Airport Capacity and Demand Calculations by Simulation - The Case of Berlin-Brandenburg International Airport

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Abstract: In globalized and dynamic economies airports are vital parts of traffic infrastructure securing the prosperity of inter- and also transcontinental mobility of goods and passengers in spatially dislocated market structures. Because their capability is determined by the available infrastructure, the layout and the operational capacity must be dimensioned under a long-term view. Future expansion to correct existing bottlenecks needs a timeframe of up to twenty years of negotiation, planning and construction time for say, an additional runway, which is today the state of affairs in most, if not all, European countries.

From this point of view we will be analyzing the forecast of demand and throughput capacity for the currently constructed Berlin-Brandenburg International (BBI) airport over a 20-year timeframe. The approach taken in this study is based on an independent parallel runway layout, and the development is calculated by applying data from a SIMMOD simulation. The practical capacity, which is the suggested maximum throughput under the defined assumptions, is estimated for a given level of service measured in average delay per flight. Our examples will be discussed and critically examined with regard to existing airports with a comparable runway layout.

Keywords: Aviation, airport operations, runway capacity, simulation

1 Problem description

Mobility of *passengers* and *goods* represents an essential basis for the development of economic structures resulting from the spatial dislocation of production facilities and labor in industries as well as in the retail trade. Adequate systems and capacities are mandatory to serve the demand for transport services. Each situation requires its specific technical and functional framework for mode and type of transport. In this respect the *characteristics of quality rating* of transport modes play an essential role, because these can give an answer concerning case-specific ability (see e.g. [9]). In this context the traffic infrastructure and the technical development of equipment is of great importance for transport mode performance.

Especially when dealing with inter- and transcontinental transport of passengers and (small sized and high value, as well as special) cargo, air transport is the dominant mode. Competitive advantages mainly result from high speed and therefore shorter travel times between origins and destinations; these are associated with convenience and cost reductions (such as tied capital costs and insurance costs). Disadvantages of air transport services are clearly the limited aircraft capacity and the comparably costly tonnage. Also hurdles must be overcome to raise air transport capacities to attain *economies of scale* and to reduce fares by increasing competition. In the foreground are market-entry barriers resulting from the need for large capital investment and trained labor for new market entrants as well as from current and forecasted *slot constraints* at some of the largest hub-airports. These slot-coordinated airports (see [18]: p. 11 ff.) operating at (declared) capacity during peak hours are, e.g., *London Heathrow Airport* (LHR), *Frankfurt Rhine-Main Airport* (FRA), and *Munich Franz Josef Strauss-Airport* (MUC), each of which can be considered congested (see [13]: p. 64). However, for certain products and market segments there is no substitute for air transport, which leads to a (de facto) monopoly situation for certain routes and origin / destination markets, especially concerning intercontinental transport.

When designing international and national *air transport systems* (ATS), the *airports* and particularly *runway capacities* play a key role. On the one hand airports are *core elements* of infrastructure representing the nodes of air transport networks, and on the other hand they serve as gateways in connection with the land transport modes in pre- and on-carriage services. With these characteristics ATS act as the crucial point in operating multi-modal transport networks, so airport-related *capacity bottlenecks* limit the *productivity* of the entire system (see [6]).

On the landside, airport capacity is restricted by road and rail accessibility, airport facilities and ground handling performance. The airside capacity is determined by *local topography*, *prevailing weather conditions*, *layout*, *configuration*, and *availability* of *runway*(*s*), *runway exits*, *taxiways*, *apron area*, *aircraft parking stands* and *air traffic control* (ATC) *capabilities* (mainly limited by availability of specially trained controllers and / or technical equipment). The enhancement of airside capacity, especially the realization of additional runway capacity, requires lengthy planning, negotiation and approval processes as well as construction time. Furthermore large investments are needed and therefore detailed forecasts of future demand are required.

The focus of our study is to analyze the impact of different scenarios and increasing levels of demand on the *runway throughput*, *capacity utilization*, *congestion delays*, and associated *level-of-service* (LoS) as well as *delay costs* (see [17]: p. 157 ff.; [13]: p. 9 ff.; [26]: p. 14 ff.). Based on a given runway layout and common safety regulations, a SIMMOD simulation approach is applied in this study (see e.g. [3]: p. 5 ff.). Only by employing simulations is it possible to analyze and calculate airside capacity in such a complex and dynamic environment as that of an airport (see e.g. [5]: p. 1235 ff.).

"What if" questions, whether the planned maximum capacity is adequate for serving forecasted demand or what are the consequences for airport users if capacity is not sufficient, will be analyzed in the case of the *Berlin-Brandenburg International* (BBI) *airport*, which is currently under construction, by applying a simulation approach. This airport (current construction plans were drawn up in the early 1990's) is expected to go into operation at the beginning of June 2012. It is located on the south-eastern periphery of Berlin partly on the territory of the existing airport *Berlin-Schönefeld* (SXF). The planned airside configuration of BBI airport will be critically examined with regard to the future development of demand, assuming a range of growth patterns. Finally a best-practice comparison will be conducted with data from *Munich* (MUC) and *London-Heathrow* (LHR) airports.

