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#110 NEW EMPIRICAL EVIDENCE ON AIRPORT CAPACITY UTILISATION: RELATIONSHIPS BETWEEN HOURLY AND ANNUAL AIR TRAFFIC VOLUMES

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ABSTRACT

An important question in forecasting air traffic at airports is: How does the future traffic volume compare with capacity, i.e. will the forecast demand for using airport infrastructure not exceed the existing or planned capacity? We concentrate in this paper on air transport movements (ATM's) and runway capacity, since runways form in many instances the airport component most critical for expansion, due to environmental constraints. Air traffic forecasts like those of aircraft manufacturers typically yield annual volumes, whereas capacities are measured more often in short time periods, i.e. hours. Annual "capacities" are used for long term planning purposes as a measure of available service volume as well, however, not for measuring the true through-put of the system. In answering the question of conformity of the demand (here in ATM's) with capacity, future annual volumes have to be converted therefore into peak hour volumes and then compared with capacity. The paper discusses the problem of selecting a suited peak hour and of defining capacity. For capacity estimation, simulation, functional relationships, consensus processes (in the case of declared capacity) and/or benchmarks may be used. Based on OAG data, the paper informs on the annual capacity utilisation of airports world wide in form of "ranking functions", which show the distribution of the number of hours at each volume level (between zero and highest hourly volume) over all hours of operation within a year. These functions are the basis for deriving functional relationships between peak hour and annual ATM volumes for each airport capacity type, which are presented and discussed in the paper.

KEYWORDS

Airport capacity; capacity utilisation being the ratio of traffic volume and capacity; capacity reserve being the difference between capacity and traffic volume; peak hour demand; hourly and annual capacity; volume ranking curves; functional relationship between peak hour and annual traffic volume.

1. Introduction

With a few exceptions, caused by war, terror and economic crises, air traffic has grown in the past substantially and much faster than the more traditional modes rail and road. Due to the rapid growth some airports are struggling with capacity problems, and these airports belong typically to the most important nodes of the global air traffic system, like for instance London Heathrow, Amsterdam, Frankfurt, New York J. F. Kennedy airport and Tokyo Narita airport and some other airports. Given the various industry forecasts of air traffic, airports have to adapt their capacity to the further growing demand and plan for new system components like ground access, terminals, and air side facilities, in particular runways.

An important prerequisite of planning new airport infrastructure is the existence of forecasts of demand and supply. Based on air traffic forecasts ground access and terminal facilities are designed and new air side infrastructure like runways are planned. The most critical element of capacity enhancement measures is the runway system, since planning procedures often require the involvement of the public, which is more or less opposed to the realisation of new runways on grounds of protecting the neighbourhood against further noise immissions. The public planning process therefore requires the proof that the future demand for runway usage, which is the volume of air transport movements (ATMs), is such that the existing infrastructure will not suffice to accommodate the forecast demand.

In order to be able to compare the future ATM volume with the future capacity both the demand and capacity have to be forecast in a consistent way since the aircraft size distribution of future flight volume is influencing the future capacity of a runway. Furthermore, both the volume and capacity have to have the same definition, that is the number of aircraft movements (take offs and landings) per time unit. Demand and flight movements are normally forecast on an annual basis, while the capacity as a measure of the true through-put of the system is calculated or estimated for a short time period, typically for one hour or even shorter intervals. Annual "capacities" are used for long term planning purposes as a measure of available service volume as well, however, not for measuring the maximum through-put of a runway.

Given this two-fold approach, the annual demand forecast and the estimation of hourly capacity, a conversion is needed to harmonize the time units. Since an annual capacity value fails to describe the through-put capability of the runway system in a meaningful way – due to the fact that demand will never reach near capacity levels in all 8760 hours of the year – the annual traffic volume has to be converted to an hourly volume. In this context several methodological issues have to be treated, they are first of all:

- How to estimate the hourly capacity of a runway system, and
- how to estimate the hourly demand for runway usage, that is the traffic volume of ATMs.

The latter issue requires first a selection of an hour of the year the traffic of which is relevant to be compared with capacity. Thus, the question has to be answered

- which hour of the year is to be determined for comparing traffic with capacity, and then
- how to estimate on the basis of the forecast annual demand the traffic volume of this hour?

This paper will primarily concentrate on the last issue, which is the question of how to determine the relevant hourly volume, given the forecast annual traffic volume. The issues of the capacity concept and the selection of a relevant “peak hour” will also be dealt with, however, not in great detail, since they have been dealt with extensively in the literature (FAA, 1983; FAA, 1969; Horonjeff, 1980; Ashford and Wright, 1992).

The outline of the paper is as follows:

- Problems of Estimating Airport Capacity Utilisation and Reserves
- Capacity Concepts: Annual and Hourly Capacity, Saturation and Practical Capacity; Approaches to Estimating Capacity
- Traffic Patterns at Airports by Airport Type
- Relationships between Peak Hour and Annual Traffic Volume (“Ranking Curves”)
- Functions Describing Peak Hour – Annual Traffic Volume Relationships by Airport Type
- Conclusions.

2. Problems of Estimating Airport Capacity Utilisation and Reserves

For maintaining their function of connecting the ground transport system with the air transport system, airports hold out a range of facilities that are interconnected in such a way as to provide ample transfers of passengers and freight, and to provide associated services. In order to arrive at the overall capacity of an airport, one has to estimate the capacity of each functional unit, the facility with the lowest capacity determines the airport capacity.

In many instances, ground traffic access infrastructure, terminals and some of the air side facilities can be adapted to the growing demand by airport operators as part of their normal planning and enhancement procedures, with one exception, that is runway system. Increasing the capacity of the runway system more than marginally means adding a new runway, in some cases even building a new airport, for which substantial land surface is needed, and for realizing the new infrastructure often planning procedures with the involvement of the public are required. In some European countries, this has become almost an insurmountable task for most airports, because of the neighbouring population being negatively affected by airport noise and thus opposing capacity enhancement plans. The runway capacity can be regarded therefore as the controlling element of the overall airport capacity.

The public involvement is one reason why the proof of the need of the capacity extension has to be carried out in a correct and understandable way, very often are these projects subject to dispute at court level. In a long term forecast, the future passenger and cargo demand and the resulting aircraft movements have to be quantified for an unconstrained capacity situation, the future capacity has to be determined, and in an iterative procedure, the estimated ATM volume of a preset peak hour has to be compared with capacity. Ideally, the estimated demand does not reach the level of the planned capacity, however, exceeds clearly the present capacity. In Germany and other European countries it is meanwhile normal that the traffic forecast of an extension project, and thus the proof of the need, is questioned by the public affected and disputed at court.

Regardless of the inherent problems of long term forecasting the task remains to estimate the capacity reserve and utilisation respectively. The **capacity reserve** is thereby defined as:

- the difference between capacity and traffic volume (as expressed by ATMs per hour), while the **capacity utilisation** is given by

- the ratio of volume and capacity (typically in %).

The question remains which capacity concept to select for this volume-capacity relation.

3. **Capacity Concepts:** Annual and Hourly Capacity, Saturation and Practical Capacity; Approaches to Estimating Capacity

The term capacity normally refers to the capability of a facility to handle people, freight, vehicles, etc. The capacity is typically identical with the maximum number of traffic units, i. e. vehicles, that can pass through the facility within a given time span under specified conditions regarding safety regulations, operating conditions, and standards of expediency and comfort, and possibly other conditions.

As has been stated already, runway capacities are expressed both on an annual and an hourly basis. In strategic airport planning, **annual capacities** are often used as an indicator of the ability of the runway to accommodate a certain flight volume and, in comparison with a forecast volume, to estimate the future capacity reserve. Especially in long term airport planning, this capacity reserve estimate draws upon the annual capacity since the time unit of the demand and aircraft movement forecast is the year. There exist complex procedures to calculate the annual capacity, in principle, the capacity is deducted from hourly capacities multiplied by the hours of annual utilisation of the runway.

For detailed planning and dimensioning of infrastructure facilities, the **hourly capacity** is normally retained, since the significance of the annual capacity is lower because of seasonal and daily variations of traffic, which the annual capacity has to account for by applying reduction factors. Night hours, Sundays, some holidays, and other off-peak periods are typically times of low traffic demand, which are therefore not well suited for being included as such in that time span which serves as a base for capacity calculation. The time unit of measuring capacity should be defined in such a way as to allow for a continuous utilisation of the runway by the demand for aircraft movements. In practical terms, that means that a period of not more than one hour or two should be taken.

According to the concept of “ultimate” or **“saturation” capacity** the runway capacity is equal to the maximum number of flight movements – take-offs and landings – that the runway can accommodate, subject to regulations of Air Traffic Control (ATC). The ultimate capacity does not take into account time delays that aircraft encounter when they are ready for take-off or landing in conditions of peak hour traffic. As demand approaches ultimate capacity, delays to aircraft are likely to reach intolerably high levels. The phenomenon of sharply increasing delays in traffic situations approaching capacity without the possibility of reducing them after a short while can be observed in road and rail traffic as well.

To account for the delay problem another capacity concept has found wide application. Movement rates are determined in relation to average delay levels (FAA, 1969). In analogy to the “Level of Service” concept used in road transport (HRB, 1965), a **“practical” capacity** was devised primarily for planning purposes, whereby a tolerable average delay per aircraft movement was the criterion for setting the capacity as a limit to the number of movements per hour for the runway system under day-to-day operating conditions. For many airports, the practical capacity will be reached if the average delay to aircraft in the take-off queue will not exceed 4 minutes (Horonjeff, 1980). At this average delay, single aircraft delays, which may exceed the average substantially, are not likely to increase further, but rather stabilise or will eventually go down. In general, the practical capacity reaches movement rates which are in the range of 60 – 70 % of the level of the theoretical concept of saturation capacity.

