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Individual Wake Vortex Separations: Capacity and Delay Impact on Single and Dual Dependent Runway Systems

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Airport capacity constraints and growing traffic demand in air transportation cause congestion and delay on the ground and in the air. Conservative wake turbulence separation minima in the approach phase guarantee a minimum of in-flight wake encounters of trailing aircraft. On the other hand, in many situations weather-based separation minima could support more efficient runway utilization. This work estimates delay reduction and capacity gains of DLR`s Wake Vortex Prediction and Monitoring System (WSVBS) through the application of reduced time-based approach separations for a single and dual dependent runway system. The system dynamically adjusts approach separations without compromising safety. Delay calculations are conducted with a dynamic runway queuing model, which is capable to process time varying approach separations. It provides the relevant delay data, where several representative operational scenarios enabled through the application of reduced separations on a single and dual dependent runway system are considered. Capacity profiles are created by processing WSVBS separation data with the actual traffic demand. The results give insight about possible delay reductions as well as related operational impact under given implementation assumptions. It is shown that the WSVBS provides efficiency gains on both runway systems, whereas operational requirements regarding the single runway system need to be taken into account applying reduced individual separations. Regarding the dual dependent runway system, an average hourly delay reduction up to 15 minutes maximum is revealed for the defined scenario setup.

Nomenclature

DFS	=	Deutsche Flugsicherung (German Air Navigation Service Provider)
DLR	=	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
NOWVIV	=	Nowcasting Wake Vortex Impact Variables (Weather Forecast Model)
P2P	=	Probabilistic Two-Phase Wake Vortex Model
ROT	=	Runway Occupancy Time
RWY	=	Runway
SHA	=	Simplified Hazard Area
SODAR	=	Sound Detection and Ranging
RASS	=	Radio Acoustic Sounding System
WSVBS	=	Wirbelschleppenvorhersage und –beobachtungssystem (Wake Vortex Prediction and Monitoring System)
WVC	=	Wake Vortex Category
WSWS	=	Wake Vortex Warning System

I. Introduction

Throughput is a major requirement for airports to generate economic value (Graham 2008). In this sense aviation and non-aviation revenues are closely related to the overall efficiency of airside and landside airport processes. Especially the capacity of a runway system represents an important technical foundation for airside performance.

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Many technical and operational approaches exist to safely increase throughput within the final approach and landing phase at highly congested airports. However, wake vortex separation standards introduced in the early 1970s are still applied during approach and landing.

To increase the capacity of an airports runway system, a Wake Vortex Prediction and Monitoring System (WSVBS) was developed by DLR (Holzäpfel et al., 2009, Gerz et al., 2009). The system is designed to dynamically adapt aircraft wake vortex separations depending on specific weather conditions and wake vortex behavior without compromising safety. Initially designed for the closely spaced parallel runway system of Frankfurt/Main airport, current functionalities of the system include individual dynamic predictions of pairwise aircraft separations. These in-trail separation predictions extend the system`s functional scope to the single runway system (Holzäpfel et al., 2011).

The functional extension of separation predictions for the single runway system comes along with the infrastructural airside expansion of Frankfurt/Main airport (EDDF) by operationally introducing the latest runway 25R/07L north-west of the airport`s reference location in October 2011 (see Fig. 1). The parallel runway system now consists of two independent runways 25R/07L and 25L/07R, of which the center lines are separated by 1918 m from each other. They serve as approach runways, whereas the center runway 25C/07C is exclusively operated as departure runway. An additional departure runway 18W is located west of the dependent parallel runways 25C/07C and 25L/07R, crossing their extended centerlines in direction 25. The standard operational concept allows independent parallel approaches on the approach runways, whereas aircraft types A380, B747 and MD11 are not allowed to use the new northern runway 25R/07L (Fraport, 2006/2). Nevertheless, the concept of reduced separations for the dual dependent runways is not generally cleared out of the airport`s conceptual playbook.