2 Methodology

In Berlin, the capital of the *Federal Republic of Germany*, there is an ongoing heated and partly politically-motivated debate regarding not only the capacity of the new BBI airport but also the future relevance of air traffic. There are reasonable doubts that a *parallel runway* system with *two* runways will be adequate, when replacing the currently operating airports *Berlin-Tegel* (TXL) and SXF with a combined current total of *three runways*. The available capacity in the Berlin area has already been reduced, because of the closure of the *Berlin-Tempelhof* (THF) airport with its two (short) runways in 2008.

The key question is what ultimate level of demand can be served at the BBI airport given the proposed parallel runway layout (see Fig. 2.1) and when this maximum level is expected to be reached. The runways will have a length of 3,600 and 4,000 meters, and a separation of 1900 meters; also they will be staggered by 1,250 meters (see [22]: p. 222 f.). Requested and served demand will be monitored over time of day with regard to LoS, measured in average minutes of delay per flight. Different scenarios with a various aircraft mixes are derived from the baseline flight schedule. The required calculations are made with the *Visual SIMMOD* software package (see e.g. [2]) in connection with established SIMMOD tools and recommendations from the *Federal Aviation Administration* (FAA) (see [14]).

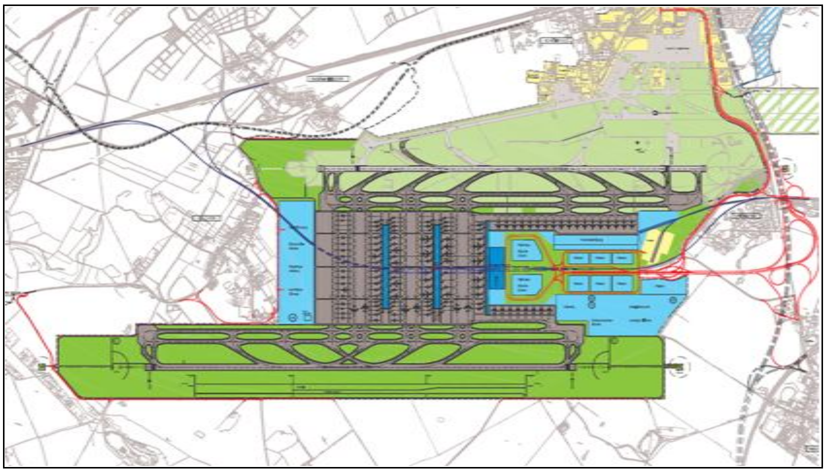

Fig. 2.1: Basic layout BBI airport

The airside airport layout structure will be simulated as a *staggered independent far parallel runway system* (see [22]: p. 409 ff.), where arrival and departures are served separately on the two runways in *segregated mode*. This is the main mode at Europe's busiest airport, LHR. The official planning documents for BBI airport posit an ultimate capacity of 83 flights in the peak hour (see [22]: p. 222) (under *mixed-mode* operations (see [1]). Other assessments in the documents reveal a capacity of 90 movements in the peak hour (see [22]: p. 334), as it is the case at MUC with a similar runway layout. MUC airport is currently able to operate at this capacity only over short periods of time during the day (see [11]: p. 18 and 27pp). Segregated and mixed-mode operations at LHR and MUC will be further discussed in section 3.

Besides mode of operation other main limiting factors regarding airport airside operations capacity are the number of *available independent* (greater than 1,380 m of lateral separation) *parallel runways*, *nighttime curfews* (between 23:00 and 7:00) or other *operating* or *environmental restrictions*, *separation minima* between succeeding aircraft, *runway occupancy times*, and the definition of LoS. For the majority of flights in Europe ATC applies *instrument flight rules* (IFR) with separation minima of at least 2.5 nautical miles (NM) on final approach (see [15]: p. 77).

2.1 Applied scenarios

The basic input for the SIMMOD simulation is the combined flight schedule with 635 flights which were operated at the Berlin airports TXL and SXF on the *design day* (Thursday, June 26th 2008). Diverted, cancelled and "unknown status" flights, representing 10% of the daily movement, have been excluded from the original peak schedule, making it a typical busy period schedule. Overcoming the decrease in aircraft movements in 2009, the traffic volume in 2010 attained previous levels of 2008, so the magnitude of the input data remains valid for the further computational tests (see Fig. 2.2). The representative flight schedule consists of the following basic information: Origin, destination, scheduled departure or arrival time, aircraft type and flight number. These flights are separated by three *wake turbulence categories* (WTC) based on *Maximum Take-off Weight* (MTOW) of each aircraft type. The categories *HEAVY* (H), with an MTOW greater than 136 tons, *MEDIUM* (M), with a MTOW between 7 and 136 tons, and *LIGHT* (L), with a MTOW below 7 tons define the types to calculate the aircraft mix at a given airport over certain periods of time (in our case on design day) (see [16]: p. 90).