As already mentioned, it is not the intension of the paper to describe and discuss the various **approaches of estimating runway capacity** but rather to give a short overview of the different possibilities. Basically, there are four lines of thought that have developed over time (Ashford and Wright, 1992):

- Empirical approaches including benchmarking
- Queuing models
- Analytical approaches
- Simulation models.

Empirical approaches are based on observations, surveys, and statistics, the analyses of which can serve as a useful tool for estimating capacities. A widespread example of this approach is the annual practice of Flight Plan Coordinators in Europe and elsewhere to determine the so-called **"declared capacity"** for partially and fully coordinated airports. The declared capacity serves as a limit to planning and coordinating flight schedules and thus, the number of flight movements, at all coordinated airports for the coming flight plan period. The capacities are determined after a consultation process with stakeholders involved, like airlines, airport operators, air navigation service providers and aviation administrations.

The process of determining the declared capacity takes account of all restrictions that hinder an airport from accommodating more aircraft movements per hour. The resulting capacity thus reflects not necessarily the current runway capacity but the airport capacity under prevailing requirements of the demand of flight movements, although at airports with runway capacity problems, the declared capacity is a good indication of the capacity of the runway system.

Runway capacities have been estimated recently more and more by using **benchmarking studies**, which try to compare traffic in near-capacity situations of airports in similar infrastructure and operating conditions. The Airport Capacity Benchmark Report 2004 of the Federal Aviation Administration of the US Department of Transportation (FAA, 2004) is an example of an empirical study which has monitored aircraft operations at the busiest 35 airports in the US and evaluated the benefits from procedural, technological, and runway improvements, with the objective to determine current and future runway capacities of these airports. "Capacity benchmarks" have been derived representing the maximum number of departures and arrivals per hour that an airport can handle safely and routinely. Three rates are given for each airport which reflect capacity in three weather conditions:

- "Optimum" represents good weather with visual separation of aircraft;
- "Marginal" describes weather not good enough for visual approaches, but still better than instrument conditions;
- "IFR" – instrument flight rules – defined as instrument conditions, the normal case in Europe, however, not the US.

To state actual examples of runway capacity as given in the report we have selected airports with different runway layouts, and thus, capacity. San Diego International-Lindbergh Field (SAN) is the only single runway airport among the 35 busiest airports in the US. The capacity benchmarks have been found to be 56 – 58 flights per hour in both Optimum and Marginal weather and in IFR conditions 48 – 50 movements, which is still a high value as compared with the declared capacity of many European airports. The German airport of Stuttgart (STR) for instance, with an annual traffic volume of about 125,000 ATMs on one runway in 2008 (based on OAG data, SAN handled roughly 200,000 ATMs in the same year), had in 2008 a declared IFR-capacity of 42 movements per hour, which is a rather typical value of runway capacity in Europe.

New York La Guardia (LGA) is an airport with two intersecting runways, the benchmark capacities of which are 78 – 85 movements in Optimum weather conditions, 74 – 84 flights in Marginal conditions and 69 – 74 flights per hour in IFR conditions. Seattle-Tacoma International (SEA) has been equipped in 2004 with two parallel runways with dependent operations. The capacity benchmark for SEA has been set to 80 – 84 flights per hour in Optimum and 74 – 76 in Marginal, and to 57 – 60 flights in IFR weather conditions. There is no airport among the 35 busiest airports in the US with just two independent parallel runways, the Portland International airport (PDX) is an example of an airport with two parallel runways with independent operations and a third runway intersecting one of the others. The capacity increases thus to 116 – 120 flights per hour in Optimum weather conditions, decreases to 79 – 80 flights in Marginal and to 77 – 80 flights in IFR conditions. The airport with the highest benchmark capacity is Dallas/Fort Worth International (DFW); the runway system consists of five parallel runways in one direction, with partly dependent and partly independent operations, and two independent parallel runways in another direction, not intersecting the others. The capacity benchmark of DFW is 270 – 279 flights per hour in Optimum weather, 231 – 252 flights in Marginal and 186 – 193 in IFR weather conditions.

It seems that queuing models and analytical approaches have been a widespread application in the past more than today. One reason is probably that these methods do not incorporate explicitly influencing factors like traffic mix and weather, which the benchmark approach does at least implicitly. **Queuing models** make use of the observable relationship between average delay per aircraft and the flight movement rate. The functional relationship according to the so called Pollazcek-Khintchin formula relates the average delay per aircraft with the flight movement rate (no. of aircraft per hour), mean separation time and the standard deviation of the mean separation time. The relationship was originally developed for the case of randomly distributed arrivals, with the assumption of a Poisson type distribution of arrivals. This assumption is less and less valid in today's scheduled traffic, since flight plans are determined before hand by the international process of the IATA flight plan coordination.

To overcome the inherent problems of queuing models **analytical approaches** have been developed and presented in several handbooks (see e. g. Ashford and Wright, 1992). They start from the concept that aircraft taking off or landing are to be found at certain times at certain points in the controlled airspace or runway system, and that these time and space coordinates can be measured through radar data and functionally interrelated. A model system developed along these lines for German airports has been based on radar data of real flight operations in the airport zone of several busy airports (Urbatzka and Wilken, 1997). The model inputs for both the arrival and departure functions by airport capacity type include online variables like

- aircraft weight mix,
- runway use,
- sequencing of arrivals and departures, and
- arrival-departure ratio

and offline parameters like

- matrix of wake turbulence,
- runway occupancy times,
- flight times for the outer marker – threshold distance, and
- matrices of theoretical minimum and real inter-movement times of two aircraft following each other.

The applicability of the analytical capacity models has been demonstrated for German airports, nevertheless, the lack of including delays of aircraft as a quality variable of throughput turned out to be a drawback for the use in planning projects.

Guided by the intention to have a more flexible tool for estimating capacities in relation to capacity enhancement measures **simulation models** have been developed. Aircraft movements are described by means of simulating single aircraft movements in space and time according to prevailing operating rules. For this, geometric data (i. e. coordinates) of flight routes and the runway and taxiway system, of ramp and terminal areas, functional data of the runway layout (i. e, priority rules), movement data of aircraft, and structural data of the aircraft population and last but not least a flight plan are to be collected, recorded, and form an essential model input. As a result of a simulation run, movement rates together with delay and other characteristics are given for critical sections of the airport. Some of the better known simulation models are ADSIM (Airport Delay Simulation Model), AIRPORT MACHINE, SIMMOD and TAAM (Total Airspace & Airport Modeller). These models are primarily used for optimising measures that are thought to enhance capacity, by simulating each flight movement step by step in time and space, and varying the configuration of runways, taxiways ramp areas, and gate positions.

4. Traffic Patterns at Airports by Airport Type

After having discussed the issue of estimating hourly capacity of a runway system a central questions of this paper remains to be solved:

- Which hour of the year is to be determined for comparing traffic with capacity, and then
- how to estimate the traffic volume of this hour on the basis of the forecast annual demand?

Theoretically, an hour with average traffic volume or with some kind of peak traffic could be selected; typically a peak hour is retained on grounds that the infrastructure should be able to handle traffic in high demand situations that occur regularly. Several concepts of "typical peak hours" have been developed and applied in airport planning, they are in particular:

- the hour with the 30th highest traffic volume of the year of planning horizon, called 30th peak hour,
- the hours with peak traffic volumes at the day with the 30th highest daily volume of the year of planning horizon, or
- the hour with a traffic volume that is reached or exceeded in 5 % of all operational hours of the planning year, called 5 %-peak hour.

In order to find and identify these hours of a base year the traffic by day and hour has to be known for all operational hours of the year and then ranked according to traffic volume. These data may be retrieved from airport statistics of flights that have been carried out at that airport or from airline schedule data that are provided for about 3500 airports by the Official Airline Guide (OAG). If the latter ones are taken one has to be aware of the fact that these data bases contain first of all airline schedule data, however, not data of other flights like ad hoc charter and transfer flights and other commercial or non-commercial flights. A comparison of traffic at all German airports in 2008 as given by official German statistics and by OAG has shown that the OAG traffic volume captures almost 90 % of the total volume. The difference between airline traffic (based on OAG data) and total traffic becomes smaller with growing importance of airports, since they concentrate on airline traffic while airports with less traffic are more frequented by non- and other commercial traffic. If we take only the five busiest airports of Germany, which handle about two thirds of total German air traffic, the difference between OAG and total traffic narrows down to 3 %. In the following, we base our analysis on OAG data since they form the only base available which offer data from airports around the world.

Before looking into the ranking of traffic by hour it is useful to study the traffic pattern by hour, day, and month in order to demonstrate that air traffic is not a uniform phenomenon over time but rather one with a high degree of variability. To visualise traffic patterns at airports we have selected – more or less arbitrarily - three airports with different volumes and traffic compositions:

- Atlanta (ATL) in the US, the busiest airport world wide with 956,000 ATMs in 2008 (OAG),
- Frankfurt (FRA) in Germany, a major hub airport with 469,000 ATMs in 2008 (OAG), however, with severe runway capacity problems,
- London Stansted (STN) in the United Kingdom, a single runway airport with mainly origin-destination traffic of 168,000 ATMs in 2008 (OAG), used to a high degree by low cost carriers.

In Fig. 1, 2, and 3 we show the hourly variation of traffic at the peak day of the year 2008 at the three airports.

