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ESTIMATING RUNWAY CAPACITIES OF GERMAN AIRPORTS

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This paper deals with two problem areas: How to make forecasts of demand for air transport services compatible with those for airport capacity, when estimating capacity surpluses or deficits; and second, an empirical method for estimating functions of runway capacities for German airports.

The first part of the paper describes the demand and capacity characteristics of the German air transport system and methodological questions of estimating capacity reserves are also discussed, regarding the definition of capacity, the selection of the time unit of volume and capacity for comparison purposes, and the estimation of comparable volume and capacity values.

The second part deals with empirically derived functions of take-off, landing and mixed mode runway capacity. It has been found that the hourly movement rate is mainly determined by the sequence pattern and the size and mix of aircraft in the landing and take-off process.

Keywords: Air transport; Runway capacity; Peak hour; Capacity forecast; Volume-capacity comparison

AIR TRANSPORTATION IN GERMANY — SOME CHARACTERISTICS

Civil aviation is yet a small part of the total transport system: 1.5 trips on average out of 1000 trips generated in Germany are made by air, on both scheduled and charter flights. The traditional modes rail and road dominate in the modal spectrum; the growth in air transportation, however, has been and is much higher than in ground transportation. It is this growth in passenger travel, air freight, and flight movements that causes and will cause capacity problems at airports and in the air traffic control system.

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In 1995 the demand for air services in Germany and between Germany and other countries amounted to more than 42 million air journeys. \([1]\) (One journey corresponds to the sum of trips that are realized in order to get to the destination or destinations and back to the origin of the journey.) Within a period of less than 10 years, demand has doubled and has reached its highest level in air transport history.

The German airport network consists of 17 international airports (Figure 1). With the reunification of Germany in 1990 the airports of Berlin-Schönefeld, Leipzig, Dresden and Erfurt have been added to the network. The number of passengers handled at the 17 international airports, corresponding to the demand described, was as high as almost 110 million. To transport these passengers the airlines offered about 1.6 million scheduled and charter flights. Altogether, more than 1.8 million commercial and non-commercial movements (ATMS) were handled by these international airports.

Air traffic was not distributed equally among airports; on the contrary, the concentration on a few airports was substantial. In 1995, more than 60% of all passengers and almost half of the total flight movement volume was handled by three airports: Frankfurt, Düsseldorf and München. Frankfurt alone attracted more than 37 million passengers, one third of all passengers handled and, with 370,000 flight movements, one quarter of all movements in scheduled and charter traffic in Germany. The concentration of traffic on Frankfurt is partly caused by the hub function of the airport, about 45% of all passengers are transfer passengers. The proportions of transfer passengers at all other airports are much lower.

With demand for air traffic services growing strongly, it could be assumed that the concentration of traffic on the busiest airports would level off; this, however, was not the case, traffic was concentrated more and more on these three airports. As a consequence, the increasing concentration of passengers on airports with service densities already comparatively high was stimulating the imbalance of utilization of total airport capacity and became thus a factor of growing importance regarding the capacity problems of German airports.

**PROBLEMS OF ESTIMATING AIRPORT CAPACITY 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 element; the facility with the lowest capacity determines the airport capacity.

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

Capacity reserves of the runway system may be expressed either by the volume-capacity ratio or by the corresponding difference. Be it the expression of the relative utilization of capacity (ratio) or of the absolute load reserve (difference), questions arise regarding primarily three problem areas:

— Which is the proper definition of capacity and, dependent on that, which capacity value should be used in estimating the capacity reserve?
— Which is the proper time unit, i.e. an hour or a year, that should be used for forecasting volumes and capacities?
— Which forecast method should be used in order to estimate in a coherent way both volumes and capacities?

Concepts of 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 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.

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 ATC regulations.\(^2\)

The ultimate capacity does not take into account time delays of aircraft that are ready for take-off or landing in peak hour conditions. As the demand approaches capacity, delays to aircraft may reach intolerably high levels. The phenomenon of sharply increasing delays in traffic situations approaching capacity can be observed in road and rail traffic as well.

To account for the delay problem another concept of capacity has found wide application. Movement rates are determined in relation to average delay levels.\(^3\) In analogy to the “level of service” concept in road transportation\(^4\), a “practical” capacity was devised primarily for planning purposes, whereby a tolerable average delay was the criterion for setting the capacity as a limit for the runway system under day-to-day operating conditions (Figure 2).
According to widespread opinion, the practical capacity will be reached if the average delay to aircraft in the take-off queue will not exceed 4 minutes. At this average delay, single aircraft delays, which may exceed the average substantially, are not likely to increase further, but rather go down.