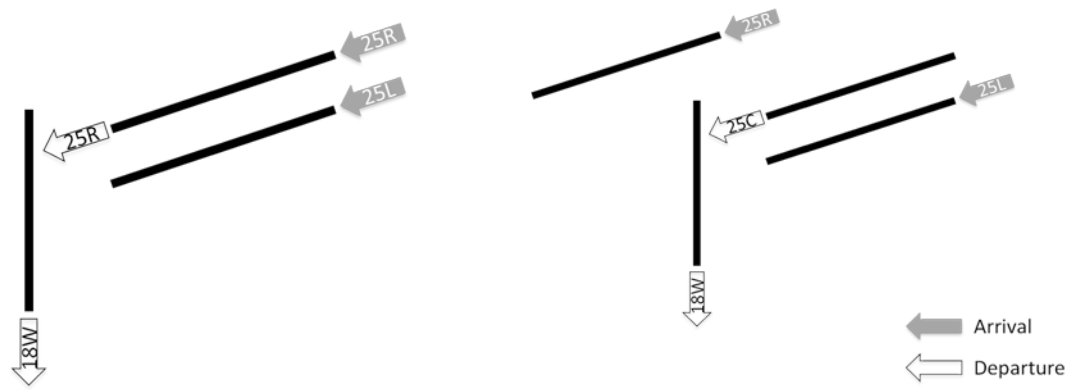

Figure 1. Frankfurt/Main (EDDF) operational procedures in runway direction 25 *Left: 3-RWY standard operations, Right: 4-RWY standard operations.*

Dependent parallel operations can be crucial to accommodate high loads of approach traffic in case of unforeseen runway closure of the north-western runway 25R/07L (Wendeberg, 2011). Reduced approach separations may improve operations during these periods. Figure 1 shows the standard operations according to the former runway layout and the new layout with the additional runway.

The performance of the WSVBS has been tested during several campaigns at Frankfurt/Main airport for dual-dependent runway operations and at Munich airport for single runway operations. Those campaigns have been conducted during several DLR projects like, e.g. “Wetter & Fliegen” (Gerz & Schwarz, 2011). During the campaign at Frankfurt/Main airport in winter 2006/2007, reduced separations could be applied in 75% of the time.

This paper describes possible performance impacts in terms of delay reduction and capacity enhancement of different implementation scenarios regarding the prediction of weight class based aircraft separations on the dual dependent runway system and the prediction of dynamic time-based separations for individual aircraft type pairings on a single runway. All results are analyzed employing meteorological data combined with representative traffic samples of Frankfurt/Main airport.

II. Technical Background

A. WSVBS system overview

This section provides a short overview of the system components of the Wake Vortex Prediction and Monitoring System WSVBS. The design and performance of the different versions of this wake vortex advisory system are described in detail in Holzäpfel et al. (2009), Gerz et al. (2009), and Holzäpfel et al. (2011).

The bottleneck of wake vortex advisory systems for approach and landing occurs in ground proximity, where stalling or rebounding wake vortices may not descend below the approach corridor. For this reason the best wake prediction skill is required near the ground. This is achieved employing measurements of meteorological conditions captured with e.g. a SODAR/RASS instrument and an ultrasonic anemometer (USA). In the residual glide path, which is not covered by direct measurements, numerical weather prediction models are used to generate the required data. During the campaign at Frankfurt/Main airport, the non-hydrostatic weather forecast model system NOWVIV was applied (Gerz et al., 2005, Frech et al., 2007, Frech & Holzäpfel, 2008). It predicts meteorological conditions for the Frankfurt/Main terminal area with a vertical resolution varying between 8 m and 50 m. At Munich airport numerical weather predictions were provided by the prediction system COSMO-MUC (Dengler et al., 2011), which is a derivate of the COSMO-DE model (Baldauf et al., 2011, Steppeler et al., 2003). Glide path adherence statistics established in the FLIP study (Frauenkorn et al., 2001) define an approach corridor within which the aircraft reside with a defined probability. Based on the meteorological input data and aircraft parameters representing either aircraft weight classes or individual aircraft types, the probabilistic wake vortex prediction model P2P predicts envelopes of vortex position and strength (Holzäpfel, 2006). Once the potential positions of the wake vortices are known, safe distances between wake vortex core positions and the follower aircraft need to be assigned. The Simplified Hazard Area (SHA) concept (Schwarz & Hahn, 2006) predicts distances that allow for safe and undisturbed operations. For this purpose SHAPe estimates the required Roll Control Ratio RCR_{req}. It relates the roll control input that is required to compensate the exerted rolling moment to the maximum available roll control power employing the maximum vortex strength predicted by P2P and parameters of the follower aircraft types or weight classes. A number of stationary 2-dimensional gates are defined along the glide path in which the areas representing the approach corridor, the vortex area, and the safety area are added up. To capture the complex vortex behavior in ground proximity the gate distance of the lower three gates is reduced from 1 NM to 1/3 NM. In the most critical gates at low altitude the LIDAR monitors the correctness of the WSVBS predictions. From the predictions of the resulting safety areas in all the gates along the glide slope, separations for heavy-heavy and heavy-medium aircraft combinations as well as individual aircraft type pairings established on the glide path can be deducted.