Hour of day	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Sum
Heavy								1	1	2		1	1	1	1	1			1	1			1		12
Medium	2	1		1	1	2	24	26	46	43	34	39	25	31	32	32	37	41	42	44	46	35	21	4	609
Light								2	1		2	1		1		2		1	2	1	1				14
Sum	2	1	0	1	1	2	24	29	48	45	36	41	26	33	33	35	37	42	45	46	47	35	22	4	635

Fig. 2.2: Daily flights by weight classes

The sequencing of aircraft in the airspace needs to be seen as an important influence on the airside capacity and performance of an airport system (see [10]: p. 395; [15]: p. 78). The WTC defines minimal separation requirements between two subsequent departures in *seconds* and between two subsequent arrivals in NM (see [17]: p. 167). In the case of simulating mixed-mode operations on the same runway (which has not been modeled in this study), *separation matrixes* for subsequent departures after arrivals and vice versa must be applied (see [23]: p. 5; [10]: p. 377 ff.; [16]: p. 113). It should be noted that different aircraft speeds may require even further separation minima during approach than the minima listed in Fig. 2.3 (see [15]: p. 78; [23]: p. B-3 ff.).

Sequence		**Arrival - Arrival (in nautical miles)**			**Departure - Departure (in seconds)**		
Leading \ Trailing	Maximum take-off weight (MTOW) (in tones)	Heavy	Medium	Light	Heavy	Medium	Light
Heavy	> 136	4	5	6	120	120	120
Medium	7 - 136	3	3	4	60	60	60
Light	< 7	3	3	3	60	60	60

Fig. 2.3: Wake turbulence related IFR aircraft separation minima

Since the separation minima for IFR flights among the three categories are not symmetric, the sequential order by type and number of aircraft during an arrival bank results in different hypothetical sequence lengths, which in turn influences the capacity of an airport (see [17]: p. 168; [28]; [20]). This can be observed in an example of combinations of H and L category aircraft. For the series of six arrivals on the same runway H→ L → H → L → H → L the calculated sequence length is 24 NM, whereas for the rearranged series L → L → L → H → H → H the resulting sequence length is reduced by 7 NM to 17 NM, which allows fitting two more aircraft into the original sequence length. This intuitive example shows the effect of aircraft sequencing and the benefits of bundling succeeding H category flights [20]. Therefore different aircraft or *traffic mixes* are examined based on possible future shifts of preference for certain aircraft types [17].

Initially a *baseline scenario* is created directly from the design day schedule (Scenario 0), which is then tailored into five additional scenarios with varying WTC shares (Scenarios I to V) (see Fig. 2.4). The original flight schedule is manipulated by the random substitution of used aircraft types with others of higher or lower WTC to reflect the change in WTC shares. A single mathematical expression describing this mix of aircraft types at a given airport over a certain period of time is the *Mix Index* (MI). The MI can be used for the estimation of future capacity using charts for long-range planning (see [14]: p. 3). To calculate the MI for the share of M category aircraft, the three-fold weighted share of H category aircraft is added, to account for its impact on capacity utilization (see [20]), and is used in this context for comparisons based on a single indicator (see e.g. [10]: p. 391 ff.; [16]: p. 515 ff.)

Scenario	**0**		**I**		**II**		**III**		**IV**		**V**	
%-Share / #	%	#	%	#	%	#	%	#	%	#	%	#
Heavy	2	12	5	32	15	95	5	32	20	127	2	13
Medium	96	609	95	603	80	508	84	533	65	413	84	533
Light	2	14	0	0	5	32	11	70	17	95	14	89
Sum	100	635	100	635	100	635	100	635	100	635	100	635
Mix-Index (%)	102		110		125		99		125		90	

Fig. 2.4: Scenario data

The baseline flight schedule and flight schedules with incremental growth rates applied serve as the main input for the SIMMOD simulations. In the six scenarios, varying in WTC shares and MI (as noted above), the 635 baseline movements are subject to a *probability of producing* a *replica* of themselves during the simulation runs, reflecting traffic and demand growth. Scenario 0 from the original design day schedule with zero growth is set as the original baseline scenario. Further variations include a 20% decline in traffic, and incremental increases of 20% up to 200% of baseline demand.

The objective of simulating the scenarios with varying aircraft mixes and levels of demand is the determination of a maximum throughput of the planned airport airside configuration. More specifically the objective is to estimate at which rate of demand and under which scenario the service rate is exceeded, flights are delayed and the average delays increase above predefined LoS. This threshold, where a stable flow of traffic can be maintained over extended periods of time, is defined as the *practical* or *sustainable capacity* of the airport (see [5]: p. 1236; [10]: p. 448; [21]: p. 379 ff.).

