport configurations and/or airport simulations. Here the emphasis should be put on simultaneous IFR operations on independent parallel runways in the short-term and on close-spaced parallel runways in the long-term. In the U.S. studies are under way researching the feasibility of quadruple parallel IFR operations (McNerney and Hargrove 2006). However, such procedures require large scale implementation of sophisticated aircraft and ATC technology and provide no feasible practical solution for many European airports.

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AUTHOR BIOGRAPHY

Branko Bubalo is a graduate in Business Administration and Engineering from Berlin School of Economics and Law (BSEL) and University of Applied Sciences Berlin. He has a major in Environmental Management and is a member of the German Airport Performance (GAP) research project and the German Aviation Research Society (GARS). His thesis on “Benchmarking Airport Productivity and the Role of Capacity Utilization” focused on airport productivity and capacity of selected European airports.

During his position as aviation environmental consultant at ENVISA Consultancy in Paris, France, Branko Bubalo worked for the Market-based Impact Mitigation for the Environment (MIME) research project, funded by the European Commission, on environmental and noise capacities, and particularly on airline noise-abatement costs and long-term strategy storyboarding. He worked together with research institutes such as NLR in the Netherlands, QINETIQ in the UK and SINTEF Group in Norway.

Currently he is a PhD candidate at University of Hamburg at the Institute of Information Systems under supervision of Prof. Dr. Stefan Voß.

City	IATA Code	ICAO Code	International Passengers in millions	Total Flights in thousands	Passengers per Flight	International Passengers as Percentage of Total Passengers	Intra-EU Passengers as Percentage of Total Passengers	Extra-EU Passengers as Percentage of Total Passengers
London Heathrow	LHR	EGLL	61.3	478.5	140	91%	33%	58%
Paris Charles de Gaulle	CDG	LFPG	55.8	559.8	109	92%	42%	50%
Amsterdam Schiphol	AMS	EHAM	47.3	446.6	106	100%	56%	44%
Hong Kong Chek Lap Kok	HKG	VHHH	47.1	309.7	155	99%	-	-
Frankfurt am Main	FRA	EDDF	46.7	485.8	110	87%	37%	50%
Dubai International	DXB	OMDB	36.6	270.4	138	98%	-	-
Singapore Changi	SIN	WSSS	36.3	234.8	161	96%	-	-
Tokyo Narita	NRT	RJAA	32.3	194.4	172	97%	-	-
London Gatwick	LGW	EGKK	30.4	263.7	130	89%	57%	32%
Bangkok Suvarnabhumi	BKK	VTBS	30.1	249.4	155	78%	-	-
Madrid Barajas	MAD	LEMD	29.8	469.7	108	59%	36%	23%
Seoul Incheon	ICN	RKSI	29.6	212.6	142	98%	-	-
Munich Franz Josef Strauss	MUC	EDDM	24.5	432.3	80	71%	44%	27%
Dublin	DUB	EIDW	22.6	211.9	111	96%	85%	11%
New York John F. Kennedy	JFK	KJFK	22.4	441.4	108	47%	-	-
Zurich	ZRH	LSZH	21.4	275.0	80	97%	66%	31%
Rome Leonardo da Vinci-Fiumicino	FCO	LIRF	21.4	346.7	101	61%	37%	24%
London Stansted	STN	EGSS	20.0	193.3	116	89%	83%	6%
Copenhagen Kastrup	CPH	EKCH	19.4	264.1	81	90%	62%	28%
Vienna Schwechat	VIE	LOWW	19.0	292.7	67	96%	63%	33%
Toronto Pearson	YYZ	CYYZ	18.4	430.6	75	57%	-	-
Brussels	BRU	EBBR	18.3	258.8	71	99%	65%	34%
Manchester	MAN	EGCC	18.1	204.8	105	85%	55%	30%
Kuala Lumpur	KUL	WMKK	17.8	211.2	130	65%	-	-
Barcelona	BCN	LEBL	17.4	321.5	94	58%	46%	12%
Istanbul Atatürk	IST	LTBA	17.1	276.1	104	60%	-	-
Los Angeles	LAX	KLAX	16.7	622.5	96	28%	-	-

Table 2: Main Global Hubs by the Number of International Passengers (Source: ACI Europe 2008, Eurostat 2008)