B. Safety and reliability

Weather prediction and prediction of the resulting wake vortex behavior are inherently compromised by uncertainties. Therefore, several conservative and probabilistic components are combined in the WSVBS system to achieve a high level of overall safety. Especially the uncertainty allowances of the approach corridor dimensions and the probabilistic wake vortex predictions as well as the safety areas represent sensitive parameters to ensure safe and reliable operations.

Currently the WSVBS employs 95.4% probabilities (two standard deviations, 2σ, for Gaussian distributions) as a basis for the probabilistic components of the WSVBS. For example, for lateral vortex transport the vortex prediction model P2P does not assume a Gaussian distribution of vortex generator positions within the approach corridor but it assumes that the vortex generator position actually deviates to the 95.4% envelope from the nominal glide path. This is a very conservative assumption. The SHAPe model then again assumes that the wake vortices reside on the 95.4% envelope of the predicted vortex area. Such a conservative addition of several 2σ margins and several other conservative elements leads to very high but still unknown safety margins that need to be determined in a comprehensive risk assessment of the WSVBS. For a single gate the probability that the distance between a follower aircraft (situated anywhere outside the predicted WSVBS ellipse) and a wake vortex center may fall below the safety distances predicted by SHAPe has been determined by Monte Carlo simulation. For typical setups this probability amounts to less than 1%. This means that the combination approach corridor, vortex area, and safety area add up to overall probabilities of more than 99%.

Regarding the single runway system the minimum separation time at a specific gate reflects the time interval between the passage of the leader aircraft and the time at which the safety area of the following aircraft no longer overlaps the approach corridor. The critical point on the dual-dependent runway system is whether the wake vortex is transported to the neighboring glide path by the cross wind component, so that the safety area overlaps the approach corridor of the other runway within the ICAO defined time horizons of 100 s for heavy-heavy pairings and 125 s for heavy-medium pairings.

The challenge related to the system implementation in an operational environment is to find the trade-off between a system calibration which is dominated by conservative elements and a worthwhile efficiency increase under the required level of safety. The WSVBS appears to be sufficiently safe due to conservative measures like worst case assumptions of aircraft parameters and the combination of probabilistic sub-models. During the demonstration campaign at Frankfurt/Main airport the WSVBS predictions were correct for all 1100 landings observed by lidar (Gerz et al., 2009). Once the methodology of a comprehensive risk analysis will be established, it is planned to adjust all components to appropriate and consistent confidence levels. Possibly, this will enable to somewhat relax the current stringent safety allowances of the WSVBS with the benefit of increased operation times with reduced separations. The primary purpose of the risk analysis, of course, is to show that the system satisfies relevant safety requirements and therefore to convince all stakeholders of the usefulness and capabilities of the system.

C. Operational application

The installation of a Wake Vortex Prediction and Monitoring System is mainly driven by two aspects. The first is to generate additional controller information regarding the existence of potentially dangerous wake vortices within the approach corridor and if desired their respective strength and position. The second operational motivation is to increase runway capacity by decreasing minimum separations below conservative ICAO separations under favorable environmental conditions. Increasing airport related throughput improves its quality of service to airlines, which is defined as the average delay rate per movement (Ashford, 1997). This is, despite increasing the general capacity value of an airport, suspected to be the major area in which benefit in terms of airport efficiency can be generated by such a system.

At most airports the wake turbulence separation rules set up by ICAO (2007) are applied which require extended separation distances of 4 NM (heavy-heavy), 5 NM (heavy-medium), 6 NM (heavy-light) and 5 NM (medium-light) depending on the assigned ICAO weight vortex category of the concerned aircraft. These separations have to be applied for pairs of aircraft approaching the same runway or parallel runways separated by less than 2500 ft.

Under favorable environmental conditions reduced runway separations (*radar* separations) may be applied between approaching aircraft using the same runway. Depending on the regulatory framework of the appropriate ATS authority the separation minimum is defined at 3 NM, 2.5 NM or 2.0 NM. This requires the proof, that the average runway occupancy time (ROT) on that runway does not exceed 50 s. Table 1 depicts a possible separation matrix for single runway operations. The longitudinal separation minima are translated into approach separation times according to the standard output format of the WSVBS. Reduced runway separations are set to conservative 70 s applying an average approach speed of 144 kn (Gerz, 2009).

