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POTENTIAL OF RUNWAY CAPACITY ENHANCEMENTS WITHOUT BUILDING A NEW RUNWAY

Stefan Kern

German Aerospace Center
Institute of Flight Guidance
Department of Air Transportation
Lilienthalplatz 7
38108 Braunschweig
GERMANY

ABSTRACT

Runway expansion planning is mainly based on specific airport studies, complicating the transfer of results to another airport. Thus a normalized airport is introduced, including a set of technologies/procedures, to investigate possibilities to gain runway capacity. The advantage of this approach is the comparability of different enhancements and understanding their effectiveness under different situations. So before establishing a new runway the current runway structure can be used more efficiently, leading to optimal solutions for individual constraints. This is shown for a set of operational enhancements like runway usage strategy or sequencing, studied under different traffic mixes as well as arrival-departure ratios. Hereby the main focus of this paper is set to dependent parallel runway configurations.

1 INTRODUCTION

The goal of reducing flight delay in combination with simultaneous increase in demand requires the current ATM (Air Traffic Management) system and infrastructure to keep pace with the latest technologies. For 2030 an increase of Europe's air traffic from 10 to 16.9 million flights is predicted, whereas without reacting EUROCONTROL sees a capacity constraint at 21 European airports in 2035, leading to 1.2 million unaccomplished flights and a delay increase from 1-2 minutes up to 5-6 minutes per flight. Due to individual airport characteristics, some airports will even reach more than 20 minutes ATFCM (air traffic flow and capacity management) delay per flight as shown in Figure 1 (EUROCONTROL 2013; European Comission 2014).

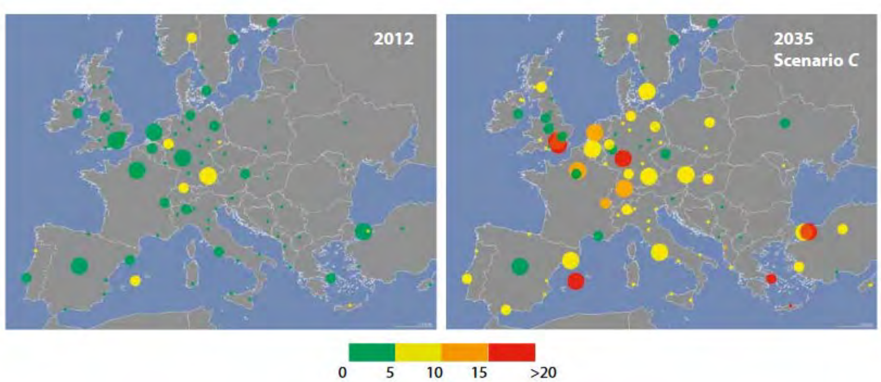

Figure 1: Summer Delay per Airport (EUROCONTROL 2013).

Additionally, airports face a more and more difficult environment to expand their capacity, especially in the case of building new runways. Declining acceptance, noise restrictions, long planning phases or a lack of land resources are just some points to name. So how can airports react to increasing demand or restrictions to offer enough capacity? What improvement steps are possible before establishing a new runway and how much demand increase can be accomplished?

Looking at different research e.g. done by SESAR, FAA (NextGen) or ICAO, there is a considerable amount of enhancements available to gain capacity, may it be new procedures, infrastructure change (e.g. Rapid Exit Taxiways) or system technologies. However, due to the current approach of individual case studies it is very difficult to adopt these particular results to another airport, leading to a lack of information how these enhancements alone or in combination with others influence runway capacity on all or a group/class of airports and how sensitive they react on infrastructural changes. Taking this one step further there is a need for a strategic expansion planning for the (European) air traffic network.

The following chapter will first of all focus on the status quo regarding runway capacity (mainly methods) and capacity enhancements showing the options for runway capacity expansion. Afterwards the method and its application in different scenarios will be described, ending in discussing results.

1.1 Status Quo

Quite a lot of literature concerning airport capacity in particular runway capacity has been published, including many case studies for different individual airports and runway configurations. But until now no standardized approach in form of a benchmark or capacity roadmap for airport classes/groups exists. Basic research on influences of aircraft mix and runway configuration was done by the FAA (FAA 1983) in form of a handbook, but over years things change regarding aircraft developments, regulation changes or further developments of capacity enhancements.

In general these methods/models are dividable in empirical, analytical and simulation-based approaches. Depending on the level of detail needed, macroscopic up to microscopic studies are possible, whereat the results have to be adequate as well as time and cost-efficient, offering a sufficient decision support (ACRP 2012).