The (theoretical) relationship between the development of demand, capacity and its utilization, and delay is shown in Fig. 2.5. To describe the level of congestion at BBI airport, a LoS of six minutes average delay per flight on design day has been defined (suggested parameters in the literature vary from four minutes (see [10]: p. 448) to eight minutes (see [21]: p. 388).

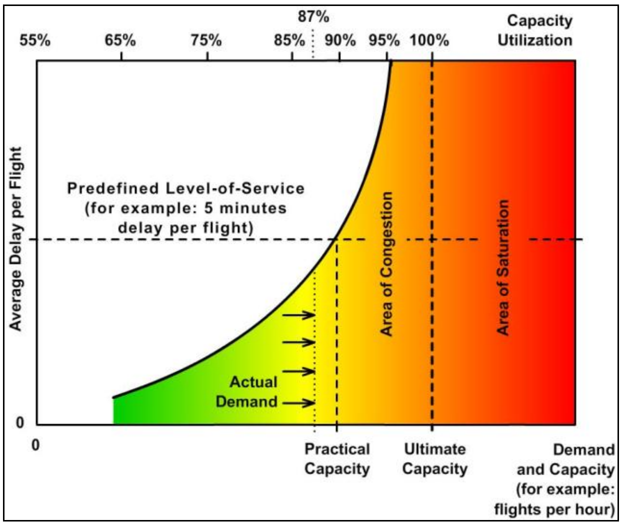

Fig. 2.5: Relationship between demand, capacity and delay

2.2 Computational results

In the context of this contribution, only the main findings from simulation Scenario 0 can be presented in detail. However, these results may safely be regarded as representative of all the other computations. In addition a comparison of different scenario-based capacity developments is shown.

From simulating the baseline Scenario 0 and subsequent runs with decreasing and incrementally increasing traffic, we get the daily and peak hour demand, throughput capacity, capacity utilization, and occurring waiting times (delay), which are the basis for subsequent capacity calculations. When aggregating the data and analyzing the flow of aircraft in the animation displaying the results of the SIMMOD simulation, we observe the creation of *capacity bottlenecks*. When the baseline demand increases above certain capacity levels, considerable *delays* in queueing aircraft emerge (see [23]: p. 2-2 ff.; [14]: p. 4).

At 60% growth to around 1,050 flights on design day, it is evident that throughput is exceeded by demand, and consequently the average delay increases sharply above a LoS of six minutes. This however would imply that, related to a planning horizon of one year, about 383,000 flights have to be operated, which would already exceed the calculation basis of 360,000 flights (see [22]: p. 222).

Estimating the performance indicator *average delay per flight* at a money value of € 42 per minute (see [12]: p. 9 ff.), exponentially rising delay costs are expected with increasing *capacity utilization* and *delays*. Ultimately, bottlenecks and delays lead to *flight cancellations*, due to unavailable replacement flight crews or aircraft, which represent serious disturbances in the daily airline fleet turnarounds. Cancellations are costly for airlines and inconvenient for the passenger. Their frequent occurrence will certainly affect airlines' profitability. Depending on aircraft size the costs may be between € 3,400 and € 75,000 per cancellation (see [12]: p. 9 ff.). The direct relationship between increasing peak levels of demand and resulting delays and costs from congestion is presented in Fig. 2.6. In Fig. 2.7 the development of capacity and demand over the incremental growth rates can be clearly followed.

Growth rate (%)	Flights per day	Design peak hour demand	Design peak hour capacity	Capacity utilization (demand / maximum capacity)	Average delay per flight (minutes)	Daily delay (minutes)	Daily delay costs (thousand €)[1]	Cancellation of flights[2]
-20	511	40	40	48%	1.1	543	22.8	0
0	635	48	48	57%	1.4	887	37.3	0
20	758	55	54	65%	2.3	1,760	73.9	0
40	886	69	71	82%	3.7	3,287	138.1	0
60	1,012	78	76	93%	5.9	5,955	250.1	0
80	1,145	94	80	112%	11.5	13,223	555.4	0
100	1,270	90	82	107%	21.2	26,968	1,132.7	1
120	1,400	96	82	114%	26.8	37,501	1,575.0	134
140	1,517	98	84	117%	27.4	41,538	1,744.6	440
160	1,639	110	83	131%	58.2	95,364	4,005.3	807

[1] Costs per minute of delay: € 42.00 approximated from EUROCONTROL (Standard Inputs for CBA Analysis)
[2] Cancellations resulting from longer than threshhold waiting times and therefore conflicting with flight injections