As can be seen from Figure 2, the two capacity concepts — the saturation and practical capacity — yield quite different results. In general one can conclude that actual values of the practical capacity, which are normally used in airport planning, are in the range of 60%–70% of the level of theoretical
capacity. Depending on the choice of the concept, capacity reserves to be estimated may vary accordingly.

Selection of the Time Unit of Volumes and Capacities

Runway capacities exist both on an hourly and an annual basis. The annual capacity is often used as an indicator of the ability of the runway to accommodate a certain flight movement volume and, in comparison with an actual or a forecast volume, to estimate the available capacity reserve. In long-range airport planning this comparison typically draws upon the annual capacity since the time unit of the demand and aircraft movement forecast is the year. There exist complex procedures to estimate the annual capacity; in principle, the capacity is deducted from hourly capacities multiplied by the hours of annual utilization 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 in one way or the other. The night hours, Sundays, some holidays, and other off-peak periods are in general times of low traffic demand, which are therefore not well suited for being included in that time span which serves as a base for capacity calculations. The time unit for which the capacity will be measured should be defined in such a way as to allow for a continuous utilization 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.

If consequently the hourly capacity has a higher significance on methodological grounds and therefore the comparison of volume and capacity should be performed on that basis then the question arises which hourly volume out of all hourly volumes of a year should be compared with the capacity.

So far it has been customary in Germany to select the volume of the so-called “typical peak hour” for the comparison. The typical peak hour is defined as the hour in which the traffic volume corresponds to the 30th highest volume of the top hourly volumes of the year. The traffic volume of the 30th peak hour has been retained as a measure for dimensioning infrastructure and facilities of airports, since such facilities should be suited to handle loadings at peak demands without causing operational problems. If facilities are planned to accommodate the absolute peak demands of the year, too, then they will be oversized for most traffic loadings during the year.

New research on the hourly distribution of traffic at German airports[6] has shown that the flight movement rate of the 30th peak hour lies in the range of
the highest loadings of the year (Figure 3), which will be achieved or exceeded only a few times within a year, and that the absolute values of these volumes vary strongly in these peak hours. They are as such not typical. In contrast, the volume variation in the range of the 500th hour or even more so in the range of the 3000th hour, that is around the mean loading, is very small, since one and the same hourly volume is observed several hundred times there.

If the objective is therefore to derive a "typical peak hour" then one has to search for this hour in that part of the ranking function of Figure 3, where the curve changes from the steep into a rather flat gradient, that is roughly between the 100th and the 400th operating hour. The exact determination of the typical peak hour within this area remains arbitrary; if one chooses in analogy to the 5% busy hour rate, which is used as a base for infrastructure planning among others in Great Britain, a 5% peak hour, then this hour is — dependent on the number of operating hours per day — around the 300th hour. There are further studies to be made, in particular regarding the associated delay statistics, before a new typical peak hour for the volume-capacity-comparison can be established.

Where annual forecast volumes of flight movements are known, then an empirical correlation between the hourly and the annual rate can be used for converting the annual forecast volumes into peak hour volumes. In Figure 4, the linear relationship between these variables is shown, based on data of seven German airports; the hourly movement rate refers to the 5% peak hour.
Methodological Questions of Forecasting Volumes and Capacities

The current air traffic volumes handled by runway systems are normally known from statistics and operational data. Capacities can often be derived from these data sources, so that the question of specifying capacity reserves for the current situation can be answered. The question is of another dimension if it comes to estimating capacity reserves for one or several alternative forecast situations. For that, forecasts have to be made both for flight volumes and capacities in a coherent way.

Forecasting air transport demand and flight movements is a complex problem on its own,\[^7\] which cannot be dealt with here. It should be noted, however, that demand forecasts typically are made on the working hypothesis that no capacity constraint will influence the development of the demand. If there is reason to assume that future capacities will not suffice to accommodate the demand, then the comparison of forecast volumes and capacities becomes a necessary part of the forecast task itself. Only in this way, is it possible to correctly interpret the forecast results.

If it is found that the forecast yields a theoretical demand surplus, then the results have another meaning than in the case of a capacity surplus; only the latter case reflects a potentially real situation.

