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The Impact of Multiple Runway Aiming Points on Runway Capacity

Technical Capacity of a Single Runway

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***Abstract*—Environmental aspects of air transport are constraining factors for the present and future air transportation system. On the local scale, especially aircraft noise impacts the potential of traffic growth negatively. In order to reduce noise impact of aircraft operations around airports there are several technological and operational approaches. A promising measure to reduce aircraft noise is the adaption of approach procedures. A variety of concepts exist that aim at the adaption of the final approach trajectory, including the concept of multiple runway aiming points in which landing trajectories are optimized with respect to individual aircraft states and environmental conditions. By shifting the individual approach path, the noise carpet generated by the aircraft is shifted as close as possible to the airport′s center. In this paper, an approach to assess the impact of multiple runway aiming points resulting from optimized aircraft landing trajectories on the technical capacity of a runway system is investigated. Therefore equations that allow for the calculation of separation times between the possible aircraft pairings as well as a simulation environment to determine technical hourly capacity of a single-runway system are introduced. For the presentation of the results, different scenarios to assess the impact of the concept of multiple runway aiming points on arrival capacity and on the capacity curve of a single-runway system are investigated.**

Keywords*—*air traffic management, multiple runway aiming points, adaptive runway aiming point, runway capacity, capacity envelope, separation, ground based landing system

I. Introduction

Air Traffic is expected to grow with a rate of ca. 5% per year until the year 2030 ([1]). There are certain challenges that will be confronted due to this growth in air transport ([3]). Climate change impacts the environment on a global scale whereas air quality and community noise are affected on a local scale. Because of its impact on human health ([2]) community noise often is a constraining factor for airport expansion and thus for air traffic growth in general.

A variety of measures to reduce aircraft noise at its source (technological measures) or by abatement procedures (operational measures) are conceivable. An approach to classify a variety of possible operational measures to reduce noise impact during final approach is given in Fig.1. The first group, denoted as ’Glide Path concepts’ aim at an increase of the glide path angle. Therefore the touchdown point is not adapted in these cases. In contrast to these approaches, the ’Aiming Point concepts’ aim at shifting the touchdown point further away from the physical threshold. As a result of both measures, the aircraft approaches the runway at higher altitudes and thereby noise impact can be reduced. ’Curved concepts’, enabled by satellite-based landing systems (e.g. Ground Based Landing Systems (GLS)), can be interpreted as revolutionary concepts compared to the aforementioned ones. Nevertheless, they have the potential to minimize aircraft noise significantly (see e.g. [4, 5]).

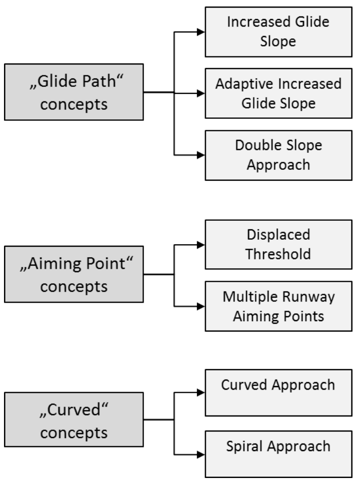

Fig. 1. Classification of different operational measures that potentially reduce noise impact during final approach.

In this paper we focus on ’Aiming Point concepts’. The approach of a ’Displaced Threshold’ has already been investigated extensively in several projects. As an example the HALS/DTOP (High Approach Landing System/Dual Threshold Operation) project was conducted at Frankfurt Airport between 1994 and 2004 [6, 7]. The main objective was to increase arrival capacity by shifting the threshold of one of the parallel runways by 1500m. A similar approach is currently investigated at Zurich airport with satellite-based landing procedures. In both cases the airport can expect benefits with respect to its noise impact (see Fig.2).

In contrast to the DTOP-approach, where the threshold is displaced by a specific distance (e.g. 1500m) the concept of ’Multiple Runway Aiming Points’ (MRAP) is based on landing trajectories which can be optimized for current aircraft states and conditions (e.g. aircraft type, aircraft weight, weather conditions). On the basis of flight-specific input parameters, a trajectory is calculated that aims at shifting the touchdown point as far as possible to the selected runway exit. Thus, environmental benefit with respect to noise can be maximized. Because of individually assigned approach paths, the touchdown point and the corresponding threshold change dynamically. In this study, we investigate the extent to which runway capacity is impacted due to such a concept. We focus on the capacity of a single runway in the first instance.