Runway capacity is influenced by many different parameters, as shown in (Kern and Schultz 2016). Each of the capacity enhancements picks up one or more of these parameters to potentially gain capacity. To evaluate its capacity increase, a suitable model has to be used. Analytical models have a simple setup with many generalizations, used for macroscopic analyses. Due to the simplified approach not all influencing parameters are included leading to a lack of possibility to evaluate capacity enhancements. In contrast simulation models (e.g. AirTOp or Simmod), which may differ concerning their main purpose, offer a more detailed modeling approach. However, these models come along with a time-consuming setup of scenarios mainly focusing on one special case or individual airport. Also these models are not fully appropriate for a holistic picture to understand capacity enhancements with its effects and sensitivities. (ACRP 2012)

Regarding the assessment of capacity enhancements or strategic capacity expansion planning, models from Stamatopoulos (Stamatopoulos, Zografos, and Odoni 2002) or Miller and Clarke (Miller and Clarke 2003) are to name. However these models mainly focus on capacity gain due to runway infrastructure changes, neglecting procedural enhancements. Pinon, Mavris and Garcia (Pinon, Garcia, and Mavris 2010; Mavris and Garcia 2003) extend the scope of capacity influencing factors in their work, so do (Mavris and Kirby 1999; Mavris and Garcia 2000) also look at aircraft performance changes. Nevertheless the holistic approach is missing with many models covering only parts of influencing factors and enhancements, less looking at interdependencies or sensitivities.

In consequence, CORE (**C**omputing **R**unway capacity **E**nhancements) has been developed here. It is based on a modular and generic approach, including all capacity influencing factors of current enhancements, with the goal to understand their behavior. Further detail is given in chapter 2 and (Kern 2017).

1.2 Runway Capacity Enhancements

Beside the review on capacity models and assessment methods, capacity enhancements itself shall be discussed. In this paper these are infrastructural, procedural or technological improvements gaining runway capacity. Here, it is measured in terms of theoretical capacity as aircraft movements per defined time period without taking delay into account (Horonjeff, et al. 2010). However, limited to the area of application between final approach fix (FAF), exiting and entering the runway as well as the take off procedure.

Summarizing the outcome of various research programs like SESAR, FAA NextGen or ICAO Aviation System Block Upgrade, Figure 2 gives an overview on possibilities to increase runway capacity (FAA 2015; ICAO 2013; EUROCONTROL 2015) before establishing a new runway. For better understanding these have been grouped, including enhancements triggered by the demand, trying to improve aircraft separation minima or to introduce a more individual aircraft separation (RECAT). Moreover homogenization of aircraft performance or sequencing methods can be applied. Approach and departure enhancements are mainly driven by navigational accuracy as well as the use of certain procedures, like CREDOS, which may reduce the separation minima due to crosswind.

Based on the current runway system and its characteristics, rapid exit taxiways can help to reduce the runway occupancy time. Furthermore runway usage strategy may avoid large separation minima due to optimized runway allocation. Time-based separation compared to the international standard of distance based separation has an advantage in strong headwind conditions resulting in higher runway throughput. (Morris, Peters, and Choroba 2013)

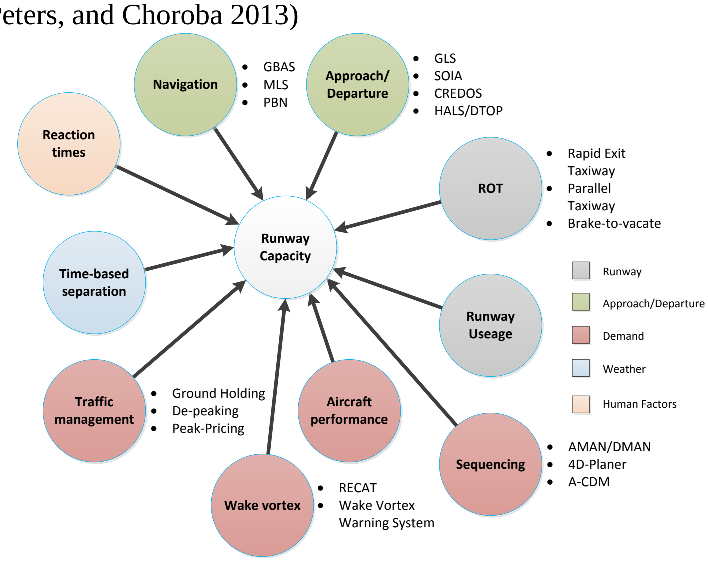

Figure 2: Overview on capacity enhancements.

Besides the technologies/procedures shown in Figure 2 it is important to study capacity changes under different arrival/departure ratios and traffic mixes.

2 METHODOLOGY

2.1 Model Description

The following approach has been developed to determine reliable results for the assessment of capacity enhancements. In this context it is based on runway capacity influencing factors, which are changed by the current enhancement under investigation. Furthermore each enhancement is addressed separately from others, leading to a modular approach. In this way individual effects or interactions with other enhancements are possible, to understand the underlying effectiveness. Also as a result the effort to implement and study new developments is reduced.

CORE consists of several components (more detailed described in (Kern 2017)), able to study airports with a maximum of two runways by using the international standards and regulations (ICAO 2007). Complex airports may then be described by sets of these runway configurations, due to the fact that in most cases and during certain operating hours not all runways are used at the same time.