Future system loadings should only be compared with capacities that have been estimated for the same year. For this, the capacity influencing measures planned by governments and airport companies, and their quantitative effect on capacity change have to be known.

Equally important is the fact that those factors which influence both the future structure of flight movements and capacity have to be introduced in

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**FIGURE 4** 5% peak hour volume as a function of the annual flight movement volume.
the two forecasts in the same way. This refers primarily to the seat capacity structure of the aircraft population, i.e. aircraft type and mix.

The capacity of a runway system does not have a constant value but is rather a function depending on many factors, the most important of which are the "traffic mix", i.e. the size distribution of aircraft taking off and landing, the ratio of landings and take-offs, and the separation minima as given by the ATC rules. The size structure of the flight movement volume becomes thus a connecting link between the volume and the capacity forecast, being a result of the first and an input for the second.

If for methodological reasons the volume-capacity-comparison is carried out on the basis of hourly flight movement rates, then there is, besides the conversion problem of deriving a peak hour volume from an annual volume, the forecast problem which consists of estimating the aircraft size distribution in this peak hour that corresponds to the given annual volume. The traffic mix in any given peak hour differs normally from the annual distribution. Given statistical data of time and size distributions of aircraft movements, it seems that these problems can be solved.

APPROACHES TO ESTIMATING RUNWAY CAPACITY

It is not the intention of this paper to describe and discuss alternative approaches of estimating runway capacity but rather to present one method that yields for the first time capacity functions based on traffic data of German airports. Nevertheless, before doing so, it is worth examining those methods and integrate our approach into the concepts that have been used so far. Basically, there are four lines of thought, that have been developed over time:[9]

- Empirical approaches.
- Queueing models.
- Analytical approaches.
- Simulation models.

Empirical approaches are based on observations, surveys, and statistics, the analyses of which, for instance in the form of extrapolations, can serve as a useful tool for estimating capacities. An example of this approach is the practice of the Flight Plan Coordinator of Germany to determine annually the so-called "capacity constraint" which serves as a limit on the loading capacity of airports in the process of coordinating schedules of airlines with respect to slots available for the forthcoming flight plan period (see Table I for the summer period 1995).

The capacity constraint is determined for each international airport after consultations with air traffic control, airport operators, and the Federal Ministry
TABLE I Capacity constraint values of the German international airports for the summer period 1995

<table>
<thead>
<tr>
<th>International Airport</th>
<th>Capacity Constraint [Flight Movements/Hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamburg</td>
<td>42</td>
</tr>
<tr>
<td>Hannover</td>
<td>36</td>
</tr>
<tr>
<td>Bremen</td>
<td>15</td>
</tr>
<tr>
<td>Düsseldorf</td>
<td>34</td>
</tr>
<tr>
<td>Köln/Bonn</td>
<td>52</td>
</tr>
<tr>
<td>Frankfurt</td>
<td>70</td>
</tr>
<tr>
<td>Stuttgart</td>
<td>24</td>
</tr>
<tr>
<td>Nürnberg</td>
<td>30</td>
</tr>
<tr>
<td>München</td>
<td>90*</td>
</tr>
<tr>
<td>Berlin:</td>
<td></td>
</tr>
<tr>
<td>— Tegel</td>
<td>34</td>
</tr>
<tr>
<td>— Tempelhof</td>
<td>30</td>
</tr>
<tr>
<td>— Schönefeld</td>
<td>24</td>
</tr>
<tr>
<td>Saarbrücken</td>
<td>18</td>
</tr>
<tr>
<td>Münster/Osnabrück</td>
<td>14</td>
</tr>
<tr>
<td>Leipzig/Halle</td>
<td>19</td>
</tr>
<tr>
<td>Dresden</td>
<td>15</td>
</tr>
<tr>
<td>Erfurt</td>
<td>8</td>
</tr>
</tbody>
</table>

*Estimated value, no official capacity constraint

of Transportation. The estimation process takes account of all restrictions that hinder the airport from accommodating more aircraft movements per hour. Such restrictions are not only physical conditions of the runway system itself, like lack of fast off-ramps, but also constraints in all parts of the airport system, like lack of manpower in the passenger handling area. The capacity constraint thus reflects not necessarily the current runway capacity but the airport capacity under the current requirements of the demand for flight movements.