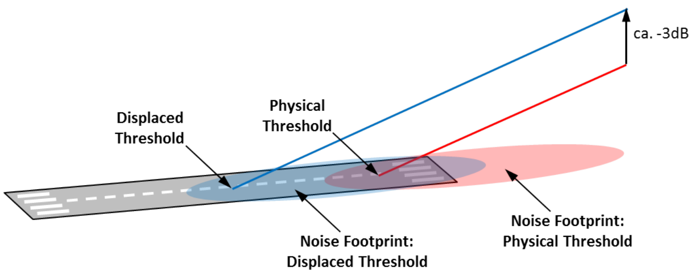

Fig. 2. Schematic diagram showing the effect of a displaced threshold on the noise footprint (adopted from [7]).

In chapter 2 the approach taken to determine separation times that ensure the necessary separation between arriving and departing aircraft is introduced. In chapter 3 a model chain is described that enables the calculation of hourly technical capacity of a single-runway system. Exemplary results are presented in chapter 4. The paper concludes with a summary of the results and gives an outlook for future enhancements of the model as well as the inclusion of more aspects for a holistic assessment of the technology in the airport and air transportation system.

II. Calculation of Separation Times

As stated in the introduction the MRAP concept assigns an optimal landing trajectory for an arriving aircraft. We define threshold as a point within the approach trajectory of an aircraft where it crosses a specific height, e.g. 50ft. Therefore the threshold differs for every MRAP-capable aircraft. To meet the safety requirements, following rules apply:

- 1^{st} rule: Wake Vortex Separations (WVS) have to be kept and a are based on the threshold of the leading aircraft
- 2^{nd} rule: Only one aircraft must be on the runway at a time

Based on this, a decision tree is developed which captures every possible combination of two arriving aircraft, independent of whether it is a conventional aircraft or MRAP-capable. The parameter $\Delta d_{offset}([m])$ represents the difference between the offset of the leading to the trailing aircraft. For a pairing of two conventional aircraft Δd_{offset} is '0', accordingly. The case $\Delta d_{offset} > 0m$ constitutes the situation where the threshold of the leading aircraft is further than the threshold of the trailing aircraft with respect to the physical threshold. The variables v_i and $v_j([kts])$ represent the approach speeds of the leading and the trailing aircraft, respectively.

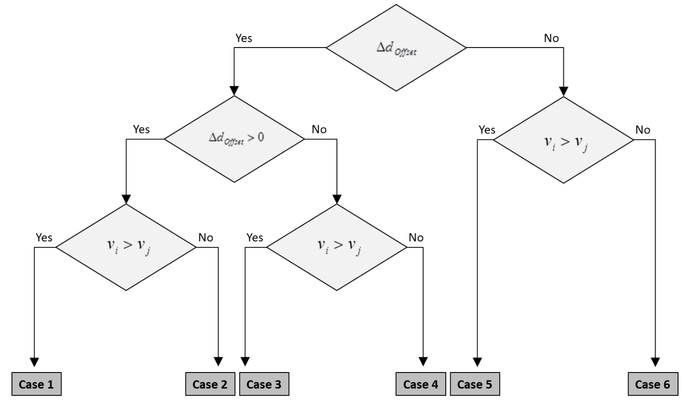

Fig. 3. Decision tree for the calculation of separation times between a couple of arriving aircraft.

For illustration 'case 2' is described in more detail in the following. An example for this case might be a MRAP-capable aircraft that is followed by a conventional aircraft of wake vortex category 'medium' (e.g. A320). The threshold of the MRAP-capable aircraft is further than the threshold of the trailing aircraft. This results in $\Delta d_{offset} > 0m$. The approach speed of the leading aircraft is equal or less compared to the approach speed of the trailing aircraft, i.e. $v_i <= v_j$. According to [8] this represents the 'closing case'. In Fig.4 'case 2' is illustrated:

- 1^{st} subfigure: The WVS is established when the leading aircraft reaches its threshold (1^{st} rule).
- 2^{nd} subfigure: Since the threshold of the trailing aircraft is closer to the physical threshold, the remaining distance until is shorter than the WVS, i.e. it is determined by d_{offset} of the leading aircraft.
- 3^{rd} subfigure: Depending on the threshold-offset of the leading aircraft, its Runway Occupancy Time (ROT) and the approach speed of the trailing aircraft, an additional time might be needed in order to avoid two aircraft on the runway at the same time (2^{nd} rule).

Therefore the separation time between the two aircraft is:

$$t_{Sep} = max[t_{Sep1}; t_{Sep2}] \quad (1)$$

Where t_{Sep1} is calculated by:

$$t_{Sep1} = (S_{ij}/v_j) \cdot 3600 \quad (2)$$

and t_{Sep2} is determined by:

$$t_{Sep2} = t_{Sep1} + max[0; ROT_i - t_{toTHR}] \quad (3)$$

The value of t_{toThr} represents the time the trailing aircraft needs to reach its threshold:

$$t_{toTHR} = (S_{ij}/v_j) \cdot 3600 - (\Delta d_{Offset}/(v_j \cdot 0.5144)) \quad (4)$$

A similar approach applies for 'case 4'. It is noted that in this case the value for Δd_{Offset} becomes negative, thus this case is less restrictive.