Starting with the input module (see Figure 3) the type of runway system, active enhancements and the traffic mix can be specified. This information is transferred to the aircraft combination module, representing an artificial flight plan, which consists of the defined traffic mix and arrival/departure ratio. The separation between two aircraft is then calculated by the separation module. Each separation is influenced by the setup of active enhancements, the runway system (e.g. dependencies), aircraft performance and the mode of operation (arrival/departure combination). Additional parameters like touchdown distances or reaction times are determined stochastically. So for each aircraft combination in the "flight plan" a separation value is calculated repeatedly for several replications. The results of the separation module are used to determine runway capacities based on throughputs, which are then summarized in a Pareto curve and tabular form.

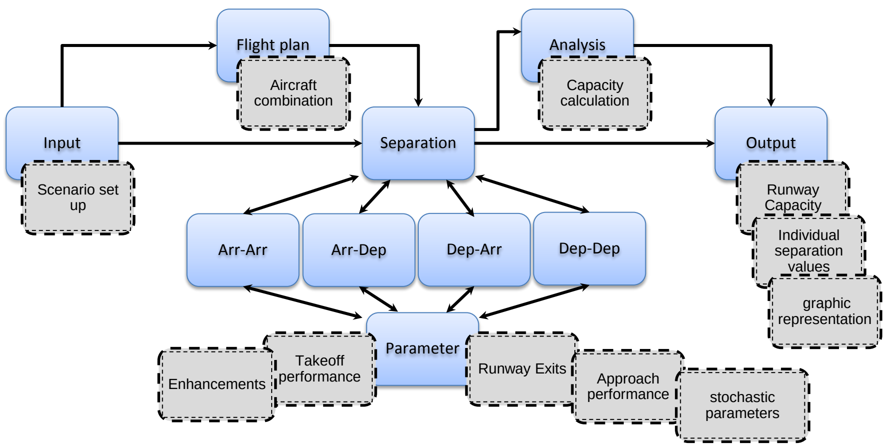

Figure 3: Structure of the Runway capacity model CORE.

2.2 Normalized airport

For assessing and comparing runway capacity enhancements airport/traffic scenarios are required. These scenarios should consider a consistent baseline as well as a normalized set of technologies/procedures to be used as a reliable baseline or respectively a benchmark for individual airport scenarios. Moreover, the idea of normalization addresses the challenge to enable a consistent comparison of runway capacity gain.

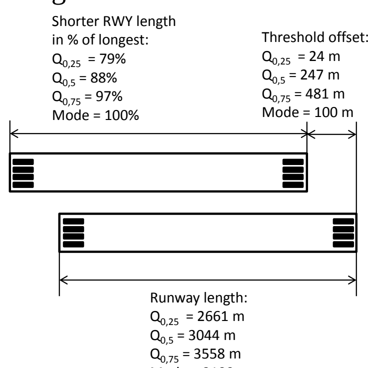

Figure 4: Parameter variation for dependent parallel runways.

In this context, the efficiency of a runway system is measured in terms of realized movements in a capacity constrained timeframe in regard to the maximum number of movements resulting from the normalized environment.

To derive a normalized airport for different runway configurations the approach of (Kern and Schultz 2016) has been used, leading to the following results for dependent parallel runways shown in Figure 4. In this case the mode values (both runway lengths 3100 m, runway offset 100 m) are used for evaluation in this paper. Furthermore the analysis on Flightstats data (FlightStats 2013) provides Traffic Mixes for the model.

3 SCENARIO DESCRIPTION

As a starting point for scenario definition, an analysis of schedule flight data for the year 2013 (using (FlightStats 2013)) at busy airports with dependent parallel runways like Shanghai (SHA), Berlin (TXL), Moscow (SVO), or Dubai (DXB) was done. However, Dubai can be operated in an independent segregated mode due to its runway offset. While neglecting night hours (23 p.m.-05 a.m.) the 95% Pareto curve (enclosing 95% of observed data) was calculated by using the approach of (Gilbo 1993) (see Figure 5).