Queueing models: The relationship shown in Figure 2 between the average delay and the flight movement rate reflects a function that has been developed in queueing theory. According to the so-called Pollazcek-Khintchin formula the equation of the function can be written:

\[ D = \frac{\lambda}{2} \star \left[(\mu^2 + \sigma^2)/(1 - \lambda \star \mu)\right] \]

where

\[ D = \text{average delay per aircraft in the take-off or landing process} \]
\[ \lambda = \text{flight movement rate (aircraft per hour)} \]
\[ \mu = \text{mean separation time} \]
\[ \sigma = \text{standard deviation of} \ \mu \]
The relationship was originally developed for the case of landing aircraft only, whereby the actual separation times had been distributed in a form similar to a Poisson distribution. A prerequisite for the validity of the function is that there are always aircraft in the landing queue. The saturation capacity is then $\lambda = 1/\mu$.

**Analytical approaches:** With the queueing model it is possible to estimate the practical runway capacity for a range of aircraft delay levels, i.e. the four-minute delay; important factors influencing capacity, however, like in particular the traffic mix, are not part of the function. To overcome this insufficiency analytical approaches have been developed and presented in several handbooks (see e.g. FAA\(^9\)). They start from the concept that aircraft taking off or landing are to be found at certain times at certain points in the airspace or runway system, and that these time and space coordinates can be measured and functionally interrelated. A model developed along these lines will be described in the following part of the paper.

**Simulation models:** Since high performance personal computers have been available, computer simulation has become a valuable tool for estimating capacity changes due to variations of measures in the airport and in ATC sectors. Aircraft movements are described by means of simulating single aircraft movements in space and time according to the operating rules. For this, geometric data (i.e. coordinates) of flight routes, the runway and taxiway system, ramp and terminal areas, movement data of aircraft, and structural data of the aircraft population are collected, recorded, and form an essential model input. As a result of a simulation run, following an input flight plan, movement rates together with delay and other characteristics are given for critical sections of the airport.\(^{10}\)

Some of the better known simulation models are ADSIM (Airport Delay Simulation Model), SIMMOD (Airport and Airspace Simulation Model), and AIRPORT MACHINE. With ADSIM and AIRPORT MACHINE, the capacity elements of the airport can be simulated, while SIMMOD is better suited for simulating the terminal area of the controlled air space. These models can be used for optimizing measures that have been conceived for capacity enhancement, by simulating each flight movement step by step in time and space and varying the configurations of runways, taxiways, ramp areas, and gate positions.

**Empirical Functions of Take-off and Landing Capacity for German Airports**

**Overview**

The method proposed here for estimating runway capacity is based on radar data of real flight operations in the airport control zone. The method thus
draws data from the international airports in Germany with their local and operational procedures.

In the following account, the runway capacity is defined as the maximum number of aircraft movements per hour. Both a wide range of capacity values reflecting different situations of operation and the present respectively future movement capacity can be estimated by means of parameter variation.

Empirical functions have been developed for estimating the capacity by taking into account the following factors:¹¹

— air traffic control separation standards;
— aircraft characteristics like weight, speed, and propulsion;
— mix of the aircraft types;
— movement mix (arrival-departure ratio);
— runway configuration and distribution of departure routes.

For considering the optimization of operations of existing facilities or extending infrastructure, these factors reflect important planning inputs.

The minimum separation standards as laid down by air traffic control rules influence the capacity most of all. The weight of the previous and the successive aircraft determines the separation between them due to possible wake turbulence. Therefore, the estimated capacity values are plotted as a function of the aircraft population.

The theoretical capacity of a runway system is derived from operations that assume the application of the rules of ATC without any variation of minimum separation standards (theoretical values). By analysing radar data, the actual separation distances of two landing or starting aircraft in operating conditions near capacity can be determined (actual values). From actual separations, the so-called buffer times can be derived, which are the difference between actual and minimum separation times. Thus, practical capacity values can be estimated on the basis of minimum spacing plus buffer times.