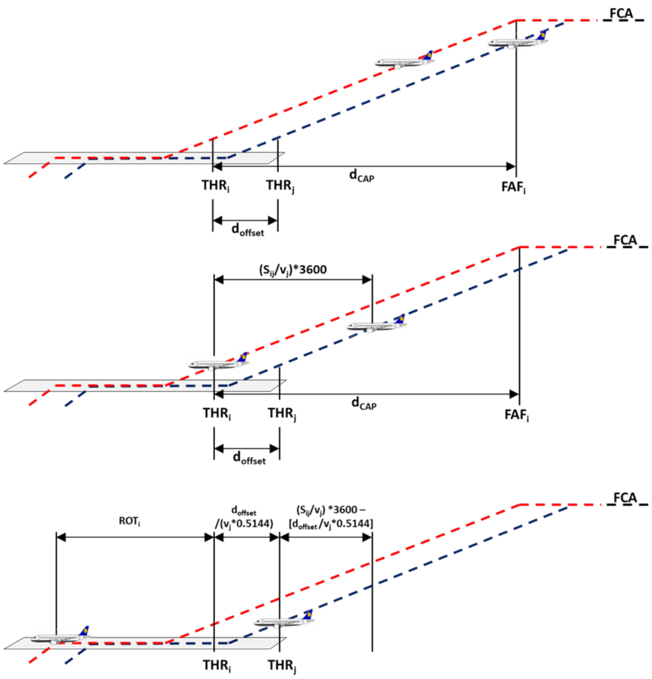

Fig. 4. Exemplary, graphical representation of 'case 2' for the combination Arrival/Arrival for the derivation of separation times (Final Cruise Altitude (FCA), Final Approach Fix (FAF), Common Approach Path length (d_{CAP}), Threshold (THR), Wake Vortex Separation (S_{ij}).

For the cases 1 and 3 the different speeds of the aircraft (Opening Case) lead to slightly different equations. Again Eq.1 and 3 apply, whereas the value for t_{Sep1} is calculated from:

$$t_{Sep1} = [(S_{ij}/v_j) + d_{CAP} \cdot (1/v_j - 1/v_i)] \cdot 3600 \quad (5)$$

and t_{toTHR} is calculated from:

$$t_{toTHR} = [(S_{ij}/v_j) + d_{CAP} \cdot (1/v_j - 1/v_i)] \cdot 3600 - (\Delta d_{Offset}/(v_j \cdot 0.5144)) \quad (6)$$

Again, it is noted that for 'case 3' the value for Δd_{Offset} is negative. The cases 5 and 6 represent the conventional cases with no MRAP-capable aircraft types involved.

Since the technology does not affect the departure procedure, the separation times for other parings, i.e. arrival followed by a departure, a departure followed by an arrival, and two succeeding departures, are determined by well-known approaches published in e.g.[8]:

For the combination arrival/departure, the leading aircraft must have vacated the runway before the trailing aircraft can start the take-off roll. For this case it is important to consider that the ROT of the landing aircraft is based on the physical threshold. In case of an MRAP-capable aircraft this results in a much longer ROT than for conventional aircraft types. In Fig.5 a graphical representation is given. The time from crossing the physical threshold to the point when the aircraft has vacated the runway is denominated as ROT_{Total}, whereas ROT_{THR} is the time the aircraft occupies the runway based on its threshold, i.e. after crossing a height of 50ft.

For the separation of an arriving flight from a departing flight, it is assumed that the arrival must be in front of the threshold for prescribed distance, e.g. 2nm.

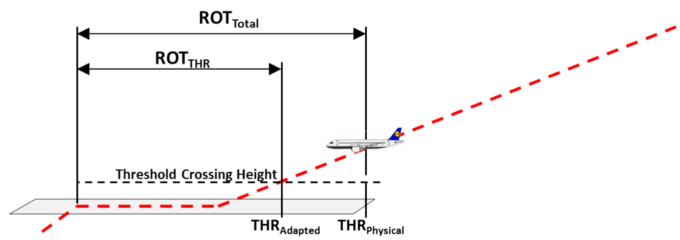

Fig. 5. Schematic diagram for the definition of ROTs.

Departures are separated from each other by defined separation times which are dependent on the combination of aircraft with respect to their wake vortex categories.