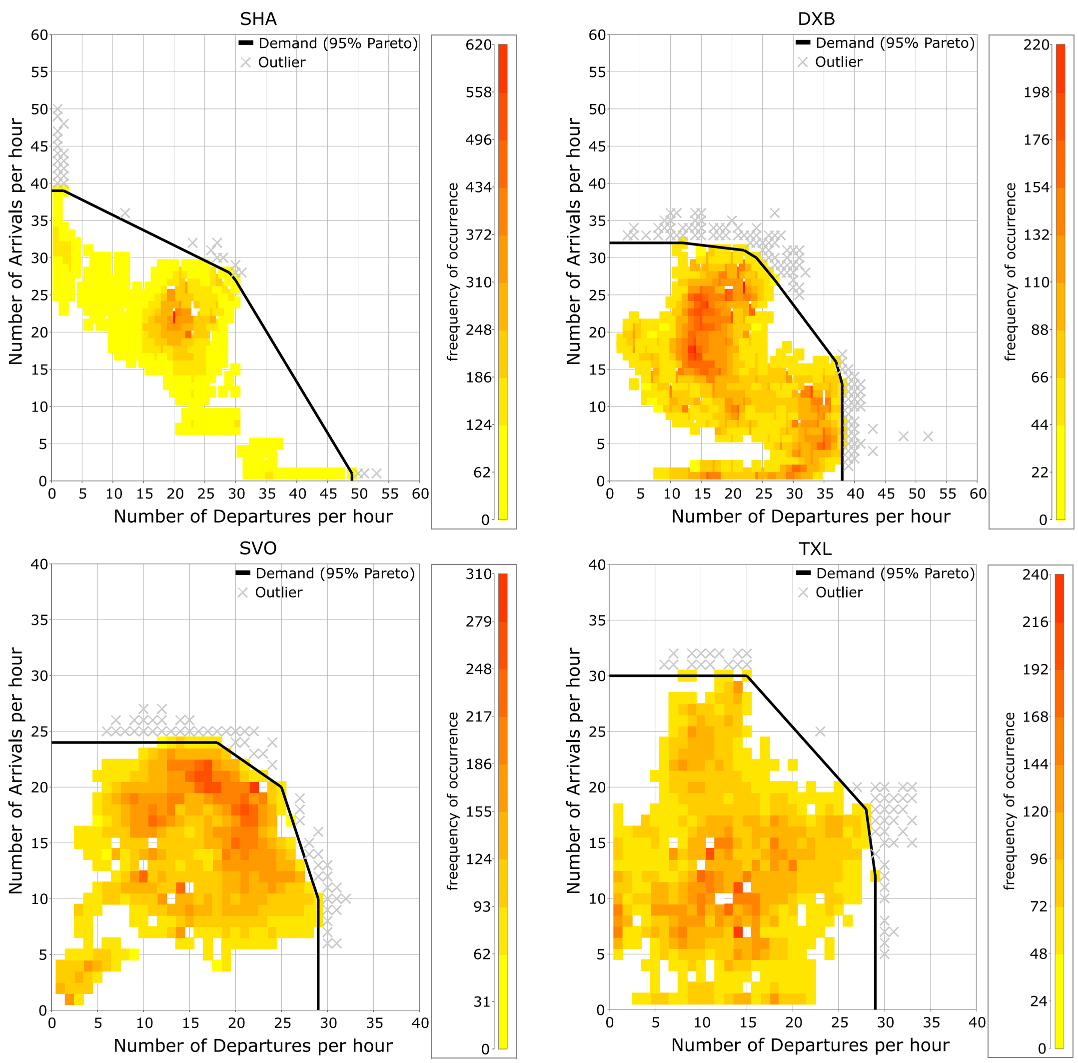

Figure 5: Pareto demand for selected airports with dependent parallel runways.

These demands are used as an indicator to assess if a certain expansion stage is able to accommodate the shown demand. For now, only operational enhancements and the implementation of rapid exit taxiways are studied in this paper. Each enhancement will be compared with a baseline scenario and against each other, whereat each of them is built on one another. The setup of the baseline will be described before discussing the application of each enhancement.

In general each scenario will be run in 500 replications to simulate one arrival/departure ratio of each aircraft mix. The sequence of events in the flight plan (containing 300 flights) is randomized as well as stochastic parameters depending on their distributions (see (Kern 2017)).

3.1 Baseline Scenario

Normalized airport analysis, described in chapter 2.2, shows only traffic mixes with Heavy and Medium Aircraft but no Super Heavy or Light Aircraft. Heavy and Medium Aircraft are changed in 20% increments beginning with 100% down to 40% Medium.

All safety and separation regulations are based on ICAO PANS ATM (ICAO 2007) and SOIR (ICAO 2004) under IMC CAT I conditions, leading to a minimum radar separation of 3NM used in all scenarios. Additionally the ICAO allows only one aircraft at a time on the runway. Based on the assumption that there are no weather limitations, for departure procedures this requirement is weakened by applying a reduced separation (preceding aircraft has reached at least 2400 m and/or is airborne, described under PANS ATM 7.11.7) in consideration of minimum separation for same and different departure routes as well as wake turbulence separation. The probability for using the same departure route is set to 50%.

For departure before arrival operations a blocking distance of 3NM plus safety buffer (Gaussian distributed with a standard deviation of 0.25NM and a 5% probability of underrun). The final approach length is 10NM and aircraft are expected to fly speed profiles based on BADA 3.9 (EUROCONTROL 2011). The inter-arrival Error has a standard deviation of 15 sec and a probability of underrun of 5% (Gaussian distributed) (Weiss and Barrer 1984). Additional in the Baseline Scenario only 90 degree runway exits occur.

3.2 Rapid Exit Taxiways

By establishing rapid exit taxiways not only the exit speed increases, also the distance to leave the runway safety zone (lateral extend of 75m from runway centerline for CAT I operation seems adequate based on (ICAO 2006; DFS, DSNA, NATS, and LVNL 2010)) increases. Based on the ICAO recommendations (ICAO 2005) the following speed and determined distance for a radius of 550 m will be used. There is no change of the position of the runway exits, only the radius is changed from 40 to 550 m.

Table 1: Runway Exit characteristics depending on its radius.