Aspects of the Empirical Basis

Since it is the objective to establish capacity functions that reflect real operating conditions at German airports, the method asks for an extensive collection and preparation of empirical data. The configuration of airport and airspace systems, weather conditions like visibility and wind, and all functions of radar control must be described in order to establish the inputs necessary for calibrating the model. In Figure 5 a schematic flow chart of the program called PRORAD is shown. The main outputs are "intermovement time" matrices specified according to the kind of movements and types of aircraft, and frequency distributions of these intermovement times.
As an example, Figure 6 shows for Düsseldorf airport — with one runway — the distribution of interarrival times for all aircraft classes on the basis of observations for several days. The average separation time is about 130 seconds, the service volume can be calculated as 28 landings per hour, which may be interpreted as one value of the practical capacity.
The sequence of arrivals and/or departures is often regarded as following a Poisson distribution. The Poisson distribution represents the probability of isolated events in a certain time interval, whereby the occurrence of events must be affected by chance alone. Regarding uninterrupted sequences of movements in busy hours on international airports, it was not clear whether or not these demand processes follow a Poisson distribution, particularly if one considers the tendency of abandoning the “first-come, first-served” discipline and introducing air traffic flow management instruments like COMPAS (Computer Oriented Metering Planning and Advisory System).

For several airports in Germany, arrival/departure sequences over several days were tested in order to find out how well the observed data would fit the assumed frequency distributions. It could be shown that most — not all — distributions are significant at the 5 and 10 percent level. This means that the distributions found are approximately normal or Poisson distributions; however, it is not proven for all cases. Before drawing a reliable conclusion, further tests with greater data sets should be made.

Figure 7 shows the separation times of take-offs and landings in alternate sequence being normally distributed, for an airport with intersecting runways. The mean time interval is $\mu = 112$ sec, with the standard deviation $\sigma = 36$ sec. Assuming the normal distribution curve in a standard form, the variable $z$ for a probability of 10 percent is about 1.281 and $z*\sigma = 46$ sec. That means that for the confidence level of 90 percent the confidence limits are: $(\mu - z*\sigma) = 66$ sec and $(\mu + z*\sigma) = 158$ sec.
With the results of the statistical tests and with plausible assumptions regarding the separation intervals, buffer times have been determined for all possible mixes of aircraft classes and types of movement combinations.

**Structure of the Runway Capacity Model**

Taking into account the results of the empirical analysis, three partial models have been developed characterizing the three possible kinds of movements on a runway system, that is arrivals only, departures only, and the mix of arrivals and departures.

Figure 8 shows the flow chart for the model program GARCAM (German Airports Runway Capacity Model) that is employed for estimating capacity values of a single runway system. The model inputs are online variables and offline parameters:

- online variables reflecting runway operating strategies like:
  - POR\textsubscript{CLA} .......... aircraft mix
  - POR\textsubscript{R} .......... runway use
  - POR\textsubscript{SEQAD} .......... part of sequence A D A D ..., (A = Arrival, D = Departure)
  - R .......... arrival-departure ratio;
- offline parameters in files like:

\( \delta_{\text{Wake}} \) matrix of wake turbulence

\( \text{ROT} \) runway occupancy times

\( t_{\text{OMTH}} \) flight times for the distances

Outer Marker - threshold

\( t_{\text{Buffer}} \) matrices of buffer times in connection with intermovement times.
The capacity is calculated by pair probability \( p_{ij} \) (aircraft class \( i \) followed by aircraft class \( j \)) and intermovement time \( T_{ij} \) separately for take-offs and landings. The results of model parts ARR1RWY named CAPLAN and of DEP1RWY named CAPTO serve as input for the AD1RWY algorithm which estimates the capacity for the case of a combination of take-offs and landings. AD1RWY calculates upper and lower limits of possible capacity values according to given arrival-departure ratios, and in consequence one runway capacity value \( \text{CAP} \).

This capacity value is composed of the number of aircraft movements of each aircraft class. In an additional step an aircraft sequence for arrivals and/or departures is determined in order to verify both the total estimated capacity value and the partial capacity values of movements in each aircraft class.

**Single Runway Capacity**

On a single runway system the *arrival capacity* depends, above all, on the overall aircraft mix in a landing sequence and the sequencing of single aircraft by weight class. Minimum separation standards, that account among others for the effects of wake turbulence, are fixed on the three aircraft weight classes: Heavy, Medium, and Light. The class \( M \) is again subdivided into aircraft powered by jet engines (called \( M \)) and propeller-driven aircraft (called \( MP \)), because of distinctly different speeds, especially in the take-off phase.