Fig. 2.6: Computational results from Scenario 0

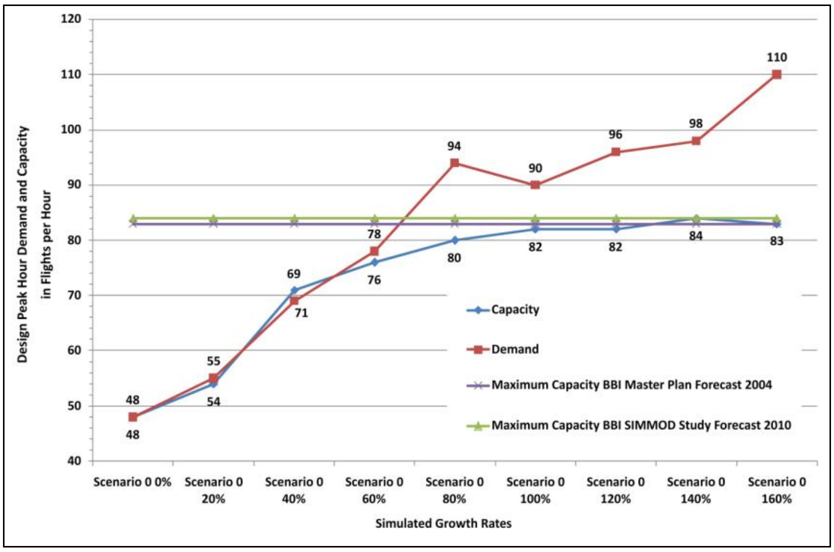

Fig. 2.7: Development of peak hour capacity and demand (Scenario 0)

While performing various simulation runs with incrementally increasing growth rates of daily traffic volume, we observe in the results of the SIMMOD simulation a capacity bottleneck, when demand increases beyond a threshold of around 76 flights in the peak hour and at the growth rate of 60 % (for Scenario 0). As the number of flights waiting to land or take-off continues to increase, peak capacity is clearly exceeded (Fig. 2.7). In reality (and in the simulation processes) this divergence of demand and capacity is solved because of the fact that as arrivals stack up in the holding airspace and departures queue at the runway entries (or remain at the aircraft parking positions during *ground delay programs*) (see [10]: p. 17), the waiting time and length of queues increase.

A runway can only be occupied by one aircraft at a time, which ultimately sets the capacity to the *service time*, consisting of *runway occupancy time* (ROT) and a *safety time buffer*, depending on aircraft weight and type of operation (see section 2.1). For instance the maximum peak hour capacity of 76 flights per hour corresponds to a service time of 1/76 flights per hour, which equals about 47 seconds per flight, whereas the 78 flights during the peak hour request service every 46 seconds. Another measure of congestion is the quotient of demand and capacity, the *capacity utilization*. In the presented example the demand of 78 flights per hour is divided by the practical capacity of 76 flights per hour, resulting in a capacity utilization of 103%. Alternatively the *ultimate capacity* could be taken as the denominator, so in this case the capacity utilization equals 93% (78 divided by 84 flights per hour) (see Fig. 2.6 and Fig 2.7). Therefore peak hour demand cannot be served with current peak hour capacity beyond 60% growth rate.

By defining a LoS (e.g. six minutes of average delay per flight) and by balancing the capacities of the various airport processes (e.g. aircraft and ground handling, air traffic control capabilities and flight restrictions) each airport has a specific operational limit (per hour) - this is the practical capacity (see [18]: p. 17).

This practical capacity can be used as declared capacity and then translated into available *landing rights* for a determined number of scheduled flights per hour at an airport over the course of the day. These are defined as the airport *slots* (see [10]: p. 373; [8]: p. 7; [18]: p. 11 ff.; [29]). The airport slots are coordinated by appointed national slot coordinators in bi-annual *Schedules Conferences* (SC) organized by the *International Air Transport Association* (IATA).

When demand is higher than available hourly slots, airlines typically try to adjust their schedules and aircraft rotations to find desired slots at some earlier or later time of the day. So eventually at congested and slot-coordinated airports demand is capped during peak hours and additional demand could fill the idle capacity periods in off-peak hours. If such shifts are not possible, these *flights-in-demand* will have to be rejected. In Fig. 2.8 this effect is demonstrated clearly by showing the *unconstrained* (theoretical) demand at BBI airport expressed in hourly requested movements and the *constrained* supply expressed in maximum hourly throughput. During the peak hour from 18:00 to 19:00 in Scenario 0 the demand grows continuously from 48 to 110 requested flights per hour compared to the peak capacity of 48 to 84 flights per hour. At growth rates beyond 80% delayed demand is shifted into the night hours after 23:00.