Radius R [m]	Exit Speed [kt]	Distance [m]
40	14	98
160	28	162
550	52	290

3.3 Segregated operation

As runway usage strategy, segregated operations separate arrivals and departure to different runways. However, CORE is setup in a way that departures in segregated mode are using the longest runway. The opportunity for independent segregated operation based on ICAO PANS-ATM 6.7.3.5 and ICAO SOIR 4.2 is excluded here, due to the fact that a minimum runway offset of 150 m is required and the runway spacing is assumed to be below 760m. (ICAO 2007; ICAO 2004)

3.4 Sequencing

Aircraft combinations occur on a random base. For the arrival stream of a runway, sequencing methods can be used to optimize the aircraft order based on their wake vortex separation. For optimization, the simulated annealing approach is used (Kirkpatrick, Gelat, and Vecchi 1983), building an arrival stream containing a maximum of 5 aircraft. Here, at the most 3 departures interrupting the arrival stream are allowed, otherwise the stream contains less than 5 aircraft. Furthermore to prevent aircraft to be delayed too far, each aircraft is included only once for optimization. This means that aircraft 1 to 5 in a 10 aircraft arrival stream will be optimized separately from aircraft 6 to 10.

3.5 Radar Separation

To increase the runway throughput, there is also the possibility to reduce the minimum radar separation (MRS) between two aircraft. In this case ICAO recommends specific requirements to be fulfilled before the separation minima may be reduced. This includes an average runway occupancy time of 50 seconds or below (ICAO 2007). During simulations the runway occupancy time of the preceding aircraft (on the same runway) is compared to the actual aircraft separation. In case the trailing aircraft overflies the runway threshold while the preceding aircraft is still on the runway, a go-around is performed. This action is not counted for capacity.

3.6 Departure Routing

The separation between two departures is driven by the separation minima based on route dependencies as well as wake turbulence separation. As described in ICAO PANS ATM 5.6 the minimum separation using the same departure route is at least 2 minutes, extended by wake turbulence separation if applicable. In case departure routes diverge by at least 45 degrees minimum separation can be reduced to 1 minute. (ICAO 2007)
Based on this fact the capacity gain resulting from a decreasing probability for using the same departure route is investigated. Starting with a 50% probability in the baseline scenario and 25% as well as 10% in further scenarios.

4 RESULTS

The assessment on enhancements impact is based on average saturation throughput values as well as maximum saturation throughput. The average saturation throughput uses the maximum throughput value from each Replication (one throughput per Replication) and determines the average. Again for understanding, each scenario will be run in 500 replications to simulate one arrival/departure ratio of each aircraft mix.
The maximum saturation throughput defines the overall maximum throughput taking into account all replications of on arrival/departure ratio. However runway capacity results from throughput as defined in (FAA 1983). In both cases simulations have been conducted for different traffic mixes as they occur in reality.

4.1 Average saturation throughput

As described in the previous chapters, each enhancement influences runway capacity in a different manner, reducing runway occupancy time, changing runway usage, optimizing arrival sequence or adjusting separation minima. Looking at Figure 6 the highest values and biggest capacity gains can be achieved with homogeneous traffic (100% Medium aircraft). As the share of heavy aircraft increases the runway capacity decreases. This mainly results from higher separation minima, necessary due to wake vortex. However, the capacity gain by implementing all enhancements results in 5 movements at most for pure arrivals streams, 9 movements for mixed operations and 10 movements for pure departure streams.