The maximum number of movements is achieved, if aircraft are always landing in the sequence of minimum separation intervals ("Best Case"), i.e. first all aircraft of class \( L \), then all aircraft of class \( M \) and \( MP \), and all the heavy ones last. On the other side, the hourly capacity would be a minimum, if aircraft are landing in sequence intervals of highest separations ("Worst Case"), i.e. each aircraft of class \( L \) behind one of class \( H \) and vice versa, then each aircraft of class \( M \) respectively of class \( MP \) following one of class \( H \), etc.

The functions for the best and worst case envelop the field of all possible hourly capacity functions for given separation standards and approach speeds. The landing capacity is shown in Figure 9 as a function of the aircraft population. Since large aircraft have a strong influence on capacity, the function is shown in relation to the portion of aircraft of class \( H \), whereas for the other classes functions are given for some selected constellations of aircraft class portions. They have been selected in such a way as to represent the envelope for all other class proportions, both for the best case and for the worst case.

This shall be explained by means of the following example for a given aircraft population of \( H = 30\% \), \( M = 20\% \), \( MP = 0\% \), and \( L = 50\% \).
According to the sequence of aircraft by class in the landing process, all possible capacity values are lying on a straight line for the given portion of $H = 30\%$. In the best case the arrival capacity is about 40 movements per hour, in the worst case only 29 movements. In general, Figure 9 shows that the landing rate is higher if aircraft of the same class always follow each other; if there is a continuous change of aircraft by class, the landing rate may be reduced significantly.

Within the range of 29 to 40 hourly landings a distinct capacity is to be estimated for any given situation. Provided that

$$[p_{ij}] = p_{HH} + p_{HM} + \cdots = 1$$

the pair porbability matrix $[p_{ij}]$ can be derived given the portion of each class combination. The intermovement time matrix $[T_{ij}]$ is determined in relation of the separation standards of ATC and different approach speeds of aircraft classes. The average intermovement time is given by:

$$T_{Sum,LAN} = [T_{ij}] = \sum p_{ij} * T_{ij}$$

and the arrival capacity — expressed in movements per hour — then:

$$CAP_{LAN} = 3600 * (T_{Sum,LAN})^{-1}$$

The results of the estimation procedure of both capacity values and aircraft class portions are typically given in real figures. Iteration procedures are necessary therefore, resulting in integer numbers for both items. Referring to the
example above, the balanced capacity value is 33 landings per hour and the distribution according to aircraft class is: 10 movements of class \(H\), 7 of class \(M\), and 16 of class \(L\).

Making use of probability calculations and iteration procedures, a sequence of the aircraft class distribution found is estimated that verifies the calculated capacity value. A pattern of landing aircraft by class is derived that follows a ranking of movements which is in accordance with the set of input conditions. With the matrix representing the number of aircraft of each possible class combination, the following landing sequence can be presented for the given example:

\[
MHMH|HHH|LHLHLHLH|MM|MLMLML|LLLLLLL\]

This sequence is in accordance with the hourly capacity value of 33 movements. It represents one possible “landing sequence”, however, it is not the only one.

In a similar way the departure capacity can be estimated. Similar to the arrival capacity, separation standards and the sequencing of departing aircraft have a considerable influence on the capacity. In addition, however, it is the potential use of several departure routes which may increase the capacity significantly as compared with the landing capacity. If two departure routes diverge by at least 45° within 5 nm from the runway, the waiting time for the following take-off can be reduced substantially. This is demonstrated with Figure 10 for Düsseldorf airport, where two departure routes diverge at the Middle Marker.

![Graph showing functions of theoretical runway capacity](image-url)
In general, one can state that if diverging departure routes are used alternately, the number of hourly take-offs is considerably higher than in the case if only one and the same departure route would be used. The intermovement time is determined by the time the aircraft needs for the take-off run, that is from starting point to the diverging point of the departure routes. In the case of always the same departure route, in contrast, the separation is determined essentially by wake turbulence.

In Figure 10 the functions of theoretical departure capacity are shown together with the area of possible capacity values for the range of aircraft class compositions, with the upper curve, if diverging departure routes are used, and the lower curve for the worst case, that is, if only one and the same departure route is used.

Dependent on the use of the departure routes, the departure capacity can be estimated by:

\[
\text{CAPTO} = \left( \frac{\text{POR}_{EQ}}{T_{ij}\text{EQ}} + \frac{\text{POR}_{ALT}}{T_{ij}\text{ALT}} \right) \times 3600,
\]

with \( \text{POR}_{EQ} = \) portion of aircraft using the same departure route

\( \text{POR}_{ALT} = \) portion of aircraft using diverging departure routes alternately.