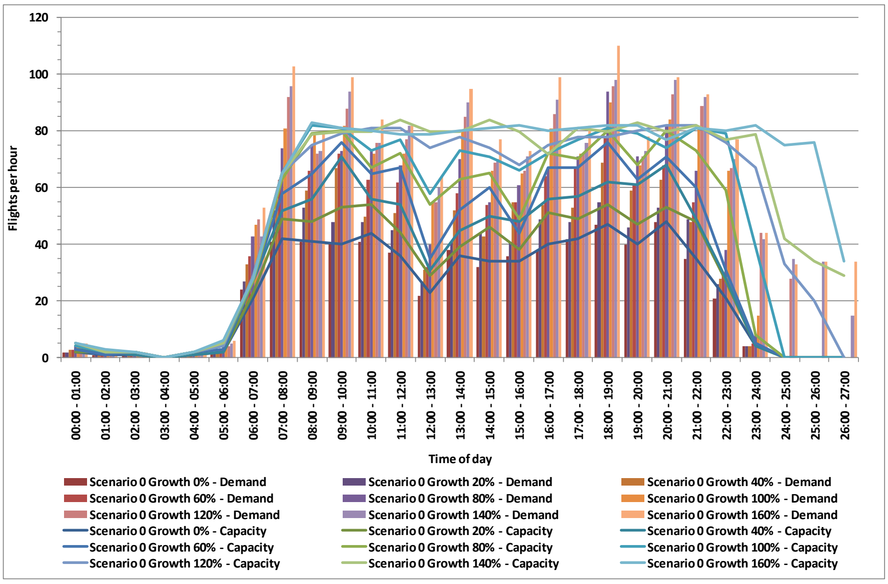

Fig. 2.8: Daily pattern of capacity and demand

A comparison of the results of all analyzed scenarios shows trends strongly growing *exponential functions* for the daily *number of flights* and the computed *delays*, which demonstrate a significant correlation (see [10]: p. 449; [16]: p. 488). For all scenarios, the clearly recognizable sharp increase starts beyond 1,000 daily operations (see Fig. 2.9). With the help of the simulation runs, it is shown that delays mainly occur at three bottlenecks. These are on the one hand (for arrivals) the entry into the airspace *holding stack*, and on the other hand (for departures) the *departures queue* of the runway or else directly at the *gate*. The very close correlation of the functions below 1,000 daily flights proves that the aircraft mixes within the given range used in the scenarios do not have a significant impact on congestion (under current conditions and rules). In Scenario II and IV with an increasing number of category L and H flights (both scenarios have a MI of 125%), in the range of 1,000 to 1,300 daily flights at around 80% growth, clearly higher average delays per flight can be seen than in other scenarios (see Fig. 2.9). Therefore the current aircraft mix at both Berlin airports in Scenario 0, with a very high share of category M aircraft and carrying approximately 100 passengers per flight, is beneficial regarding airport throughput and LoS.

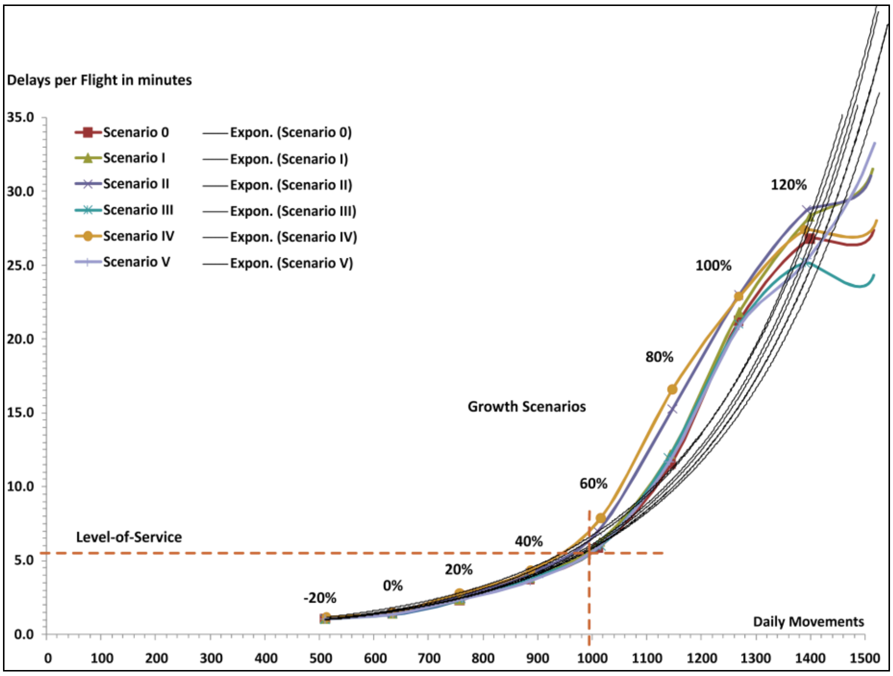

Fig. 2.9: Comparison of delay extends and number of flights

3 Analysis and evaluation

The results for scenario 0 (starting with the demand development of 2010) have shown that a cumulative growth above 60% from the baseline demand results in mid- and long-term capacity shortages (see Fig. 3.1). The time when these bottlenecks occur depends on (assumed) annual growth rates. In our case study we assume a range of average annual growth rates between 3% and 6%. Therefore we expect the practical capacity to be reached as early as 2018, but in any case by 2026 the latest. A growth rate of 6% can be seen as realistic, since the Berlin airports (TXL, SXF, THF) experienced a traffic growth of 36% between 2003 and 2008. This corresponds to an annual increase in traffic of 5.3%, but without accounting for the additional growth effects which will emerge from the future role of BBI airport as an international hub.