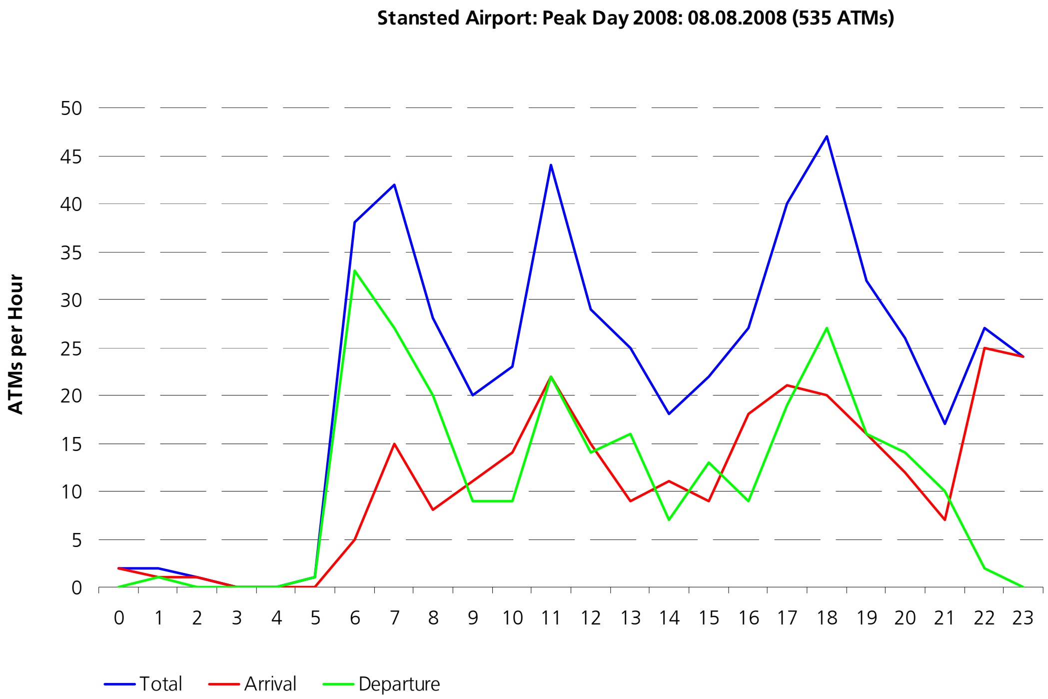

Fig. 1: Hourly Variation of Flight Movements during Peak Day 2008 at Stansted Airport (Source: OAG, DLR)

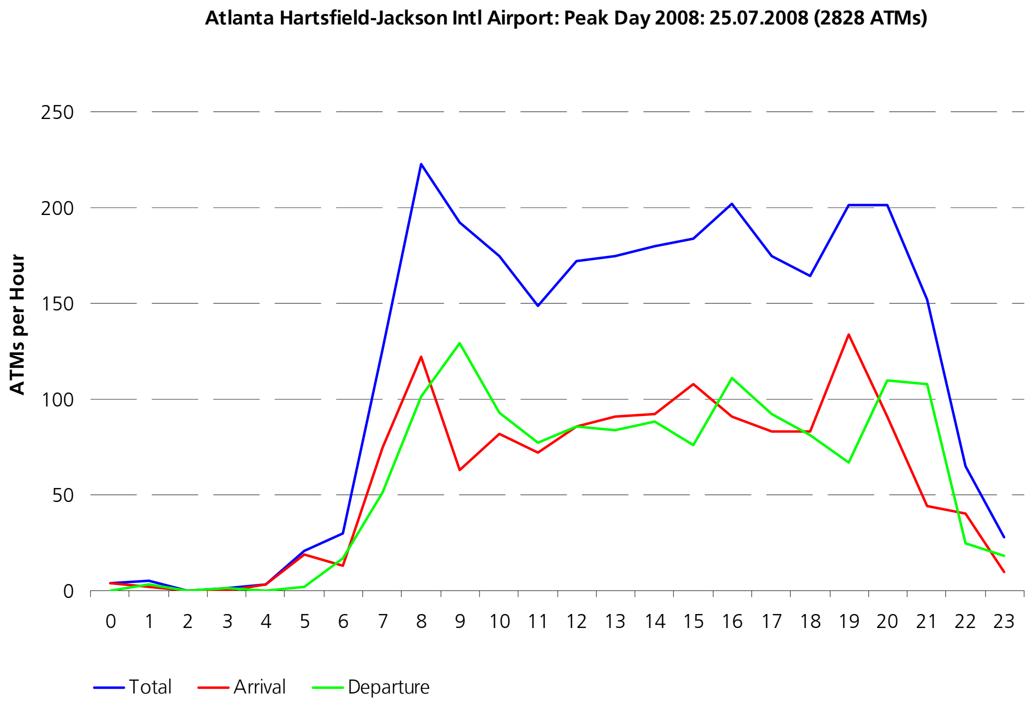

Fig. 2: Hourly Variation of Flight Movements during Peak Day 2008 at Atlanta Airport (Source: OAG, DLR)

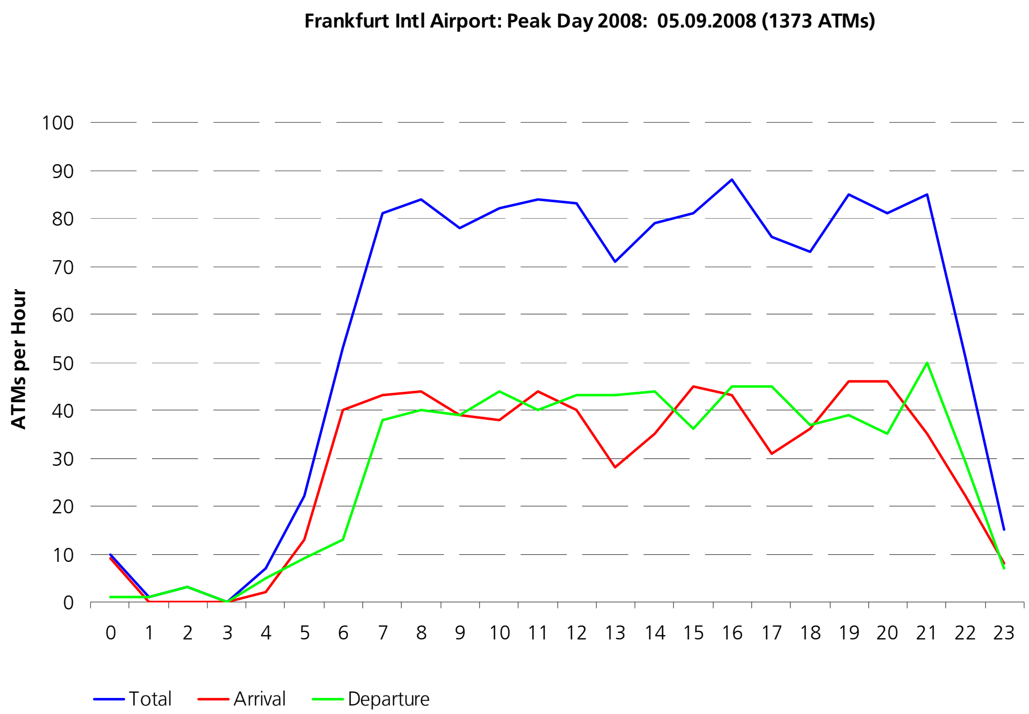

Fig. 3: Hourly Variation of Flight Movements during Peak Day 2008 at Frankfurt Airport (Source: OAG, DLR)

As can be seen, the traffic variation is very pronounced at Stansted airport, with the ratio between high and low traffic in the order of more than two, and is less so in Atlanta, however, still with a difference between peak hour and off-peak hour volume of more than 70 movements, and decreases further at Frankfurt airport, due to the capacity constraint governing there. The benchmark capacity of Atlanta as given by the Airport Capacity Benchmark Report 2004 (FAA, 2004) is around 240 ATMs per hour in Optimum weather conditions; this capacity was reached in Atlanta at the peak day only in one morning hour, traffic volumes were otherwise between 150 and 200 movements per hour. In contrast, Frankfurt had a declared capacity of 83 ATMs per hour in 2008, which was reached and even exceeded in many hours of the day. The traffic during night is rather small at all three airports, in particular between midnight and 5:00 h in the morning. Such a low demand is typical for most airports, however, not for all. Cargo traffic, in particular integrator freight, is concentrated during night hours and on some airports only, there are only relatively few airports with intensive night operations like Memphis and Köln/Bonn.

The variation of traffic by day during a week shows the low demand for night movements, too, and in addition the weaker demand at weekends at many airports. In Fig. 4, 5, and 6 the hourly traffic variation is shown for the peak week in 2008 for each selected airport.