In order to enhance landing capacity of the dual dependent runway system of Frankfurt/Main airport, the German Air Navigation Service Provider DFS developed three alternative modes of operation for aircraft separation under IMC conditions (Gurke & Lafferton, 1997) which are sketched in Figure 2. These can only be applied during favorable weather conditions and require the use of DLR`s WSVBS or DFS's Wake Vortex Warning System, WSWS (Konopka, 2005). Either weak winds or reliable cross winds enable reduced separations. In the former case wake vortices are not transported to the adjacent approach corridor and both runways can be used independently. In the latter case lateral wake transport allows for reduced diagonal separation minima depending on the crosswind direction. This means that reduced runway separation minima may be applied between aircraft landing on *different* runways. In all modes, the aircraft in-trail separation remains untouched according to ICAO standards.

Table 1. WVC based separation matrix (single runway) *Wake vortex separation minima are highlighted.*

		ARRIVAL FOLLOWER		
		Heavy	Medium	Light
ARRIVAL LEADER	Heavy	**4.0 NM** 100 s	**5.0 NM** 125 s	**6.0 NM** 150 s
	Medium	**2.5 NM** 62.5 s (~70 s)	**2.5 NM** 62.5 s (~70 s)	**5 NM** 125s
	Light	**2.5 NM** 62.5 s (~70 s)	**2.5 NM** 62.5 s (~70 s)	**2.5 NM** 62.5 s (~70 s)

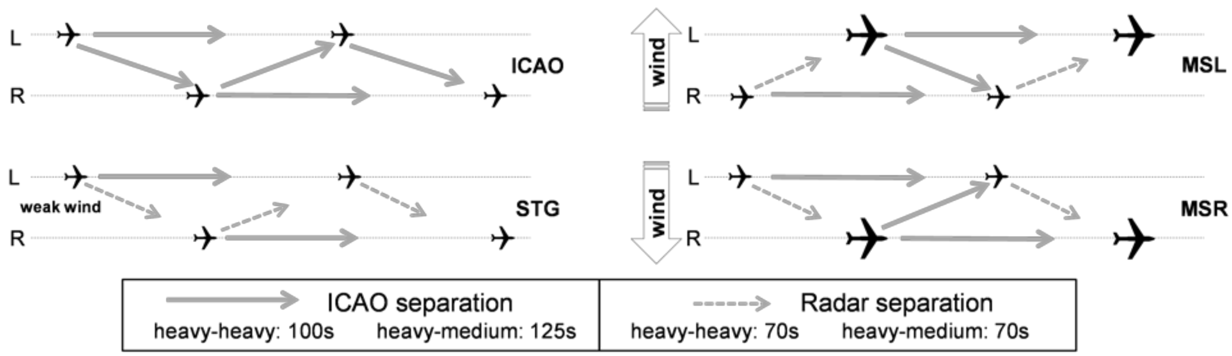

Figure 2. Concepts of operations for a dual dependent runway system *The concept was developed by DFS for the former dual dependent runway system of Frankfurt/Main airport. The figure is adapted from Gerz et al. (2009).*

For the dual dependent runway system the minimum separation times predicted by the WSVBS are transformed into the appropriate conceptual modes shown in Figure 2 (Staggered STG, Modified Staggered Left MSL and Modified Staggered Right MSR). The suggested separation minima do not represent the full performance of the system, because the calculated separation times will be assigned to hard separation minima (see Tab. 1) corresponding to either ICAO or radar separations. Quite frequently the proposed minima are below the ICAO separations and above radar separations. For that reason an additional operational mode was defined which uses the unchanged minimum separation times between pairs of aircraft depending on their individual weight vortex category.

For the single runway system the WSVBS was modified in a way that the system evaluates pairs of aircraft *types* instead of aircraft wake vortex categories. The latest version of the WSVBS includes the following heavy leader types: A306, A310, A332, A333, A343, A346, AB744, B762, B763, B764, B772, B773, B77W, IL96, MD11 and medium follower types: A319, A320, A321, AT43, AT45, AT72, B462, B463, B712, B733, B734, B735, B736, B737, B738, B752, B753, CRJ1, CRJ2, CRJ7, CRJ9, D328, DH8D, E145, E170, E190, F100, F70, MD82, MD83, RJ1H, RJ85, SB20 and SF34.