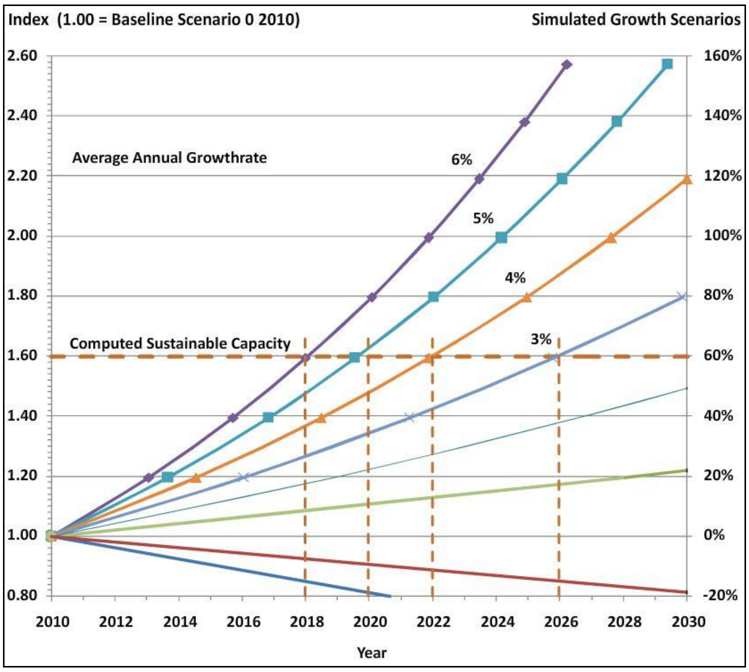

Fig. 3.1: Influences of different (annual) growth rates

With regard to the future development and the market position of the BBI airport, this study reveals serious planning failures by the authorities involved. The possible risk of the occurrence of capacity bottlenecks six to eight years following the opening of the airport raises some questions. An essential aspect of this is the *underestimation* of the *future demand* and *attractiveness* for the *Berlin-Brandenburg region* and its main airport, as it is stated in the official forecasts and master planning documents. The traffic increase at BBI airport can be even more critical, if the airport will be used as a hub for flights to and from Scandinavia and Eastern Europe and / or if airlines (e.g. Emirates airline) or an airline alliance (e.g. oneworld) decide to use BBI as their main German base (see [22]: p. 343 ff.). Should this occur, the number of transfer passengers at BBI airport is going to grow strongly.

Certain similarities can be observed when comparing the developments presented for BBI airport with other already highly utilized European airports also operating a far parallel runway configuration. Particularly the airports LHR and MUC will be used as benchmarks, which will be briefly explained below.

° LHR: Operating an *independent far parallel runway system* in *segregated mode* (due to federal regulations, which provide respite time from aircraft noise and pollution during daytime for the airport community). LHR is able to use both runways in mixed mode only in rare exceptions to ease morning congestion under peak demand (see [4]: p. 16 f.).

In principal at this mode of operation the same *ultimate capacity* can be identified as calculated for the BBI airport. The actual peak throughput of up to 100 flights per hour and 1,550 daily flights can only be achieved at the expense of LoS and congestion delays. Over the year LHR airport operates on average 90 flights (45 departures and 45 arrivals) per hour and approximately 1,300 daily flights, allowing a minimum LoS of 10 minutes delay per flight (see [24]: p. 5 ff.). Operating the airport at such a low LoS, the system is extremely sensitive to operational disturbances (see [10]: p. 448; [25]: p. 7 ff.).

° MUC: Operating as a *staggered independent far parallel runway system* in *mixed mode* (during peak banks of connecting arrivals and departures of airline hub operations)

On average MUC has an hourly throughput of 84 flights (42 arrivals and 42 departures) and approximately 1,100 daily flights. During peaks, MUC operates under mixed mode, where the airport can achieve and schedule 90 flights per hour (e.g. 60 arrivals and 30 departures per hour), under the premise that arrivals and departure are not equally distributed during these hours (see Fig. 3.2).

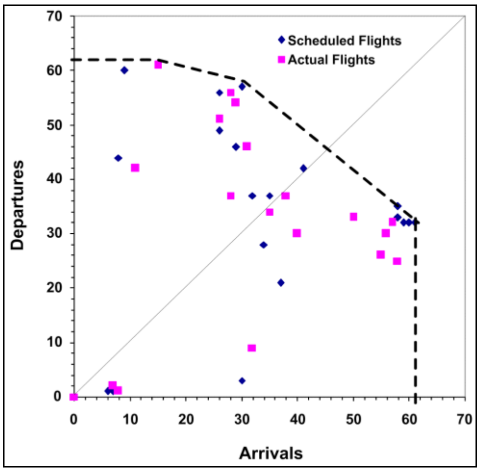

Fig. 3.2: Capacity envelope for peak traffic at MUC in 2008

During higher traffic density it is questionable if a mixed-mode operation of the runways would be sustainable over longer periods of time (see [10]: p. 394 ff.). This mode of operation has a direct impact both on the air traffic control workload and on the required surveillance equipment and overall safety, since departures have to be fitted into incoming arrival streams on the same runway. This reduces *safety buffers* between parallel and succeeding flights in the event of missed approaches, runway incursions or other unintended events (see [25]). The airport system is becoming vulnerable with regard to small changes in capacity or demand, e.g. during changes in weather or by *unscheduled* (e.g. charter or general aviation) *flights*.