III. Simulation

To assess the impact of MRAP-capable aircraft on the capacity of a single runway, a model chain is developed. An essential component of this chain is a simulation model that calculates landing trajectories of MRAP-capable aircraft based on user-specified input parameters. A more detailed description of the trajectory simulation model and the corresponding input parameters is given later. At this point it is noted that, since the resulting trajectories are individual for every movement, the impact of the MRAP-concept is assessed by a simulation rather than by an analytical model. A schematic flow-chart of the simulation chain is depicted in Fig.6.

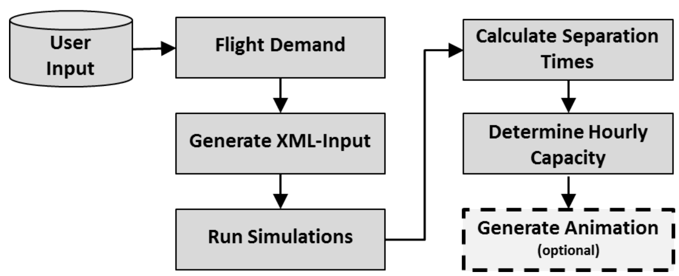

Fig. 6. Flow-chart of the simulation chain.

The modules, namely the module to generate the demand (Fig.6: 'Flight Demand') as well as the trajectory simulation module (Fig.6: 'Run Simulations'), need a variety of parameters which can be set by the user, among them:

- Number of flight movements
- Share of arriving and departing aircraft
- Share of aircraft classes, i.e. heavy/medium/light
- Share of MRAP-capable aircraft (at the moment limited to aircraft in the 'medium' category, e.g. A320)
- Airport-specific parameters: final cruise altitude, final glide slope, length of common approach path, wake vortex separation matrix, departure separation matrix, separation distance for departure/arrival combinations

In a simulation run the sequence of arriving and departing aircraft is randomly distributed, i.e. the arrival or departure peaks are not explicitly considered. The simulation of 4D-approach trajectories for MRAP-capable aircraft also needs user-defined input, including the following parameters:

- Airline Strategy Index (ASI) (indicating to what extent the pilot allows for an extra buffer through a longer landing distance and consequently ROT (see upper subfigure of Fig.8))
- final weight of the aircraft (which has a direct influence on the approach speed (see lower subfigure of Fig.8)
- distance of the runway exit to the nominal threshold
- meteorological parameters (e.g. temperature, wind)

The primary purpose of the trajectory simulation module is the calculation of aircraft noise. For the capacity assessment and under consideration of the equations introduced in the previous chapter, the parameter d_{Offset}, the final approach speed and the ROTs, namely ROT_{Total} for arrival-departure combinations and ROT_{THR} for arrival-arrival-combinations, are of particular interest. In Fig.7 an exemplary landing trajectory is shown as a result of the trajectory simulation module. It is noted that, when the aircraft reaches the final segment it approaches the runway with a constant speed.

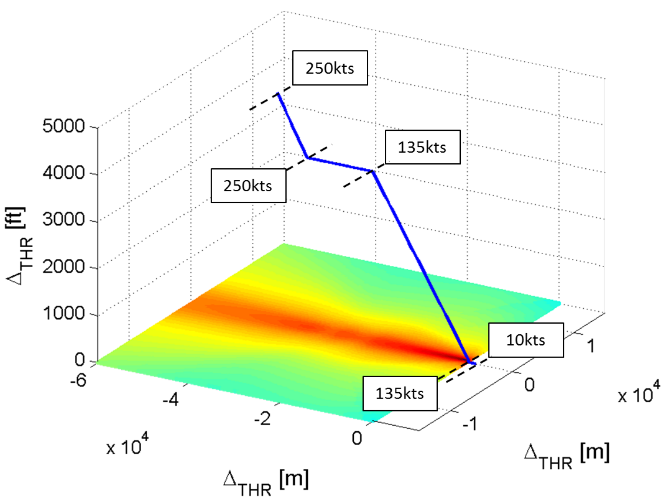

Fig. 7. Exemplary output of the trajectory simulation module for MRAP-capable aircraft.

With the information coming from the flight schedule, airport specific data as well as the individual results of the landing trajectories (namely approach speed, distance of the touchdown point to the physical threshold and ROTs), the separation times between the flight movements are calculated based on the equations introduced in the previous chapter (Fig.6: 'Calculate Separation Times'). By summing up these separation times, the hourly capacity can be determined (Fig.6: 'Determine Hourly Capacity'). It is noted that the simulation starts when the first aircraft reaches its threshold. Finally an animation of the simulation scenario can be generated for visual validation (Fig.6: 'Generate Animation').