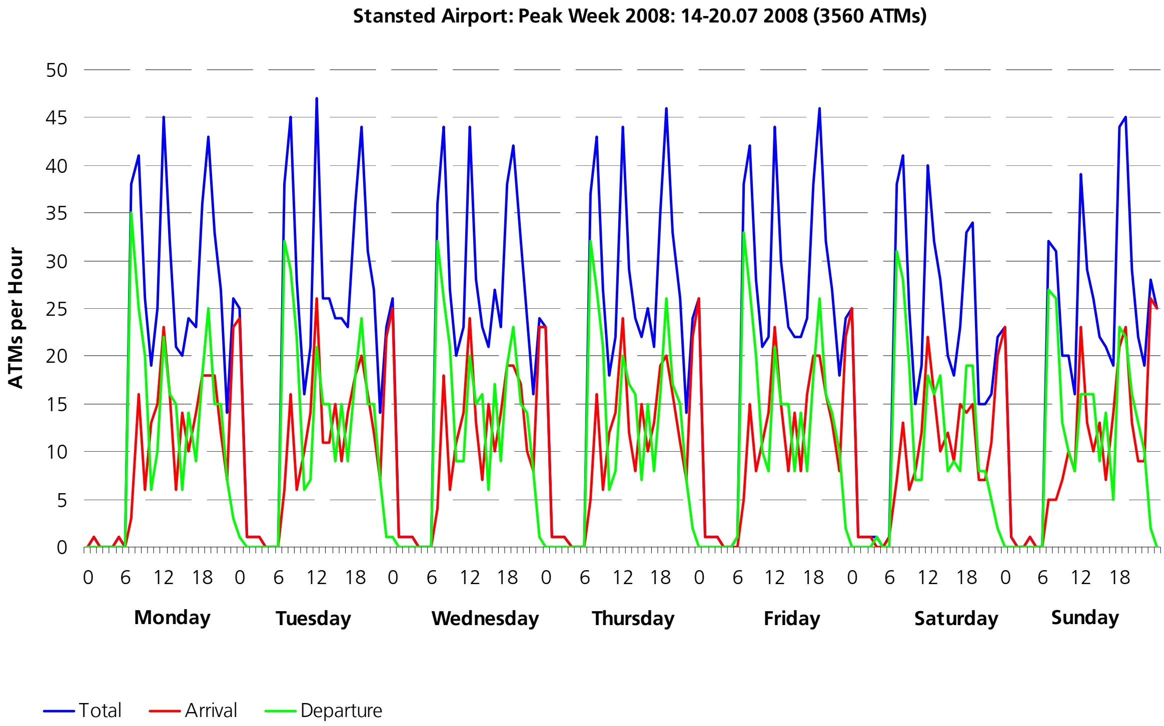

Fig. 4: Hourly Variation of Flight Movements during the Peak Week in 2008 at Stansted Airport (Source: OAG, DLR)

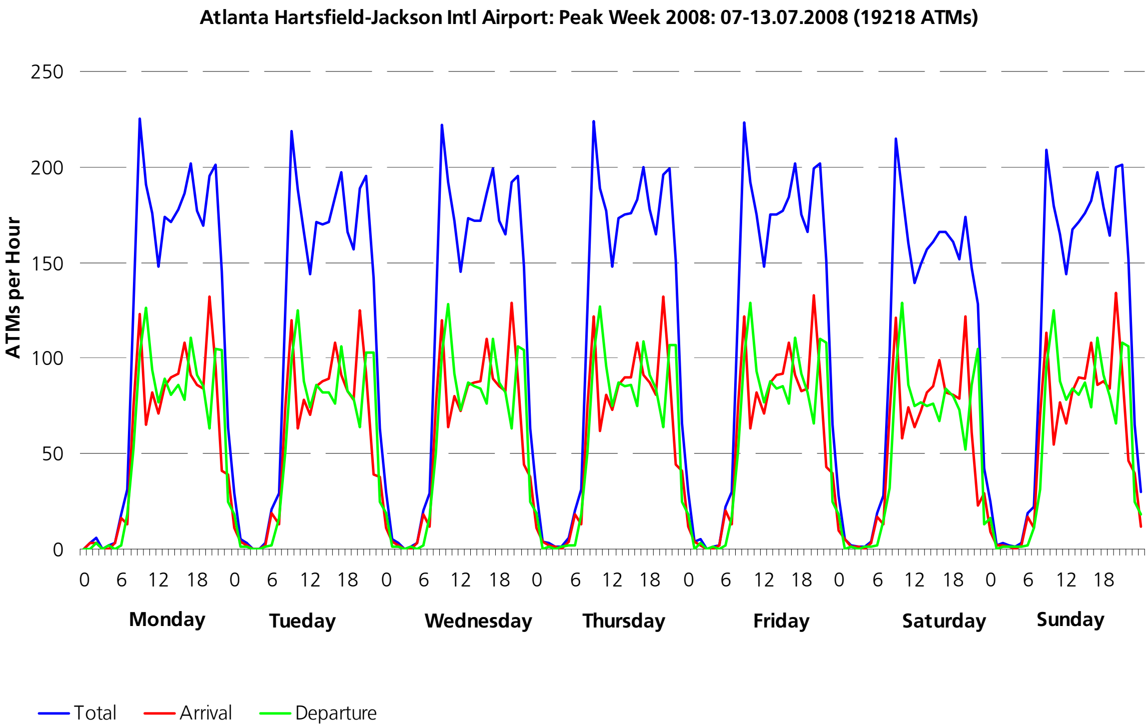

Fig. 5: Hourly Variation of Flight Movements during the Peak Week in 2008 at Atlanta Airport (Source: OAG, DLR)

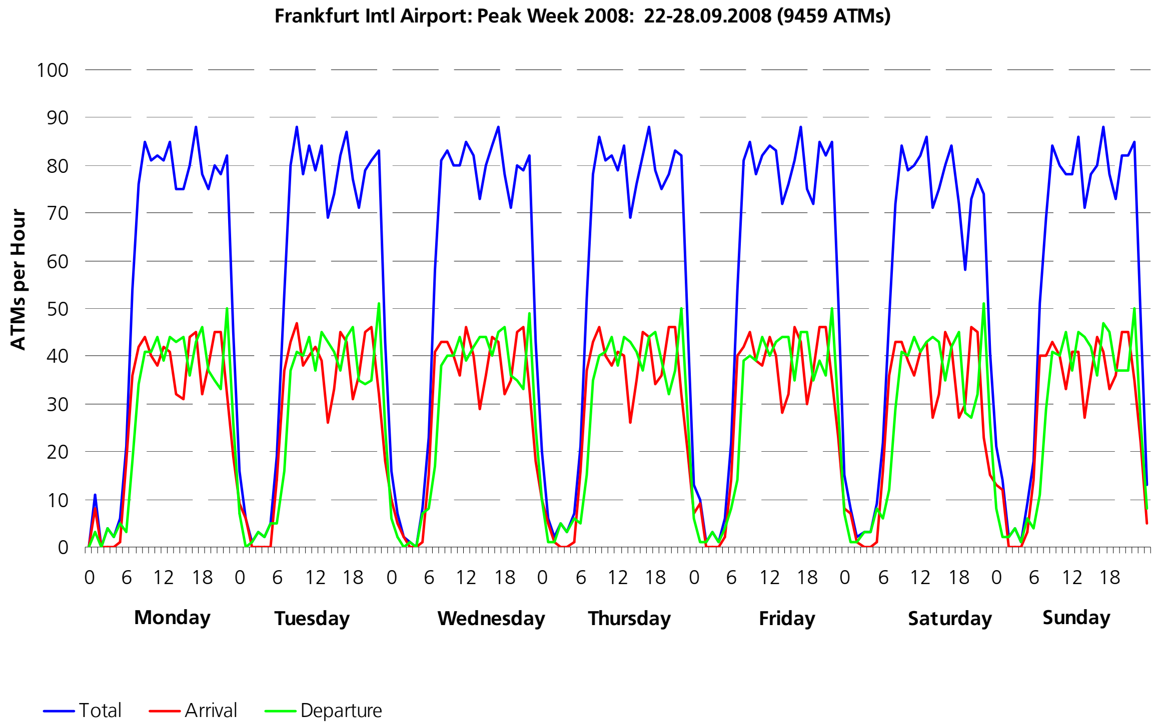

Fig. 6: Hourly Variation of Flight Movements during the Peak Week in 2008 at Frankfurt Airport (Source: OAG, DLR)

As can be seen the demand at weekends is not so much lower than during the week at these airports. At Stansted, the traffic drops by about 50 movements (10 %) at weekends, with a week daily volume of about 500 movements in the summer season. Atlanta handles about 2800 movements at week days and at weekends around 2500, thus 300 movements (11 %) less. In Frankfurt, the relative weekend traffic reduction is still smaller; on a typical week day Frankfurt handles around 1350 movements while on Saturdays the traffic drops by about 60 movements (4 %). Other airports with smaller traffic volumes are likely to have a more pronounced difference between weekend and weekday traffic. In Köln/Bonn for instance, the traffic during the week is about 310 movements per day, except on Fridays, when traffic increases to about 340 movements, and then drops to 240 movements on Saturdays.

In addition to the hourly and daily variation of traffic there is the seasonal variation during a year. Typically, the summer months are characterised with high demand levels, whereas from November to March traffic is relatively low. Even in Frankfurt, where airlines are hindered from freely planning and offering flight schedules adequate to demand due to capacity restraints, the traffic is around 10 % smaller in winter months than in the summer season. In Hamburg, an airport with 150,000 flights in 2008 (OAG) and with less capacity problems than Frankfurt, the difference between summer and winter season traffic is around 15 %.

Concluding we can say that the variation of traffic is typically great, in particular between day and night, also during the day, between week days and weekend, and within a year. The variation decreases with the traffic importance of the airport, but also with the seriousness of the capacity constraint of the airport. Nevertheless, even in important hub airports and capacity restrained airports, the difference between traffic in low demand situations, like at night, and in peak demand situations remains very high. The high degree of traffic variation is therefore a fundamental argument for an hourly capacity concept, any kind of annual capacity would be subject to a discussion of how to account for the low demand time intervals during a year.

5. Relationships between Peak Hour and Annual Traffic Volume ("Ranking Curves")

As stated, the ranking of traffic by hour for all hours of operation of a year allows us to discuss and determine a peak hour that might be suited to represent a typical peak demand and thus suited to be compared with the capacity of the facility. Based on OAG data, traffic ranking curves have been derived for around 3500 airports world wide. They form the empirical base for establishing a functional relationship between peak hour traffic and annual traffic so that such a relationship may be used for comparing forecast demand with planned capacity.

Fig. 7, 8, and 9 show the hourly traffic ranking at Stansted, Atlanta and Frankfurt airport over the year 2008. The horizontal axis gives the ranking of all traffic hours of the year, starting with the hour with the highest traffic, followed by the hour (or hours) with the second highest volume, and so on until the hour (or hours) with the lowest traffic volume. On the vertical axis, hourly traffic volumes are shown. As can be seen, in the middle range of traffic volume there are many hours with the same level of traffic, whereas at the very high traffic volumes (at the left end of the curve) this is not the case. Equally, there are likely to be many hours with very low demand or zero demand, which are normally the hours at night.