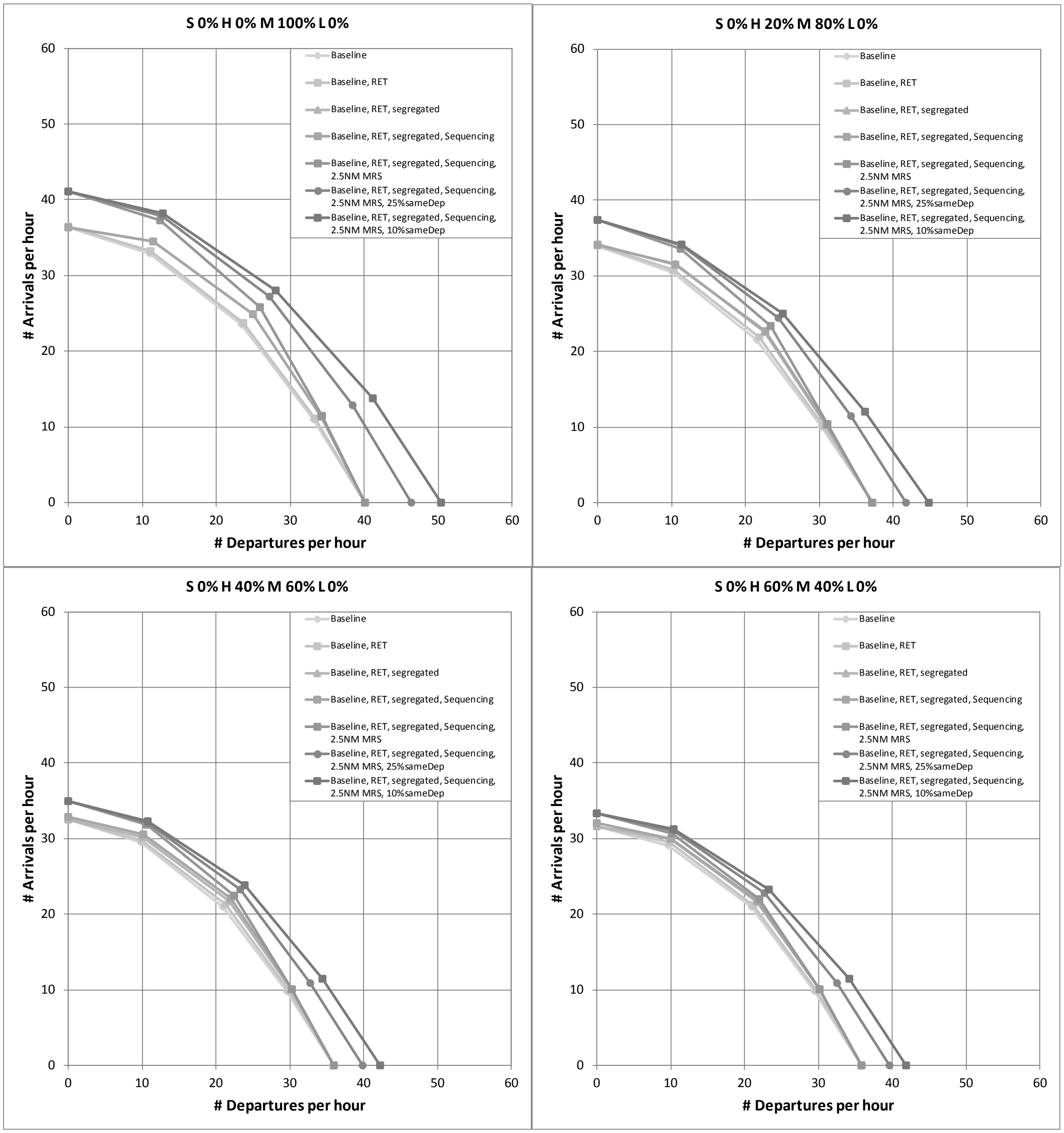

Figure 6: Runway capacity results using different enhancements.

Looking more detailed at the capacity gains of each enhancement it can be seen that the benefit of rapid exit taxiways in relation to others is marginal (Table 2). However, it is evident, that its main influence occurs in the mixture of arrivals and departures. Capacity gain is relatively small due to the minor occurrence (about 12%) of arrival-departure separation on same runways.

Furthermore, the effectivity of segregated runway usage can be increased if the runways are used in sequence, which also may be subject for further studies. Thereby the advantage of segregated mode is the reduced arrival-departure separation on different runways, while the departure does not have to wait until the arrival has left the runway before starting its takeoff run.

Table 2: Capacity change for S0% H0% M100% L0% traffic mix.

Enhancement	0% Arrivals	25% Arrivals	50% Arrivals	75% Arrivals	100% Arrivals
Baseline	40.1	44.1	46.9	43.8	36.4
RET	0 (0%)	0.3 (1%)	0.5 (1%)	0.5 (1%)	0.1 (0%)
Segregated	0 (0%)	1.1 (2%)	2.4 (5%)	1.7 (4%)	-0.1 (0%)
Sequencing	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
2.5NM	0 (0%)	0.2 (0%)	1.9 (4%)	3.7 (8%)	4.7 (13%)
25%sameDep	6.3 (16%)	5.5 (12%)	2.7 (5%)	0.8 (2%)	0 (0%)
10%sameDep	4 (9%)	3.7 (7%)	1.7 (3%)	0.5 (1%)	0 (0%)

Sequencing and reducing minimum radar separation (MRS) are useful for arrival streams. As their biggest capacity gain occurs during 100% arrival ratios. However their effectiveness is contrary with increasing heavy share, capacity gain decreases for reducing MRS to 2.5NM. The reason for this can be found in the application of MRS only for non-wake vortex critical aircraft pairs. With heavy aircraft included, wake turbulence separation occurs, so the frequency of MRS use decreases.

Sequencing on the other hand shows no capacity gain at 100% medium aircraft, but for traffic mix including heavy aircraft (Table 2 to Table 5). Particular for aircraft mixes containing different separation minima sequencing is able to optimize the arrival sequence. Up to 40% heavy aircraft sequencing is more or less described by fluctuations of the traffic mix inside the flight plan. However, with 40 and 60% heavy share the general impact of sequencing arises. Furthermore, a simplified approach has been used, which may have influence on the extent of the capacity gain, but showing the basic effects of sequencing.

Table 3: Capacity change for S0% H20% M80% L0% traffic mix.