III. Methodology

A. Delay Calculation Model

A delay model has been employed which can be categorized as process simulation model. The model integrates representative traffic data as well as WSVBS separation minima to generate individual delay rates according to chosen scenarios. The model uses the runway threshold as geometric reference. This is possible if the applied schedule contains individual threshold- or landing times. In most cases this is not the case, so that threshold times have to be calculated by subtracting a certain taxi-in time from a given on-block time. Related to Frankfurt/Main airport a standard taxi-time, which is also used in the airport coordination and slot allocation process, will be considered for the dual dependent runway system. The forecast traffic sample used for the single runway case contains some arrival gate group specific taxi time data which is incorporated. The threshold time is referred as landing time in the following documentation.

The WSVBS generates minimum target separations which represent a limit below which no aircraft pairing is allowed to be separated without endangering flight safety for the trailing aircraft. In a first step these separations are processed by the delay model to account for position uncertainties. This will be done by considering two parameters. First there is the safety buffer, a margin the controller adds to the separation requirement to avoid infringement of minimum separations. Additionally this buffer will be superimposed with a Gaussian distribution to take into account uncertainties arising from the controller-pilot-interaction which finally determines the separation that can be measured at landing threshold. The distribution uses the safety buffer as standard deviation σ. Therewith the model computes the corresponding separations ensuring that separation minima will not be violated beyond a pre-defined amount (for this study 95 % of the separations at least equal the required minimum).

Note here, that the WSVBS separation minima are not directly applied without preprocessing. After assigning individual pairwise separations according to the separation mode the model calculates the actual landing time of the trailing aircraft by verifying the following inequality.

(1) $E/LT_j < C/LT_i + t_{ij}$

where C/LT_i is the landing time of the leading aircraft, E/LT_j is the planned landing time of the trailing aircraft and t_{ij} is the separation time between the two aircraft at threshold. If the condition is true, the calculated landing time of the trailing aircraft is

(2) $C/LT_j = C/LT_i + t_{ij}$

Otherwise the planned landing time according to the flight plan is applied.

(3) $C/LT_j = E/LT_j$

This may occur during periods of lower demand or a steady period of reduced WSVBS separations over several minutes of time. The calculated landing time is then shifted to the next pair of aircraft.

(4) $C/LT_j \rightarrow C/LT_i$ (for j = 2 … n-1)

Figure 3 depicts the delay model structure.

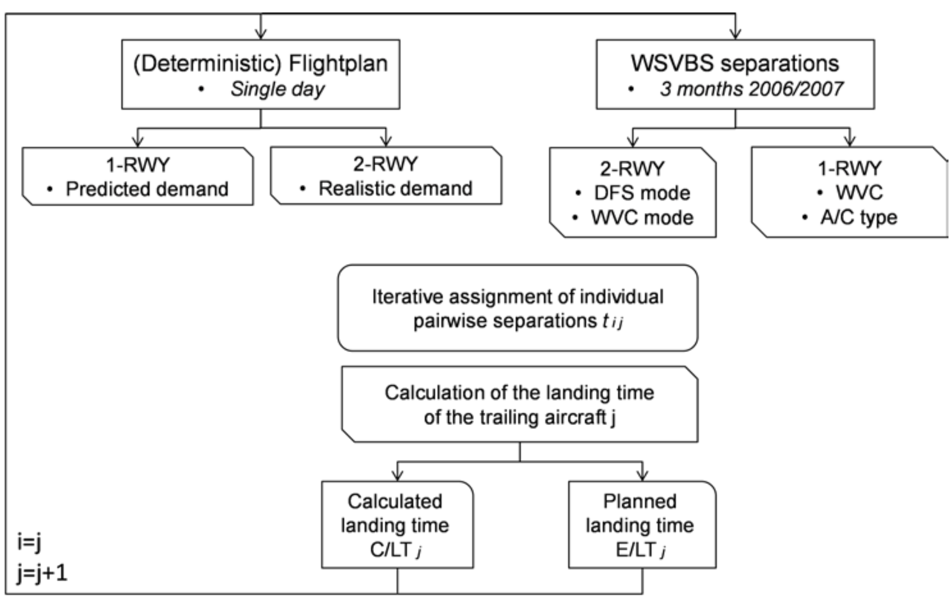

Figure 3. Delay model structure *The model assigns dynamic (time-variant) separations to pairs of aircraft according to individual aircraft parameters and separation mode.*

B. Capacity estimation

For the purpose of this study it seems to be favorable to not only calculate delay figures but to have an impression of what these WSVBS separations mean in terms of runway arrival capacity. Horonjeff & Francis (1994) show an appropriate capacity computation as follows:

(5) $C_a = 1/E(T)$

C_a is the ultimate capacity for arrivals, E(T) represents the expected value of service time with T as a matrix of service times. This service time is computed summing up the multiplication of the aircraft landing pair probability p_{ij} with the sum of the required separation t_{ij} and the safety buffer b_{ij}.