Furthermore the coordination and surveillance of air and ground movements by ATC becomes much more complex. On the ground, on the apron and the taxiways aircraft movements in *opposite directions* has to be coordinated by ground control, which leads to greatly increased coordination complexity and staff requirements. But it should be noted that additional terminal facilities, necessary to accommodate the (long-term) desired volume of 30 million passengers at BBI by 2023, will reduce precious apron area and will lead to *substantial taxiing inefficiencies* (see [7]: p. 96).

Compared to a segregated mode, mixed-mode operations of the runways, spreads aircraft noise over a larger part of the countryside, due to the resulting simultaneous take-offs and landings from parallel runways (see [19]: p. 14 ff.). This is one of the main reasons for not allowing mixed-mode operations at LHR, where the government ruled that the community has a right to respite from aircraft noise. At LHR take-off and landing runways are consequently alternated daily at around 15:00 by an openly published scheme.

Segregated mode parallel runway operations at an airport can be seen as second-best choice with regard to capacity, since only one incoming and one outgoing flow is used, compared to mixed-mode operations, where *each* runway has one incoming and outgoing flow, thus four flows in total. With regard to safety, sustainability, and respite from noise the segregated mode, as it is modeled in this study, is arguably the best solution.

The comparison between LHR, MUC and BBI shows that with a similar runway configuration, but under different modes of operation and with different demand patterns the same ultimate capacity can be expected. Although mixed mode operation is viewed as mandatory by planners of BBI for successfully managing the airport (see e.g. [1]), we observe that LHR achieves a higher throughput in segregated mode than MUC in mixed mode. This leads to the conclusion that mixed mode is not a necessity for operating an airport. It must be noted that during peak periods in the morning (between 6:00 and 7:00) mixed-mode operations (parallel approaches with *Tactically Enhanced Arrival Measures* (TEAM) in place) are allowed at LHR to ease congestion, thus the second runway is used for "overflows" capacity from primary runway (see [10]: p. 395). Permanent mixed mode operations at LHR would provide around 15% increase of airside capacity (see [25]: p. 4).

Since the benchmark airports MUC and LHR are already operating at full capacity, expansion plans for both airports have begun. In 2007 MUC started a feasibility study regarding alternative locations for a third runway, which is expected to go into operation in 2020. LHR had similar expansion plans, but these resulted in the plan for a full length third runway north of the existing runway system being scrapped. This discussion implies that generally in the future it will certainly be difficult to expand runway capacity at congested airports in line with growing demand. So delays can be expected to increase in the future, since, while technical developments and further improvements in operational processes can temporarily prevent capacity bottlenecks for a few years, they cannot in principle by themselves solve the capacity problem.

4 Conclusions and outlook

To avoid the risk of capacity bottlenecks and congestion at BBI (especially at the demand peaks), one must ask what threshold values are suggested. The simulation has shown that a LoS below six minutes of average delay, resulting in approximately 1,000 daily movements and 76 flights in the peak hour, must be seen as a practical limitation. At this stage, daily delays already cumulate to about 6,000 minutes and 250,000 € delay costs. Lowering the LoS to ten minutes, as is the case at LHR, around 130 additional daily flights can be operated but with the consequence of more than doubling delay and delay costs.

However it must be remembered that airport expansion projects not only have a technical and operational dimension, but even more so have a *political* and *economic aspect* concerning the proposed expansion location. Therefore this predictable lack of capacity must be included in German national traffic planning and has to be put on the political agenda with high priority within a clearly short-term horizon. Otherwise opportunity costs will rise during periods in which runway capacity is unable to satisfy all demand (see e.g. [27]). These costs refer not only to occurring bottlenecks in air traffic, but in this case also to the considerable negative impact on economic and political development. More specifically long-term unconstrained growth of BBI is important for a prosperous development of the Berlin-Brandenburg region with the capital of the Federal Republic of Germany at its center.

When looking at the time-consuming and long-term procedures involved in planning and realizing large transportation infrastructure projects (and not only in the Federal Republic of Germany), the discussion for a demand-oriented and timely expansion of BBI beyond the current runway layout should already have been started. This is necessary to guarantee reliable and efficient processes in airside and terminal operations for the airport users and also to provide an attractive service in air transport now and in the future.

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