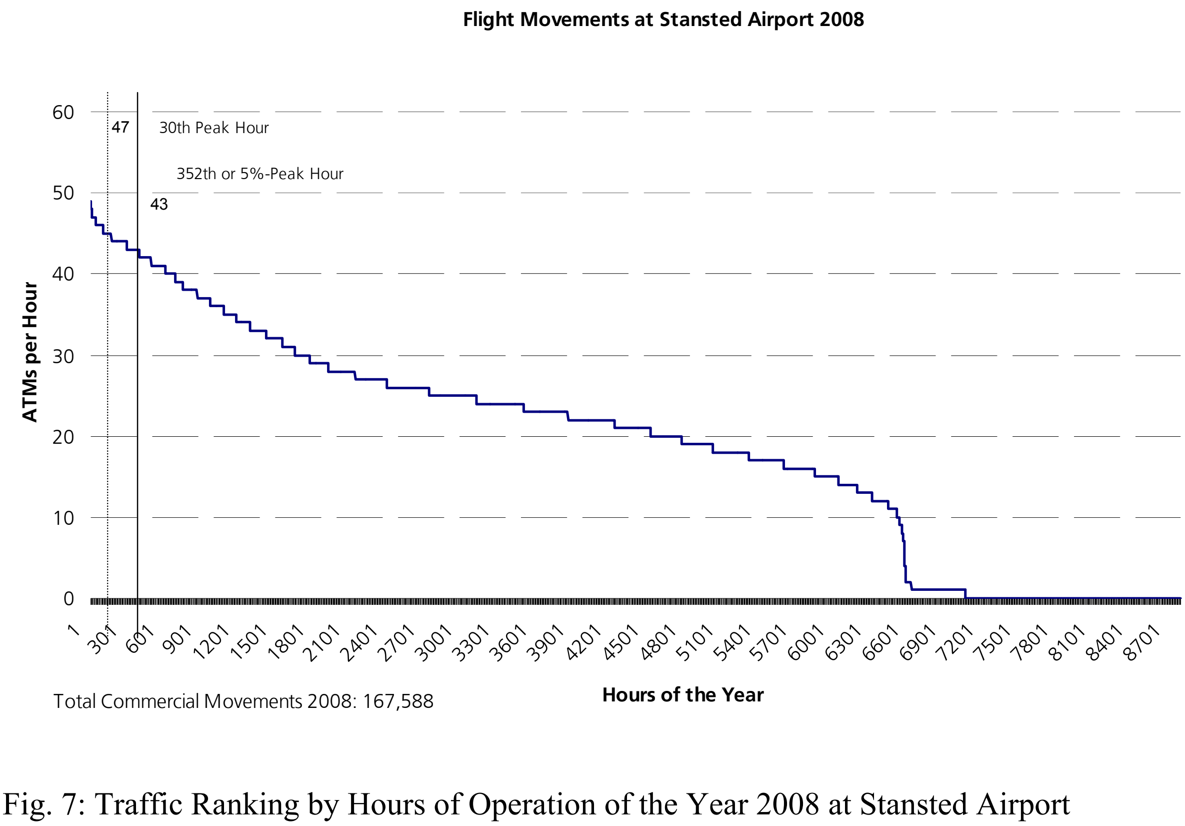

Fig. 7: Traffic Ranking by Hours of Operation of the Year 2008 at Stansted Airport (Source: OAG, DLR)

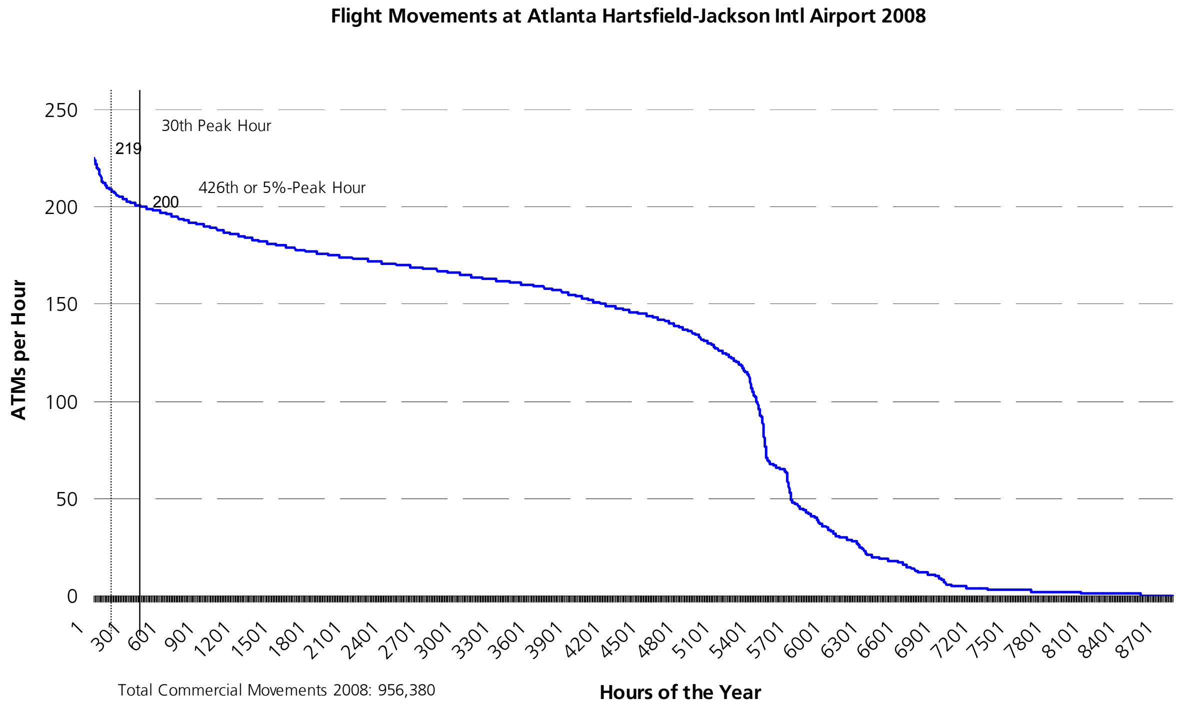

Fig. 8: Traffic Ranking by Hours of Operation of the Year 2008 at Atlanta Airport (Source: OAG, DLR)

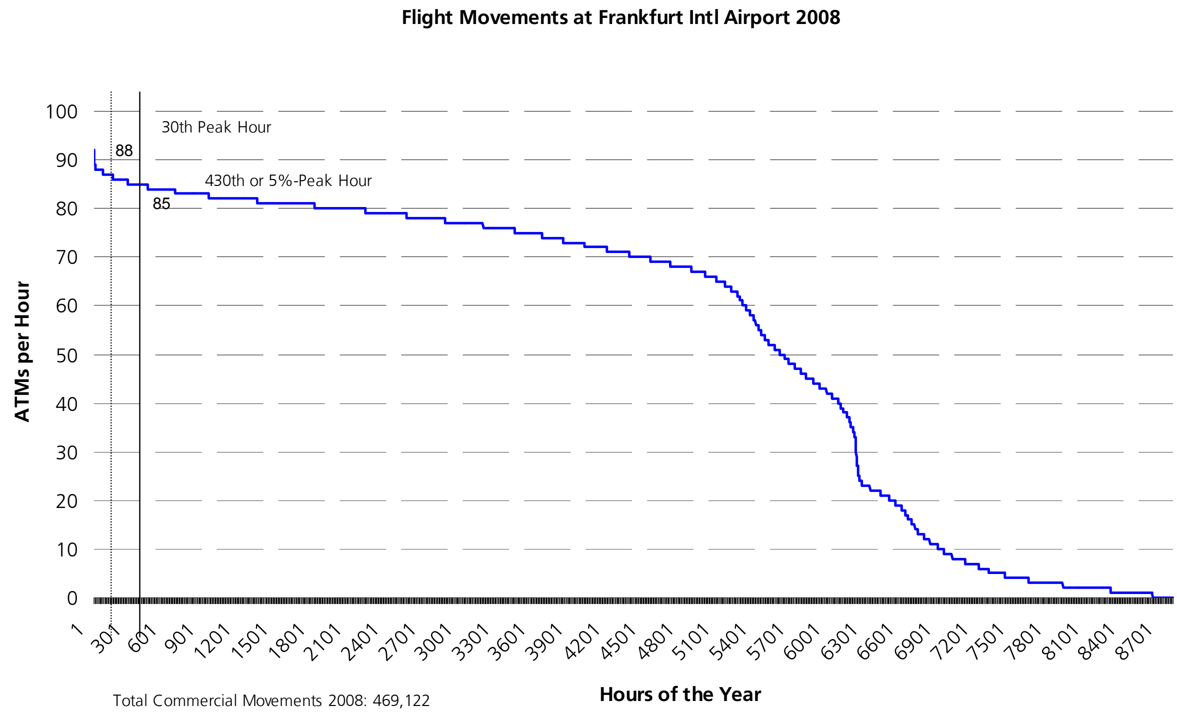

Fig. 9: Traffic Ranking by Hours of Operation of the Year 2008 at Frankfurt Airport (Source: OAG, DLR)

The three curves have in common the general form, however, differ in the slope over the hours with high volumes. As higher the traffic in relation to the capacity available, meaning as higher the capacity utilisation the less inclined is the slope, with the exception of the starting part of the curve: The traffic in the hours with the absolute highest hourly volumes differs strongly in volume, the slope of the curve is accordingly very inclined. As can be seen, after about 300 to 500 hours of operation, depending on the capacity utilisation, the slope changes and becomes less inclined. Over the following 5000 hours or so the slope is rather constant and changes again to become more or even very inclined during the following 1000 hours or so, and levels off in the remaining hours. In the case of Stansted we can observe a second change of slope in the range of the 2000th hour. Looking at the hourly variation of traffic (see Fig. 1), we can distinguish three peak periods of traffic during the day which last about 5 to 6 hours, with significantly higher traffic volumes than during all other hours of the day. These daily peak hours sum up to a total of about 2000 hours per year.