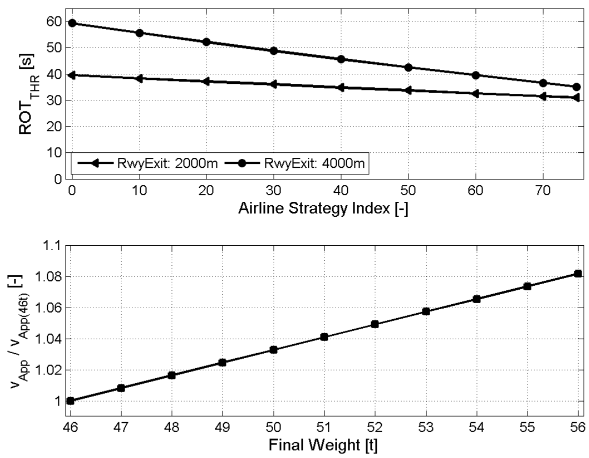

Fig. 8. ROT as fiunction of the airline strategy index (upper subfigure) and approach speed as a function of final aircraft weight indexed to the approach speed at a final weight of 46t (lower subfigure) as calculated by the trajectory simulation module.

IV. Results

In the following results obtained from the simulation chain, described in the previous chapter, underlying different scenarios are presented:

In the first subchapter, we focus on arrival capacity only, whereas in the second subchapter the capacity envelope of a single-runway system is analyzed. Most of the aforementioned input parameters are kept constant for these simulations (see Tables 1-3). Additionally, for the scope of this study, we do not investigate different fleet mixes, i.e. only aircraft of the wake vortex category 'medium' are considered. The main reason is that only aircraft similar to the A320 are covered by the trajectory-simulation module to derive precise landing trajectories so far. Nevertheless, it is noted that this class also represents the major share of aircraft movements at most airports. Additionally meteorological parameters are set to standard atmosphere conditions and wind is not considered.

TABLE I. Parameters for Final Approach Segment

FCA	3638 ft
FGS	3.0 deg
d_{CAP}	11.4 nm
$d_{Arr-Dep}$	2 nm

TABLE II. Wake Vortex Separation Matrix

	H_{trail}	M_{trail}	L_{trail}
H_{lead}	4 nm	5 nm	6 nm
M_{lead}	2.5 nm	2.5 nm	3 nm
L_{lead}	2.5 nm	2.5 nm	2.5 nm

TABLE III. Departure Separation Matrix

	H_{trail}	M_{trail}	L_{trail}
H_{lead}	90 s	90 s	120 s
M_{lead}	90 s	90 s	60 s
L_{lead}	60 s	60 s	60 s

A. Scenario 1: Arrival Capacity

For the assessment of the impact of the MRAP-concept on arrival capacity, the exit-location for MRAP-capable aircraft is varied. Other parameters, like the final weight of the aircraft (54 t) or the exit location for the conventional aircraft types (1850 m) are kept constant (see Fig.9). The ASI is set to a maximum value of '75', which corresponds to the case that the pilot uses the maximum deceleration capability defined in the landing distance model. Braking behavior of pilots on the runway and the corresponding ROTs are difficult to determine. Therefore ROT of conventional aircraft can vary significantly even for the same runway exit location, load and runway conditions, etc. (see e.g. [9]). In this study we simulated the braking behavior for conventional aircraft by setting the ASI to low values (in scenarios 1 and 2 it is set to zero).

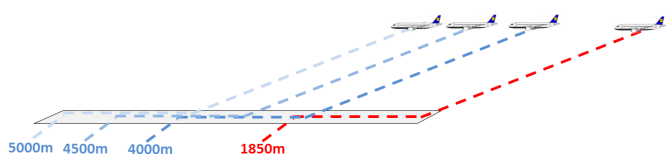

Fig. 9. Location of runway exits for Scenario 1.

Results show that with an increasing share of MRAP-capable aircraft the capacity decreases in this scenario. A minimum at 50% share (see Fig.10) is reached. The decrease in arrival capacity thereby depends on the location of the runway exit, i.e. the further away the selected runway exit is located from the nominal threshold, the more it impacts arrival capacity. Since wake vortex characteristics of the aircraft are not influenced by the MRAP-concept, arrival capacity with a fleet mix of 100% MRAP-capable aircraft is equal to the capacity of a fleet mix with 100% conventional aircraft, provided that the distance of the runway exit is constant.