Enhancement	0% Arrivals	25% Arrivals	50% Arrivals	75% Arrivals	100% Arrivals
Baseline	37.2	40.3	43.1	40.6	33.9
RET	0 (0%)	0.3 (1%)	0.6 (1%)	0.4 (1%)	0.1 (0%)
Segregated	-0.1 (0%)	0.6 (1%)	1.4 (3%)	1.1 (3%)	0 (0%)
Sequencing	0 (0%)	0.1 (0%)	0.3 (1%)	-0.1 (0%)	0.1 (0%)
2.5NM	0 (0%)	0.2 (0%)	1.4 (3%)	2.7 (6%)	3.3 (10%)
25%sameDep	4.6 (12%)	4.2 (10%)	2.1 (4%)	0.6 (1%)	0 (0%)
10%sameDep	3.1 (7%)	2.5 (5%)	1.2 (2%)	0.3 (1%)	0 (0%)

Table 4: Capacity change for S0% H40% M60% L0% traffic mix.

Enhancement	0% Arrivals	25% Arrivals	50% Arrivals	75% Arrivals	100% Arrivals
Baseline	36	39.4	41.9	39.3	32.5
RET	0 (0%)	0.4 (1%)	0.6 (1%)	0.4 (1%)	0 (0%)
Segregated	0 (0%)	0.4 (1%)	1.1 (3%)	0.6 (2%)	0 (0%)
Sequencing	0 (0%)	0.1 (0%)	0.5 (1%)	0.4 (1%)	0.4 (1%)
2.5NM	0 (0%)	0.1 (0%)	0.9 (2%)	1.7 (4%)	2.1 (6%)
25%sameDep	3.8 (11%)	3.2 (8%)	1.6 (4%)	0.4 (1%)	0 (0%)
10%sameDep	2.4 (6%)	2.3 (5%)	1.1 (2%)	0.3 (1%)	0 (0%)

Table 5: Capacity change for S0% H60% M40% L0% traffic mix.

Enhancement	0% Arrivals	25% Arrivals	50% Arrivals	75% Arrivals	100% Arrivals
Baseline	35.8	39.2	41.8	38.8	31.6
RET	0 (0%)	0.4 (1%)	0.5 (1%)	0.5 (1%)	0 (0%)
Segregated	0 (0%)	0.6 (2%)	1 (2%)	0.6 (2%)	0 (0%)
Sequencing	0 (0%)	0 (0%)	0.2 (0%)	0.1 (0%)	0.5 (2%)
2.5NM	0 (0%)	0 (0%)	0.5 (1%)	0.9 (2%)	1.2 (4%)
25%sameDep	3.8 (11%)	3.2 (8%)	1.5 (3%)	0.5 (1%)	0 (0%)
10%sameDep	2.3 (6%)	2.2 (5%)	1.1 (2%)	0.2 (0%)	0 (0%)

An additional finding of the simulation shows an increase of Go-Around procedures during 2.5NM MRS operations. In 1 to 2 % of cases the preceding aircraft has not cleared the runway, while the trailing aircraft overflies the threshold. In Comparison, the baseline scenario shows a portion of Go-Arounds, which is less than 0.5%.

After mainly discussing arrival enhancements, departure capacity can be gained by changing the departure route distribution, which in reality may be limited. However, this shows a quite impressive effectiveness on capacity. By reducing the probability of same routing to 25%, capacity can be increased by up to 6 movements, whereat the gain decreases with increasing heavy share due to necessary wake turbulence separations. A further reduction to 10% probability can additionally bring another 4 movements.

4.2 Maximum saturation throughput

Besides capacity gain per enhancement itself, also the maximum saturation throughput per enhancement shall be discussed. Compared to the average values the overall maximum exceeds previous values e.g. for 100% Medium aircraft and pure departure or arrival streams by another 3 to 4 movements, for mixed operation even by up to 6 movements (see Figure 7).

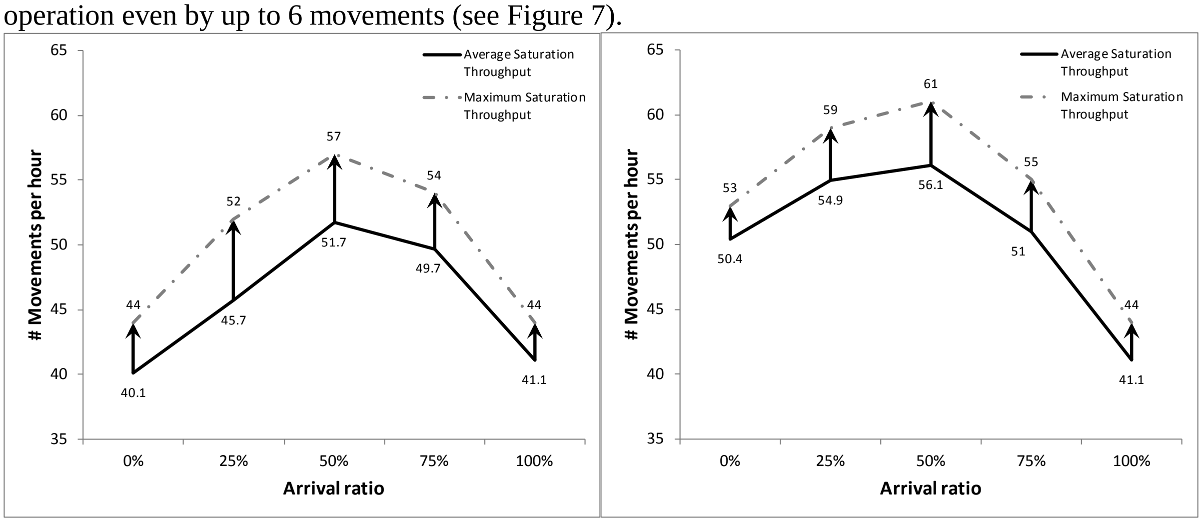

Figure 7: Saturation throughput for 2.5NM (left) and 10%sameDep (right) with 100% Medium aircraft.