Typically, the hours during the day are those with high traffic volumes, whereas the night hours are characterised by much lower traffic. Assuming around 14 - 16 hours of day demand and correspondingly 8 -10 hours of night with rather low demand or even with a night curfew with zero demand, there about 5100 to 5800 hours with relatively high demand as is demonstrated by the ranking curves, and accordingly about 2900 to 3600 hours of low or zero demand at night, depending on the existence of night flight regulations.

The ranking curves demonstrate clearly hours of typical demand and those with atypical demand, where the volume changes rapidly with the order of hours. This is the case in the hours with the highest traffic volumes of the year and in the morning and evening hours when traffic picks up or goes down rapidly. Typical traffic during the day would be found in the range of the 3000th hour, where the relative change of volume between following hours in the ranking is rather small. In the case of Frankfurt airport a typical hourly demand during a day in 2008 was about 77 ATMs. The variation of this volume during the day was rather low with a range of about 85 to 70 movements, if on the one hand the absolutely highest volumes of the first 400 hours or so and on the other hand the hours at night (beyond the 5400th hour of the year) are excluded.

As can be seen, the hour with the 30th highest traffic is a rather atypical peak hour, since the traffic varies sharply between neighbouring hours in the ranking, whereas the 5 % peak hour, which is in the range of the 330th to the 440th operational hour of the year, is a more typical peak hour, since the traffic in the hours following in the ranking is declining less sharply, and much lesser than in the hours preceding the 5 % peak hour (although this is somewhat less the case in the Stansted example). As a result airport planners have often chosen the 5 % peak hour as a base for designing facilities and capacity. After demonstrating the peak hour characteristics by means of the ranking curves of many airports we have adopted this concept and deal in the following with the 5 % peak hour as the typical peak hour chosen for estimating capacity reserves and utilisation. In a network or global analysis, the ranking curves as developed on the basis of OAG data allow determining the 5 % peak hour of airports in a consistent way. An additional advantage is given by the fact that peak hour volumes are comparable between airports.

Ranking curves are a tool for analysing and estimating hourly capacity of airports working under near capacity conditions, too. The question whether or not an airport has reached almost capacity in daily operation can be seen easily by regarding the slope of the ranking curve over all hours of the day (excluding night hours). If the slope is such that the variation of hourly traffic is rather small, as is the case in Frankfurt for instance, then the highest volume values of the curve are indicative of the capacity of the airport, which in such cases is typically the capacity of the runway system. If we look again at Atlanta and Frankfurt we see in the case of Atlanta the highest volumes being around 230 ATMs, which compare with a stated benchmark capacity of 240 ATMs per hour in Optimum weather conditions and around 200 ATMs in IFR conditions (FAA, 2004), and in the case of Frankfurt the highest volumes being around 90 movements, whereas the declared capacity of the flight scheduling process is only 83 movements per hour. Even the 5 % peak hour volume is with 85 ATMs higher than the declared capacity, indicating the demand pressure on that airport, which operates since years at capacity level. Even in Stansted, which does not operate near capacity, the highest traffic volumes reach levels of 45 to almost 50 movements per hour, which correspond roughly with the IFR capacity of a single runway. It should be noted in this context that the number of movements according to OAG data corresponds to the on-block and off-block occurrences, whereas the capacity refers to the number of movements on the runway.

By relating the demand of the 5 % peak hour with the capacity we can quantify the degree of capacity utilisation. In Stansted the volume-capacity-ratio in 2008 was about 43/50, thus a capacity utilisation of 86 % in IFR conditions. In the case of Atlanta the capacity utilisation was in 2008 about 83 % (200/240) in Optimum weather conditions, which represent the typical situation at that airport, whereas in Frankfurt the utilisation was about 102 % (85/83), indicating that even in typical peak hours occurring every day the declared capacity (under IFR conditions) was exceeded. It is important to note that these utilisation levels in Atlanta and Frankfurt are not directly comparable since the benchmark capacity in the US and the declared capacity in Europe are based on different concepts and do not have the same meaning. Nevertheless the two examples clearly prove the near capacity utilisation at both airports.

6. Functions Describing Peak Hour – Annual Traffic Volume Relationships by Airport Type

The objective to establish a functional relationship between peak hour and annual traffic volume is to estimate the peak hour traffic for a planned situation, when the annual volume of this situation is known, e. g. as a result of a forecast. The need for applying the function is typically given in airport planning processes, when due to lack of existing capacity reserves extensions of runway capacity are studied. Demand forecasts of annual traffic form usually the quantitative base for evaluating planning proposals.

Since the need for planning new capacity is given primarily in situations when the existing traffic approaches capacity we have concentrated our analysis on those airports which are characterised by high degrees of capacity utilisation. A further subdivision of the total airport sample into “capacity classes” was indicated because the demand, and thus the peak hour volume, cannot exceed the capacity of the runway system, the level of which is dependent on the number of runways and their configuration. We have therefore identified the following capacity classes, for which functions have been calibrated:

- Single runway,
- two runways, independent parallel,
- two runways, dependent parallel,
- two runways, crossing,
- three runways,
- four runways and more.

Altogether 200 airports with high traffic volumes were included in the analysis. For these airports data on traffic schedules (OAG data) and runway configurations (DAFIF, 2006) were collected, and traffic ranking curves with 5 % peak hour volumes and the number of hours in day and night operation were calculated. In order to verify the functional relationship between peak hour volume and annual traffic we have studied several functional types in linear regression analysis, with the overall best result being a linear function describing the 5 % peak hour volume in relation of annual volume (YACM) and a factor of annual utilisation of the runway. We have chosen the number of hours with more than five aircraft movements per hour (GF), roughly corresponding to the number of day hours (as contrasted to night hours) and describing the time period with high demand. The variable “GF” is thus included to account for differences in opening hours, flight restrictions (especially night curfews) etc.

Table 1 shows the estimation results for the selected categories of runway system. The variables are significant at high significance levels and despite the many different airports in a given runway system class we have identified a surprisingly stable relationship between the 5 % peak hour and the yearly aircraft movements and the number of hours with more than five aircraft movements per hour as the values of R-squared show. The higher the yearly aircraft movements the higher is the 5% peak hour. On the other hand, the higher the number of hours with more than five aircraft movements per hour is, the lower is the 5% peak hour. This conclusion may need some explanation: As mentioned, we have included only airports which have at least a reasonably high capacity utilisation and we have thus included only airports in our analysis which have a minimum of about 70,000 aircraft movements per year. Therefore, as the number of unrestricted operating hours at an airport increases, flexibility in scheduling ATMs increases due to more capacity available, and thus peak load decreases. This leads to a reduction of the 5% peak hour. We have to keep in mind, however, that we only consider airports with high traffic volumes, and which operate near their capacity limit. If we look on the other side at small airports which have ample capacity reserves, the relation between the number of hours with more than five aircraft movements per hour and the 5% peak hour reverses, because of a low level of capacity utilisation. The focus of this paper is only on (potentially) capacity constrained airports, so our sample of airports is relatively small. Therefore, Table 1 shows the mean, minimum and maximum as well as the standard error of the dependent variables, since the estimated functions are only reliable within a certain scope, however, the minimum and the maximum values of the dependent variables in Table 1 are not a strict limit for this scope.

The model includes only a small number of independent variables for several reasons: First we are limited in the number of variables because of the small sample of relevant airports. Second, the spare number of independent variables makes the model easy to apply for forecasting purposes. As we are interested in the relationship between the 5% peak hour and the yearly aircraft movements at an airport the first independent variable is given by definition. The number of hours with more than five aircraft movements per hour at an airport is a variable which may be defined reasonably well in a scenario analysis. Model fit is good since about 90% or more of the observed variance is explained by the model, thus the simple structure of the model is not a limitation but a benefit from our point of view.

Runway System	Variable	Coefficient	Standard Error	t-ratio	p-value	Mean	Min/Max	Standard Error	R-squared	# of obs.
Single RWY	**Constant**	21.7999824	3.25314342	6.701	0				**84.57%**	**58**
	YACM	0.00021407	0,131290D-04	16.305	0	87472.5345	72360/197511	35,969.670792		
	GF	-0.00318613	0.000648	-4.917	0	5830.68966	4388/7481	708.762248		
Two RWYs, independent parallel	**Constant**	44.1221565	6.67086097	6.614	0				**97.20%**	**23**
	YACM	0.00021079	0,822116D-05	25.64	0	180545.435	75668/430154	94,322.347897		
	GF	-0.00624888	0.00102851	-6.076	0	6965.6087	5927/8581	753.946414		
Two RWYs, dependent parallel	**Constant**	31.8974232	4.82743685	6.608	0				**95.53%**	**29**
	YACM	0.00020777	0,922912D-05	22.512	0	155933.724	73367/347602	73,062.676957		
	GF	-0.00449329	0.00079799	-5.631	0	6734.65517	5124/8784	844.997787		
Two RWYs, crossing	**Constant**	28.4135462	5.42036243	5.242	0.0001				**96.48%**	**21**
	YACM	0.0001906	0,886738D-05	21.494	0	139783.095	74270/386757	79,344.387206		
	GF	-0.00366627	0.00087658	-4.182	0.0006	6613.38095	5466/8783	802.642272		
Three RWYs	**Constant**	33.6165524	12.555983	2.677	0.011				**92.76%**	**40**
	YACM	0.00020381	0,939998D-05	21.682	0	210778.4	72261/479294	121,962.906169		
	GF	-0.0043137	0.00182578	-2.363	0.0235	6780.65	5990/8641	601.519981		
Four RWYs and more	**Constant**	70.6596346	13.7595197	5.135	0				**98.72%**	**29**
	YACM	0.0002076	0,519439D-05	39.966	0	377437.897	113195/956380	209,983.186310		
	GF	-0.00977775	0.00212012	-4.612	0.0001	6927.82759	5782/8334	514.468864		

Tab. 1: Estimation Results

Figure 10 and 11 illustrate the estimated functions in which one independent variable is fixed at a time to a value equal to its mean given in Table 1. Furthermore, the functions in Figure 10 are limited to a range as given by the minimum and maximum values of yearly aircraft movements in Table 1. Figure 10 illustrates the positive relationship between the 5 % peak hour volume and the number of yearly aircraft movements. It is interesting to note that the functions follow the same path in this two-dimensional relationship, this is partly due to the fact that the value of the independent variable GF, which is not explicitly considered in this figure, is held constant at the mean value and varies only between functions. Figure 11 depicts the aforementioned negative relationship between the 5 % peak hour volume and the number of hours per year with more than five aircraft movements per hour. Here we have to keep in mind that the value of the independent variable YACM not explicitly considered in this figure, is held constant at the mean value and varies between the functions.