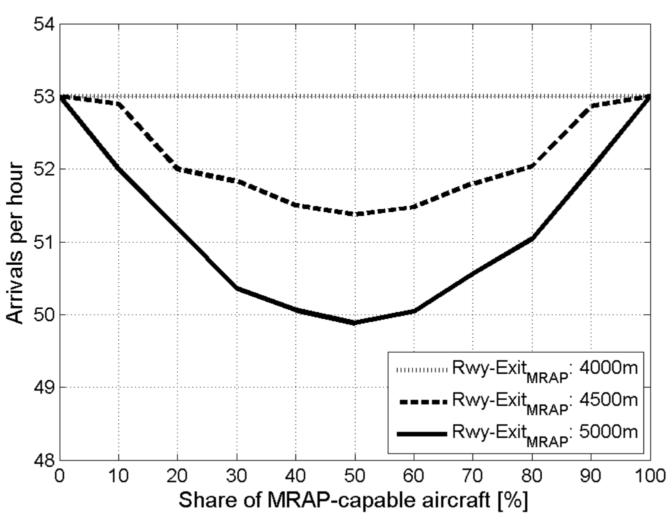

Fig. 10. Simulation results ((˜500 runs)) that show the influence of runway exit position and share of MRAP-capable aircraft on arrival capacity for 'scenario 1' (Fleet Mix: 0%heavy / 100%medium / 0%light).

B. Scenario 2: Capacity Curve of a Single-Runway System (Part 1)

In order to estimate the impact of the MRAP-concept on the capacity envelope, departures are integrated in the flight demand. The following results are based on the assumption that MRAP-capable aircraft vacate the runway via an exit that is located 3920m away from the physical threshold (see Fig.11). The other parameters are equal to the settings listed in the previous subchapter A. Basically the share of arrivals and departures is varied as well as the share of MRAP-capable aircraft (0% / 50% / 100%). The cases where the share of MRAP-capable aircraft is equal to 0% therefore constitute todays situation and the corresponding capacity curve can be interpreted as the reference case. The results of scenario 2 are summarized in Fig.12.

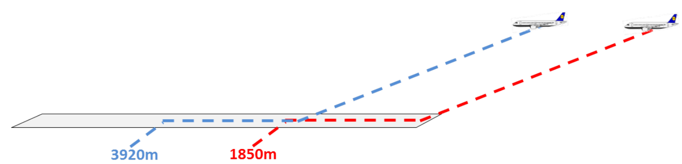

Fig. 11. Location of runway exits for Scenario 2.

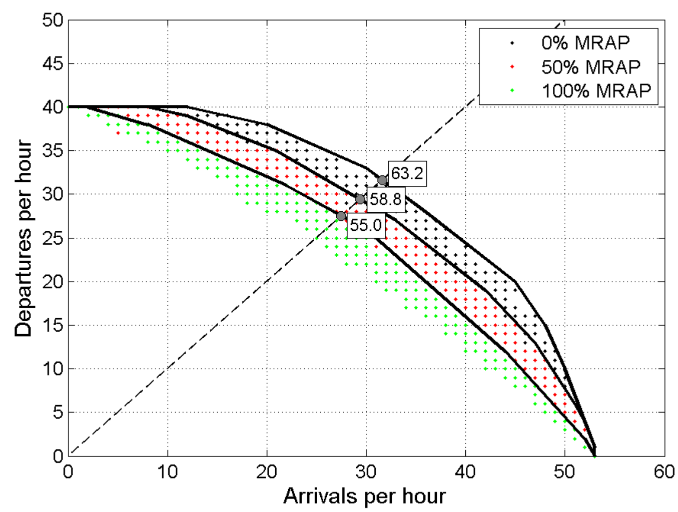

Fig. 12. Capacity curve as a result of the simulations (˜3000 runs) for 'scenario 2' with different shares of MRAP-capable aircraft (Fleet Mix: 0%heavy / 100%medium / 0%light).

Since the runway exit is close enough to the physical threshold the 'arrivals only'-point of the capacity curve is independent of the share of MRAP-capable aircraft (see also subchapter A). The MRAP-concept does not affect the departure process, therefore the capacity at the 'departures only'-point is also not affected. Depending on the share of MRAP-capable aircraft there is a significant influence on the capacity envelope when arrivals and departures are mixed. To illustrate this, the values of the '50/50'-capacity of the three different envelopes are also depicted in Fig.12. With respect to the '50/50'-point, capacity decreases in this scenario from 63.2 movements (0% MRAP share) to 58.8 movements (50% MRAP share) and 55 movements (100% MRAP share), respectively.

C. Scenario 3: Capacity Curve of a Single-Runway System (Part 2)

In 'scenario 2' most of the input parameters were kept constant. Therefore we used the simulation chain with varying input for 'scenario 3'. The following input parameters are varied:

- Airline Strategy Index: The underlying distributions for the derivation of the ASI for conventional and MRAP-capable aircraft are depicted in Fig.13. They are based on normal distributions with a mean of 12.5 (conventional) and 62.5 (MRAP-capable), respectively.
- Final Weight: For arrivals the final weight plays a crucial role for the approach speeds. Therefore it is varied, also based on a normal distribution, with a mean at 50 000kg (see Fig.14).
- Runway Exit: We assume a runway with five different exits. It is assumed that conventional aircraft tend to vacate the runway via the first three exits, whereas MRAP-capable aircraft vacate later. The runway exit distribution for conventional and MRAP-capable aircraft is shown in Fig.15.
- The share of MRAP-capable aircraft on the total number of arriving flights is set to 50% in this scenario.