(6) $$E(T) = \sum p_{ij}\,(t_{ij} + b_{ij})$$

For this study equation (6) can be simplified with some assumptions. The buffer modeling is already included in t_{ij} thus there is no additional buffer. Since the traffic sample is fixed (meaning there is a sequence of landing events in a specific time interval) the probability of a landing pair equals the reciprocal of the number of landing pairs $n_{t_{ij}}$ within this interval. In sum equation (7) can be formulated as follows.

(7) $$E(T) = \sum \frac{1}{n_{t_{ij}}} t_{ij}$$

Combined with equation (5) the hourly arrival capacity will be estimated based on the actual traffic demand.

IV. Input Data

A. Weather data

The WSVBS provides delay reduction merely under favorable weather conditions, in particular specific crosswind situations. Therefore the results of this analysis strongly depend on the selected weather scenario which is represented by system proposed separations. The selected weather scenario should either be representative for the entire cycle of a year or for a special season. On the other hand only a sample of 66 days was available for evaluation, which incorporates the data to simulate all separation modes on the two runway systems. Those were the days 2006/Dec/20 to 2006/Dec/31 and 2007/Jan/06 to 2007/Feb/28. It is not useful to investigate the whole period of available weather data. To generate meaningful statements regarding delay reduction a smart selection of a sufficient number of representative days (weather scenarios) was conducted which meets the following requirements:

1) The selected days should be spread over the whole period from 2006/Dec/20 to 2007/Feb/28.
2) Regarding the dual dependent runway system the selection should comprise a variety between the DFS modes (Staggered, Modified Staggered Left, Modified Staggered Right, or ICAO separation). The selection shall reflect the distribution of the 66 days accordingly.
3) For both runway systems WSVBS separation minima should, for a statistically relevant number of cases, be significantly below the ICAO standard.

In a first step a set of six days was chosen accordingly leading to a share of ICAO of 22.7%, STG of 3.3%, MSL of 27.4% and MSR of 46.7%. Regarding the DFS concept of operations for the dual dependent runway system these days reflect the shares of the separation modes of the total time period (ICAO 25.0%, STG 3.6%, MSL 30.7% and MSR 47.9%). Slightly higher fractions of reduced separation have been achieved employing a full year of synthetic meteorological data. In a next step the most promising weather day regarding delay reduction for both runway systems each is selected to build up the scenario structure.

B. Traffic Data

With regard to the analysis of a WSVBS introduction to a dual dependent runway system as well as a single runway system, matching traffic samples have to be applied. These daily traffic samples need to represent realistic demand profiles for the respective runway systems and – to promote the optimal application of a WSVBS – need to be close to practical capacity. Available representative daily traffic samples of Frankfurt/Main airport serve these requirements. One representative daily traffic sample for the dual dependent runway system has been made available for the analysis (2009/Apr/04) whereas the traffic sample for the single runway system is based on prognostic

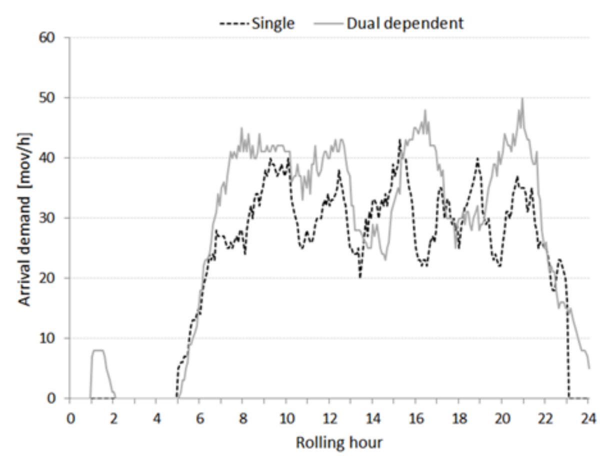

Figure 4. Arrival demand profiles *Single runway system (prognostic demand profile) and dual dependent runway system (representative demand profile: 2009/Apr/04).*

data for the year 2020 (Fraport, 2006/1). Relevant data like aircraft types and time stamps are included, whereas estimated on-block times are divided up to 5-minute time-bins. Figure 4 provides the arrival demand profiles. Maximum demand rates of the 5-minute rolling hour time horizon reach more than 40 arrival movements for both runway systems representing a high demand level. In total, 630 arrival movements are scheduled on the dual dependent runway system. 523 arrival movements are scheduled on the single runway system. According to the low share of light aircraft of approximately 3% in both traffic samples, those types of aircraft have been removed. Furthermore they are not contained in the WSVBS aircraft type list yet.