5 DISCUSSION AND CONCLUSIONS

Before establishing a new runway several options and enhancements are available. This paper helps to identify their effectiveness using a normalized airport model leading to a potential capacity enhancement roadmap. With a first approach by using operational enhancements like segregated runway usage, sequencing methods or reducing separation minima, airports like Dubai (DUB), Shanghai (SHA), Moscow (SVO) or Berlin (TXL) can handle their traffic demand (95% Pareto) with heavy ratios up to 20% (maximum saturation throughput) in general. For all airports, the capacity gain from all enhancements exceeds the demand occurring at these airports, as shown exemplary in Figure 8. In particular for Dubai a traffic mix of 10% Super Heavy, 60% Heavy and 30% Medium and for Shanghai 20% Heavy and 80% Medium has been used for comparison, as they are representative for peak periods at these airports. Berlin and Moscow are not shown here again due to less critical demand and traffic mixes, containing no Super Heavy and only up to 20% Heavy Aircraft.

As earlier mentioned, Dubai has a high runway offset, which allows an independent segregated mode operation. For comparison of Demand and saturation throughput (Figure 8), this characteristic has been used in the simulations to determine throughput values for Dubai.

There are still some outliers exceeding maximum saturation throughput, which require additional enhancements e.g. introducing RECAT-I, VMC separation or specific alternately Arrival-Departure sequencing. However, the main focus of the work is to identify the effects of the different enhancements

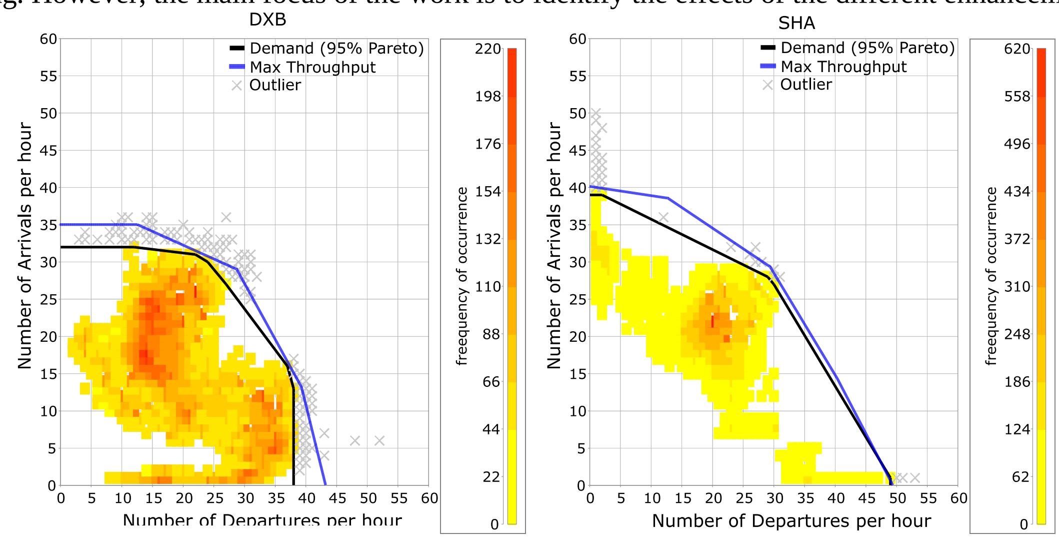

Figure 8: Demand versus saturation throughput.

For all airports both arrival and departure enhancements are needed due to their traffic mainly characterized by mixed mode operations. Thus, for Shanghai (SHA) the traffic is dividable, which makes an application of pure arrival or departure enhancements possible.

The described approach as well as the scenarios show the ability of enhancements to gain capacity in particular for constraints in runway capacity, while covering only parts of the expansion options. Additionally, CORE uses individual aircraft performances for approach procedures (speed profiles (EUROCONTROL 2011)), which besides the minima and safety buffer mainly influence the separation between two aircraft. However, a homogenization of approach speed is neglected, so aircraft performance is randomly (equal distribution) picked from the aircraft database included. This may reduce capacity values overall.

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AUTHOR BIOGRAPHIES

Stefan Kern completed his Master degree in aerospace engineering at the Technical University of Berlin. Since 2013 he is working at DLR at the Institute of Flight Guidance focusing on the field of fast-time simulations as well as development and assessment of new Air Traffic concepts. stefan.kern@dlr.de