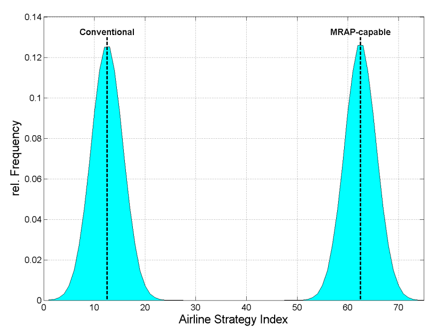

Fig. 13. Probability distribution of the Airline Strategy Index for conventional and MRAP-capable aircraft.

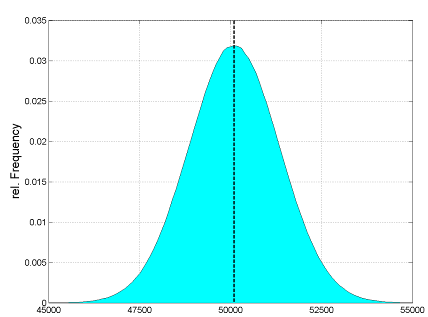

Fig. 14. Probability distribution of final weights for arriving aircraft.

In Fig.16 the capacity curve for 'scenario 3' is shown. The 50/50-capacity value is 57.4 movements and this does not differ remarkably from 'scenario 2'. It is observed that the data points are wider distributed. The minimum number of movements with respect to the 50/50-capacity value is

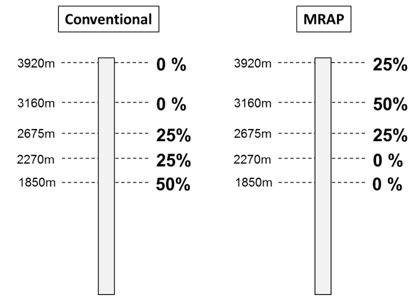

Fig. 15. Runway exit distribution for conventional and MRAP-capable aircraft.

25 arrivals and 25 departures per hour. The 'arrivals only'-capacity decreased from 53 to 50 compared to 'scenario 2'. This is mainly due to the variation of the final weight of the aircraft and the corresponding lower approach speeds.

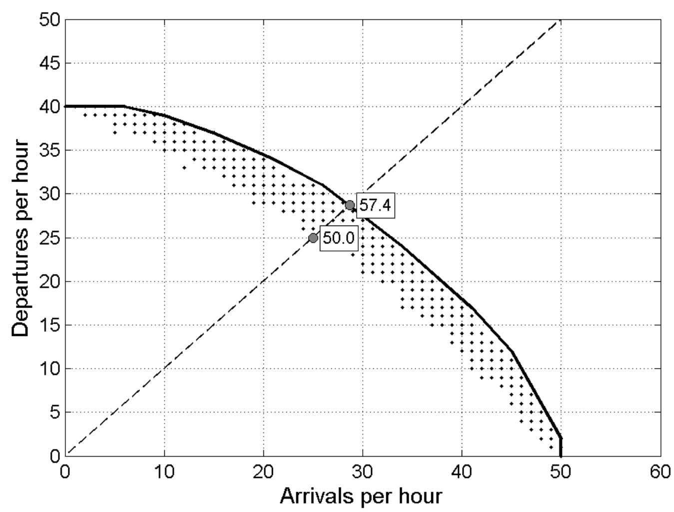

Fig. 16. Capacity curve as a result of the simulations (˜3000 runs) for 'scenario 3' with a 50% share of MRAP-capable aircraft (Fleet Mix: 0%heavy / 100%medium / 0%light).

V. Summary

In this study the impact of a MRAP-concept on the technical capacity of a single runway is investigated. Therefore equations to calculate separation times between succeeding arrivals are derived, to ensure that safety requirements during final approach are met. Based on these equations, a simulation chain is developed to determine runway hourly capacity assuming different scenarios. As the main element, the tool chain includes a simulation module that computes detailed approach trajectories for MRAP-capable aircraft. By varying a number of input parameters, the impact of the MRAP-concept on arrival capacity and the capacity envelope are investigated.