V. Results

A. Simulation scenarios

Simulation scenarios are defined to reflect WSVBS efficiency including base case scenarios for both runway systems. The selection of the representative weather days is based on the share and the consistency of reduced separations leading to decreasing delays. Figure 5 depicts average delay per aircraft for the 6 selected weather days applying DFS modes of operation as well as WVC separation minima for the respective runway system compared to the ICAO reference.

Regarding the dual dependent runway system 2007/Feb/09 represents the most promising day in terms of delay reduction potential. This day is dominated by southerly cross winds leading to MSR operations in 46.9% of the time. Favorable STG operations also have a high share of 21.9%. The average WSVBS separation value is 95 s. Regarding the single runway system, 2007/Feb/11 represents the most promising day in terms of delay reduction. This day is dominated by southerly winds leading to reduced in trail separations especially in the morning hours.

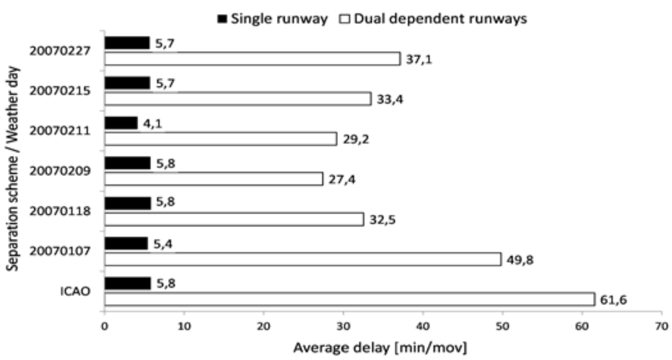

Figure 5. Average delay for individual WVC separations *Comparison of all 6 weather days to the ICAO reference for both runway systems.*

Figure 5 reveals that for the dual dependent runway system, ICAO based separations cause high average delays of 61.5 minutes. This value does not correspond to realistic approach operations conducted on this dependent runway system. Reasons are manifold. According to Wendeberg (2011) pilots and controllers saved about 5-10 s on average during good weather conditions in STG in-trail operations for heavy-heavy pairings to reduce arrival delays. Confidential performance studies as part of the approval process of the new northern runway indicate average separations of 85 s for these pairings during favorable weather conditions. Related to the calculated delay situation applying conservative separation minima like shown in figure 5, a valid average separation reduction of approximately 25% fits this value. This gives reason to implement an additional reference case for the dual dependent runway system, which is referred to as the *operational* base case (OPS).

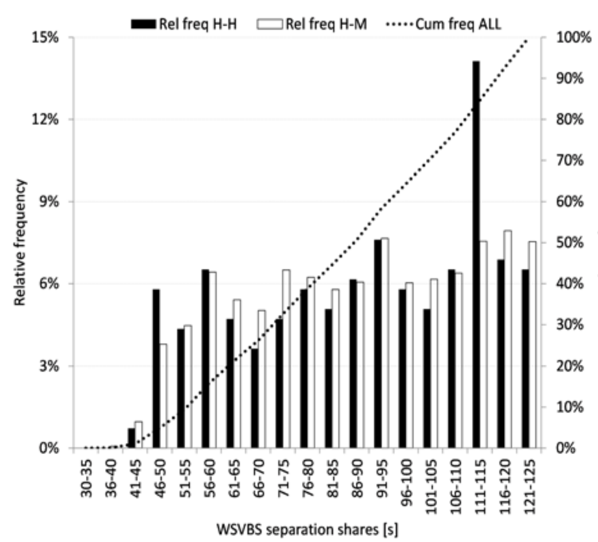

Figure 6. Frequencies of reduced individual separation minima (single runway, A/C based) *The share of separation minima between 30s and 125s is depicted representing 12% of the total number of suggested separation minima on 2007/Feb/11.*

The final scenario structure, which is shown in Table 2, is complemented by additional scenarios regarding lower separation thresholds on the single runway system (ROT scenarios). These thresholds are justified by minimum runway occupancy times of 55 s, 60 s and 65 s. Figure 6 represents the frequencies of reduced individual separation minima between 30 s to 125 s to cover all relevant separation minima for heavy-heavy and heavy-medium pairs for the single runway system. The cumulative frequency of all suggested minima below 125 seconds is also plotted in the figure. Separation shares below the defined ROT minima are therefore 12.5% (55 s), 18.4% (60 s) and 23.6% (65 s).