Iteration steps and the presentation of a “take-off sequence” are conducted in the same way as in the case of calculating landing capacity.

With the exception of a few peak-hours of arrivals or departures only at hub airports, normally there are take-offs and landings alternately or in succession on a runway system within any one hour. Besides the factors influencing capacity mentioned before, the runway capacity for a combination of arrivals and departures is determined to a great extent by the runway occupancy time (ROT) and the pattern of sequencing arrivals and departures.

Sequences with arrivals (A) and departures (D) in an alternate way (called later CAPHI) yield a much higher capacity than separate landing or take-off sequences. Analysing arrival-departure sequences at German airports it could be shown that 60%–70% of all possible sequence combinations in an hour are alternate landings and take-offs (\( \text{POR}_{SEQ\text{AD}} = 60\%–70\% \)).

On a single runway system, landing aircraft influence the capacity to a high degree. On the one hand a landing aircraft determines the intermovement time for a following departing aircraft by the ROT, and, on the other hand, a previous departing aircraft cannot begin the take-off run if a landing aircraft is not far enough away from the runway threshold, that is to say, at least to the Outer Marker.

Shorter sequences of arrivals or departures (AAA... , DDD... , etc.) in one operational hour are influenced by the same factors as in the case of arrival
or departure capacity. As in the case of the functions of departure capacity, functions of separate sequences (later called CAPLO) are dependent on the use of departure routes.

In Figure 11, functions are shown for CAPHI (sequence ADAD...), CAPLO1 (sequence 1*AD, 1*DA, AAA..., DDD...; use of the same departure route, only) and CAPLO2 (sequence 1*AD, 1*DA, AAA..., DDD...; use of diverging departure routes, alternately) for an arrival-departure ratio $R = 1$. Considering these functions and taking equally into account the predicted growing demand for air transport, optimization of runway utilization — especially at hub airports — can be achieved by realizing sequences described by CAPHI in order to achieve a throughput as high as possible.

For any given aircraft mix, the runway capacity, with values in the area being enveloped by the upper curve of CAPHI and the lower curve of CAPLO1, can be estimated as follows:

$$\text{CAP} = \text{PORSEQAD} \times \text{CAPHI} + (100 - \text{PORSEQAD}) \times \text{CAPLO}$$

with $\text{CAPHI} = 3600 \times \sum p_i / 0.5 \times (\text{ROT}(i) + t_{\text{OUTTH}}(i))$

and $\text{CAPLO} = \text{POR_EQ} \times \text{CAPLO1} + \text{POR_ALT} \times \text{CAPLO2}$

CAPLO1 and CAPLO2 are functions of the intermovement time $[T_{ij}]$ and of arrival and departure sequences. These equations are valid for the arrival-departure ratio $R = 1$.

Regarding variations of $R$, besides sequences of ADAD... respectively AD, DA, AA..., DD..., there are also sequences of landings only or take-offs only

![Figure 11](image-url)
so that CAPLAN respectively CAPTO has to be included into the capacity calculation, too.

Multiple Runway Capacity

In addition to airports with one runway system, there are in Germany airports with two intersecting runways, with dual-parallel runways, and with dual-parallel runways plus one intersecting runway.

The capacity estimation of multiple runway systems is clearly more complex than for single runway systems. The main reason is the variability of operation possibilities, which grows with the number of runways. However, besides the fact that multiple runway systems can or must be operated in a single runway mode — because of wind conditions, for instance — operational conditions, variables, and capacity influencing factors for single runways often are the basis for multiple runway systems too.

Since it is impossible to cover the capacity functions for all possible operations on multiple runway systems in this paper, the airport of Hamburg has been selected for which functions of arrival and departure capacity on an intersecting runway system shall be discussed as an example.

Figure 12 shows the runway system of Hamburg airport. For the purpose of noise abatement, RWY 23 is used for landings only, and RWY 33 for take-offs only, whenever possible. Taking this operation procedure as a basis, arrivals and departures can be handled alternately, or in another operation mode, several arrivals in succession can take place in alternation with several departures. This procedure, i.e. sequences of arrivals respectively of departures in succession, is identical with single runway operations.