With respect to the arrival capacity (scenario 1) it is shown that with increasing displacement of the adaptive threshold the arrival throughput is negatively affected. This especially applies for a 50% share of MRAP-capable aircraft of total arrivals. With an increasing share of MRAP-capable aircraft the effect is mitigated. It is noted that the values chosen for the displacement of the threshold are hardly met at airports. For example, at Runway 25L of Frankfurt Airport the displacement of the most distant runway exit is 3920m. Additionally the WVS chosen for the results presented are rather small (see Table 2) and safety buffers are not considered. The negative impact of the MRAP-concept diminishes with increasing WVS, e.g. 3nm.

With respect to the capacity envelope and the input parameters defined in 'scenario 2' it is shown that the concept primarily affects departure throughput negatively. The reason is the longer ROT, in reference to the physical threshold (ROT_{Total}), of arriving aircraft that prevents departing aircraft to start their take-off roll. Based on the 50/50-capacity value, results show that for a 50% share of MRAP-capable aircraft capacity decreases by 7%. A share of 100% results in a 13% decrease of capacity. This effect might be alleviated by assigning a closer runway exit in such situations, which in return reduces the potential to noise reduction.

In 'scenario 3' the input parameters are selected from random distributions. Therefore capacity values are wider distributed. In this scenario the 50/50-capacity is 57.4 is the best case and 50.0 in the worst case. Results for this scenario therefore do not differ significantly from 'scenario 2'.

VI. Outlook

There are some aspects that need further improvements with respect to single modules and the simulation chain as a whole:

We only considered aircraft of the wake vortex class 'medium' so far. The integration of more aircraft types of different wake vortex categories is a necessary step to improve the assessment.

As can be seen from Fig.7 the trajectory-simulation module does not differentiate between different runway exit types, i.e. high-speed exits. Since aircraft are capable to vacate the runway at higher speeds, e.g. 30kts, this impacts ROT positively and should therefore be considered.

The scope of this study is limited to single-runway systems. More complex runway systems and specific airports that suffer from the aircraft noise should be considered. For these cases the input, e.g. flight schedule and meteorological data, can also be refined. The capacity models can easily be adapted. However it is noted that the results presented in this paper allow for an estimation of the effect of the technology on runway capacity for a couple of runway systems, e.g. dependent dual runway or independent dual runway systems.

Another point of discussion that came up during the development of the simulation chain was the impact of the individual approach trajectories on wake vortex separations. Since wake vortices tend to descent after the formation this can have either a positive or negative impact on the trailing aircraft. As an illustration possible situations are depicted in Fig.17. Today aircraft approach on one common approach path, the wake vortex separations (as defined e.g. in Tab.II) ensure save operations (Fig.17, upper subfigure). Assuming that the leading aircraft is MRAP-capable and thus approaches on a shifted higher glide path compared to a trailing conventional aircraft, there might be an increased danger that the trailing aircraft could be affected by the wake vortex of the leading aircraft (Fig.17, middle subfigure). On the other hand, for pairings of conventional leading aircraft followed by an MRAP-capable aircraft, this situation might change and have positive effects with respect to the separation distance of these aircraft (Fig.17, lower subfigure). It should be discussed to what extent the wake vortex separations can be adjusted to such situations.

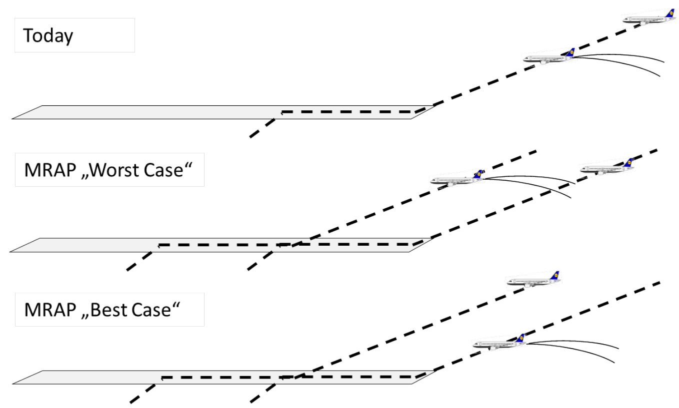

Fig. 17. Schematic diagram of the influence of individual approach paths on possible wake vortex encounters.

Additionally the population around airports ([10]) should be considered in order to derive meaningful results of the benefits that can be expected with respect to specific noise metrics like 'number of people affected'.

This study represents a first step to a more holistic assessment of the assignment of individual aircraft landing trajectories, with the MRAP-concept as a possible solution. For a more complete picture other metrics might be included as well. As an example, the technology might impact the local air quality negatively due to the longer approach phase on the one hand, but it could also have positive impact if taxi-in time could be reduced, since aircraft might reach their parking position earlier. Of course, this depends on the specific airport layout and must be assessed for individual situations.

In a final step the inclusion of different, often contradicting metrics gives room for multi-objetcive optimization.

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