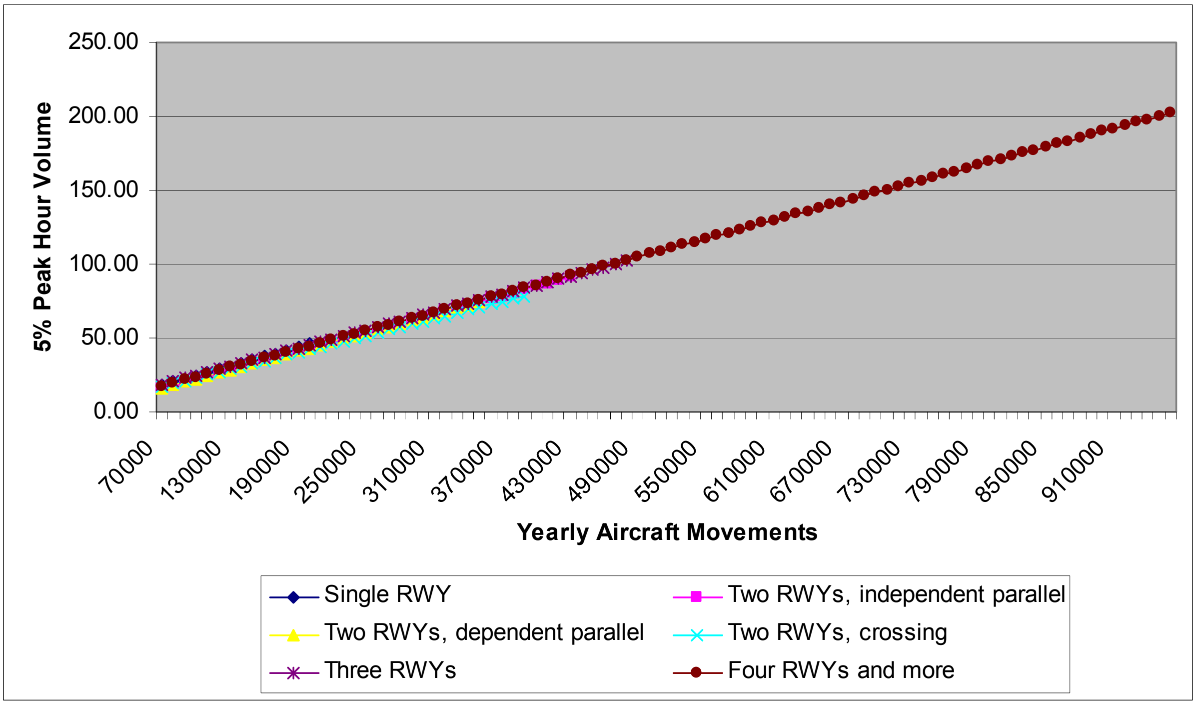

Fig. 10: Relationship between 5 % Peak Hour and Yearly Aircraft Movements (Source: OAG, DLR)

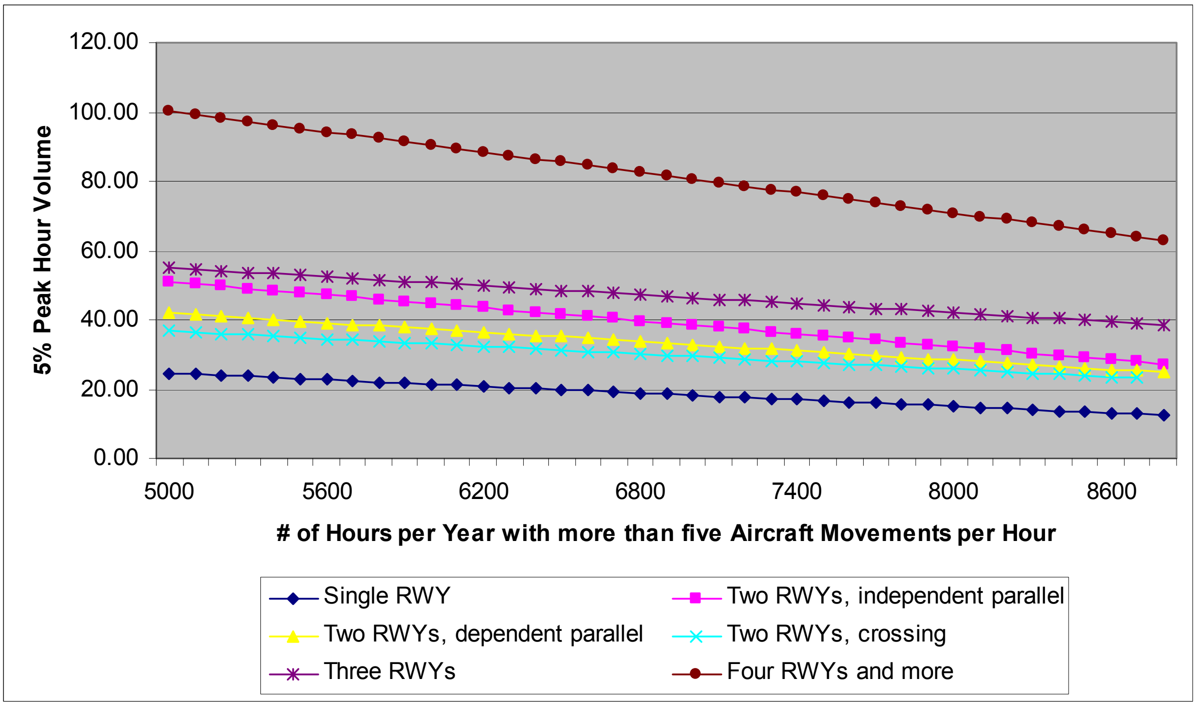

Fig. 11: Relationship between 5 % Peak Hour and the Number of Hours per Year with more than Five Aircraft Movements per Hour (Source: OAG, DLR)

Figure 12 and 13 illustrate the same relationships as the Figures 10 and 11, however, the values of the independent variables which are not explicitly considered in the figure are identical for all functions depicted. For Figure 12, we have chosen a value of 5840 hours per year with more than five aircraft movements per hour, which equals the day time period with 16 hours multiplied by 365 days a year. This value depicts only a discretionary definition; any other value would not make an essential difference. For Figure 13, we have chosen 100,000 aircraft movements, as this is a value which seems sensible as it appears in almost any runway system as depicted by Table 1. Furthermore, we have limited the range of aircraft movements in Figure 12 from 100,000 to 200,000, as this seems to be a sound overlapping between the different runway systems as shown in Table 1.

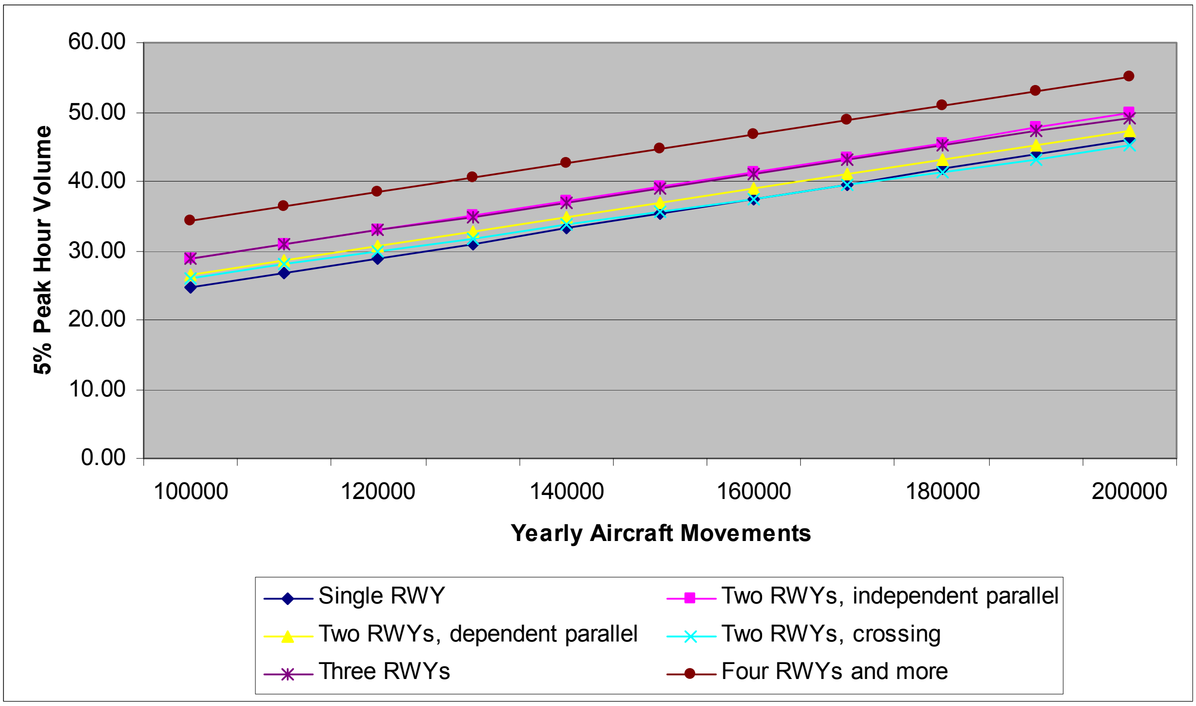

Fig. 12: Relationship between 5 % Peak Hour and Yearly Aircraft Movements, with GF = 5840 hours (Source: OAG, DLR)