Regarding a continuous change of using the two runways, with arrivals on RWY 23 and departures on RWY 33, the intermovement time between an arrival and a departure can be deduced from ATC rules as follows:

— the arriving aircraft may not cross the threshold until the previous departing aircraft has crossed the intersection point,
— the arriving aircraft shall get the landing clearance not later than 2 nm from touchdown,
— a successive departing aircraft is allowed to begin the take-off run only after the previous landing aircraft has crossed the intersection point.

Therefore, in the case of a departure previous to an arrival in a continuous flow situation, the intermovement time $[T_{DA}]$ is equal to the time that the take-off requires to cover the distance from the starting to the intersection point, plus additional 10 sec which are needed on safety grounds for "intersection point crossed", and the time the arriving aircraft needs for the distance of 2 nm to the
threshold. In the case of an arrival previous to a departure, the intermovement time $[T_{AD}]$ is equal to the time the arriving aircraft needs for the distance from the threshold to the intersection point plus the above mentioned safety time. Summarized, the capacity for this kind of operation can be expressed as:

$$\text{CAPM}_{AD} = 3600 \times (0.5 \times \frac{1}{T_{DA}} + 0.5 \times \frac{1}{T_{AD}})$$
In addition to the 'single arrival — single departure' operation the sequencing of several arrivals and departures is a common mode of operation. For that, the total capacity consists of two parts, the CAPMAD — capacity plus a movement rate that takes account of the capacity gain due to the sequencing of platoons of arrivals and departures. Besides the factors $R$ and PORSEQAD (see "single runway system") the capacity depends to a great deal on the position of the intersection point as reflected in the terms of $[T_{DA}]$ and $[T_{AD}]$. In unfavourable operating conditions — at Hamburg airport for instance, departures on RWY 15 and arrivals on RWY 23 — wake turbulence has to be taken into account too.

Figure 13 shows the function for CAPHI — capacity in a multiple runway operation in relation to the functions of CAPHI — and CAPLO1 — capacities for a single runway operation. The area of all possible capacity values is enveloped by the upper curve of CAPHIMUL and the lower curve of CAPLO1SIN.

High movement rates can be achieved (CAPHI), if RWY 23 and RWY 33 are used simultaneously, in contrast to CAPHI, with RWY 23 being exclusively used. It must be emphasized, however, that the figure only shows theoretical functions of runway capacity; that means that the capacity calculations always assume minimum separation intervals.

Because of imponderables in the ensemble of controller, pilot and aircraft acting in the airport control zone, movements with such minimum separations cannot be realized in a day-to-day practice. Therefore, in addition so-called buffer times have to be taken into account in estimating practical runway capacities. The results of including buffer times are demonstrated in Figure 14.
From the analysis of the data for Hamburg airport, buffer times have been deduced in the dimension of about 30 sec. This buffer reduces the CAPHi capacity approximately to half of the theoretical value. It demonstrates how strongly the capacity depends on the configuration of intersecting runways. Calculating CAPHi for single runway operation, the capacity is nearly 10 movements lower than for intersecting runway operation.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The forecast of capacity reserves is a valuable criterion for evaluating the future strength and weakness of the air transport system. Capacity reserves are estimated by comparing future flight movement volumes with capacities.

The discussion in the first part of the paper has shown that there are still methodological and data gaps that form a barrier to carrying out runway capacity forecasts in such a way as to allow for the estimation of capacity reserves of the future airport system. For that, the demand and the capacity forecasts have to be interconnected in order to guarantee that the aircraft population, which is an output of the traffic forecast, is identical with the input traffic mix of the capacity estimation. Only if volumes and capacities have the same traffic background, as described by the same forecast hypotheses, then they are comparable. The aircraft population is thus not only a key variable
in the forecasts but also an important factor influencing directly the extent of system reserves.

The applicability of the analytical capacity models for German airports has been demonstrated; nevertheless, it is still necessary to incorporate aircraft delay as a variable into the models. The significance of the models as a planning tool will be higher if the quality measure “aircraft delay” will be associated with the capacity functions.

Finally it is proposed to make use of both analytical and simulation models for estimating future capacities. Computer simulation of flight movements at airports is a useful and versatile tool for researching the effects of different measures on runway capacity, whereas analytical models are suited to estimate future capacities in relation to forecast aircraft populations. The combination of the two approaches should allow for a better estimation of capacities for studying future air transport strategies.

References

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