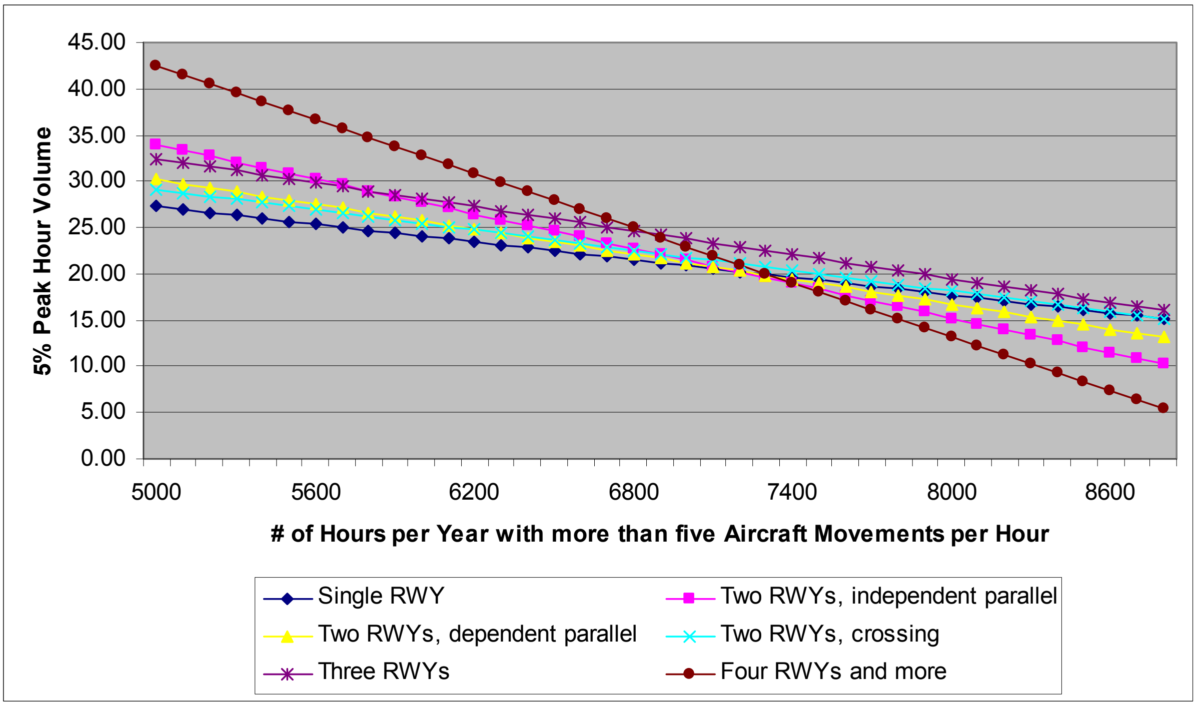

Fig.13: Relationship between 5 % Peak Hour and the Number of Hours per Year with more than Five Aircraft Movements per Hour, with YACM = 100,000 ATMs (Source: OAG, DLR)

For a given number of yearly flight movements, runway systems with a higher maximum capacity tend to exhibit a higher 5 % peak hour volume compared to runway systems with a lower maximum capacity (see Figure 12). The differences are only small if we look at single runway systems, systems with two parallel, but dependent runways, and systems with two crossing runways. However, the effect becomes more pronounced if we include systems with two independent runways, systems with three runways, and especially systems with four or more runways.

The impact of the maximum capacity of a particular runway system is not as distinct with regard to the relationship between 5 % peak hour volume and the number of hours per year with more than five aircraft movements per hour as Figure 13 displays. The slope of the different functions is approximately equal, with the exception of the two systems with two independent runways and with four runways and more. Here, the 5 % peak hour volume decreases noticeably more rapidly if the number of hours per year with more than five aircraft movements per hour increases, i.e. if flight restrictions decrease and available airport capacity increases.

The main reason for these findings is simply the difference of maximum airport capacity; a higher capacity allows for more flexibility to schedule ATMs at the airport, given a particular number of aircraft movements. Since we assume the same number of movements for two airports with different maximum capacity in this case, the ranking curve of the airport with the lower capacity utilisation has a higher starting point but runs steeper and thus the value of the 5% peak hour declines faster if we loosen flight restrictions (here: increase the number of hours per year with more than five aircraft movements per hour) and thus increase capacity.

7. Conclusions

Air traffic forecasts like those of the aircraft manufacturing industry typically yield annual flight volumes, the validity of which is related to a main forecast hypothesis of capacity unrestrained traffic conditions. Such operating conditions contradict more and more with reality. The question “Will the forecast demand for using airport infrastructure, i.e. the runway system, not exceed existing or planned capacity?” needs to be answered by comparing future flight volume with capacity.

In contrast to forecast ATM volumes, capacities are measured more often in short time periods, in particular hours. It has not been the intension of the paper to describe the various approaches of estimating **hourly capacity**, since they have been dealt with intensively in the literature; instead four lines of thought that have developed over time have been discussed, they are

- Empirical approaches including benchmarking
- Queuing models
- Analytical approaches
- Simulation models.

In answering the question of conformity of the demand (here in ATM’s) with capacity, future annual volumes have to be converted therefore into peak hour volumes and then compared with capacity. In the paper we have discussed primarily the problem of selecting and determining a suited peak hour volume in relation of a forecast annual traffic volume. Based on OAG data, the paper informs on the annual capacity utilisation of airports world wide in form of “traffic volume ranking functions”, which show the distribution of the number of hours at each volume level (between zero and highest hourly volume) over all hours of operation within a year. These functions are the basis for deriving functional relationships between peak hour and annual ATM volumes for each airport capacity type.

From the analysis of **traffic patterns** at many airports world wide (based on OAG data) we can conclude that the variation of traffic is typically great, in particular between day and night, also during the day, between week days and weekend, and within a year. The variation decreases with the traffic importance of the airport, but also with the seriousness of the capacity constraint of the airport. Nevertheless, even in important hub airports and capacity restrained airports, the difference between traffic in low demand situations, like at night, and in peak demand situations remains big. The high degree of traffic variation is therefore a fundamental argument for an hourly capacity concept, any kind of annual capacity would be subject to a discussion of how to account for the low demand time intervals during a year.

Traffic ranking curves have been derived for around 3500 airports world wide. They clearly demonstrate that the 5 % peak hour, which is in the range of the 330th to the 440th operational hour of the year, is a typical peak hour, since the traffic in the hours following in the ranking is declining less sharply, and much lesser than in the hours preceding the 5 % peak hour. As a result airport planners have often chosen the **5 % peak hour** as a base for designing facilities and capacity. After demonstrating the peak hour characteristics by means of the ranking curves of many airports we have adopted this concept and take the 5 % peak hour as the typical peak hour suited for estimating capacity reserves and utilisation. In a network or global analysis, the ranking curves as developed on the basis of OAG data allow determining the 5 % peak hour of airports in a consistent way. An additional advantage is given by the fact that peak hour volumes thus derived are comparable between airports.

Ranking curves are a tool for analysing and estimating hourly capacity of airports working under near capacity conditions, too. The question whether or not an airport has reached almost capacity in daily operation can be seen easily by regarding the slope of the ranking curve over all hours of the day (excluding night hours). If the slope is such that the variation of hourly traffic is rather small, as is the case in Frankfurt for instance, then the highest volume values of the curve are indicative of the capacity of the airport, which in such cases is typically the capacity of the runway system.

Functions relating the 5 % peak hour traffic volume with the annual traffic have been calibrated for six runway capacity classes of airports, based on data of 200 airports world wide with high traffic volumes. Statistically very good results have been reached by relating the peak hour volume in a linear function with annual traffic volume and a factor of annual utilisation of the runway system, being the number of hours with more than five aircraft movements, which corresponds roughly to the number of day hours (as contrasted to night hours) and describes the time period with high demand. This variable has been included to account for differences in opening hours and restrictions, especially night curfews respectively. For a single runway airport for instance, the function is given by

$$PACM = 21.8 + 0.00021*YACM - 0.00319*GF$$

with:

PACM = 5 % peak hour traffic volume (ATMs)
YACM = annual traffic volume (ATMs)
GF = number of hours with more than 5 ATMs

The functions of the other runway capacity classes are very similar. For a given number of yearly flight movements, runway systems with a higher maximum capacity tend to exhibit a higher 5 % peak hour volume compared to runway systems with a lower maximum capacity. The impact of the maximum capacity of a particular runway system is not as distinct with regard to the relationship between 5 % peak hour volume and the number of hours per year with more than five aircraft movements per hour.

For the time being the peak hour – annual traffic functions have been developed against an empirical background of the year 2008. In order to prove the robustness of the coefficients for applying the functions for forecast situations we intend to use data of other years, too, and calibrate these functions in a similar way.

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