Table 2. Scenario structure *OPS stands for operational base case, PTS means prognostic traffic sample.*

	Separation Schemes									
	ICAO	OPS	DFS		WVC		A/C			
			ICAO baseline	OPS baseline	ICAO baseline	OPS baseline	ICAO baseline only w/o ROT	ROT 55	ROT 60	ROT 65
Traffic Samples: PTS 2020 (Single RWY)	+				+		+	+	+	+
Traffic Samples: 2009/Apr/04 (Dual RWY)	++	++	++	++	++	++				

\+ Weather Day: 2007/Feb/11 ++ Weather Day: 2007/Feb/09

In total, 12 scenarios are investigated: 3 base case scenarios, 4 scenarios regarding reduced separations on the dual dependent runway system and 5 scenarios regarding the single runway including ROT scenarios.

B. Delay and Capacity

Table 3 depicts average individual arrival delays for all 12 scenarios. Notably, the variance between the delay values of the two base cases of the dual dependent runway system is high with an average difference greater than 55 minutes. This justifies the introduction of the additional base case in particular, because the operational average arrival delay of 6.4 minutes is a very realistic value regarding the former runway layout of Frankfurt/Main airport. Comparing both schemes of individual pairwise separations of the single runway system, no difference of values for the selected weather day is indicated, although the value of 4.1 minutes represents an average delay decrease of almost 2 minutes compared to the base case. The similarity may be due to the fact that the variability of aircraft types is lower in the prognostic traffic sample, which is set up to accommodate prognostic passenger numbers providing a sufficient number of seats. From the runway capacity perspective, information about the wake vortex category of an aircraft is sufficient. On the other side, the variability of aircraft types impacts the sensitivity of predicted separation minima and therefore WSVBS performance.

As expected, average arrival delay values of the ROT scenarios are higher and leave only low margins of delay benefit on the single runway system. At this point it has to be acknowledged that even 65 seconds are a rather optimistic assumption for the ROT of heavy type aircraft. Thus there seems to be only a little chance to obtain an operational separation benefit below the actual radar separation minimum. Most promising arrival delay reductions can be expected on the dual dependent runway system applying WVC based individual separations. Based on the absence of the runway occupancy problem, interarrival separations achieve values down to almost zero, an operational status that can be observed already today under favorable weather / visibility conditions ("visual separation").

Table 3. Average individual arrival delays [min/mov] *Average individual delay values are derived from several replications of the specific scenario.*

	Separation Schemes									
	ICAO	OPS	DFS		WVC		A/C			
			ICAO baseline	OPS baseline	ICAO baseline	OPS baseline	ICAO baseline only w/o ROT	ROT 55	ROT 60	ROT 65
Traffic Samples: PTS 2020 (Single RWY)	5.8				4.1		4.1	4.8	5.2	5.5
Traffic Samples: 2009/Apr/04 (Dual RWY)	61.6	6.4	27.4	4.7	7.7	2.8				

Figures 7 and 8 illustrate four parameters on a daily basis plotted against a rolling hour with an increment of 5 min (one data point contains all data having a time stamp greater equal an hour before and less than the actual x-coordinate, the subsequent data point is at x + 5 min accordingly). This applies to the demand, capacity and separation reduction figures on the left y-axis (primary axis). Separation reduction represents the time (in minutes) that can be saved by using the specified mode of the WSVBS (WVC, DFS or A/C) compared to the corresponding base cases (ICAO or OPS) within the considered time interval. As opposed to this, the average delay is counted cumulative meaning that the corresponding delay figure according to the latest comment above sums the average delay of all movements with a time stamp less than the actual x-coordinate. In this way the latest value on the right y-axis (secondary axis) equals the average daily delay of the corresponding scenario as shown in Table 3. Each of the mentioned parameters is averaged over 20 independent replications of a specific simulation run to achieve some kind of confidence regarding the modeled controller buffer when comparing the results. This is done by re-initializing each replication with a different pseudo-random number seed.

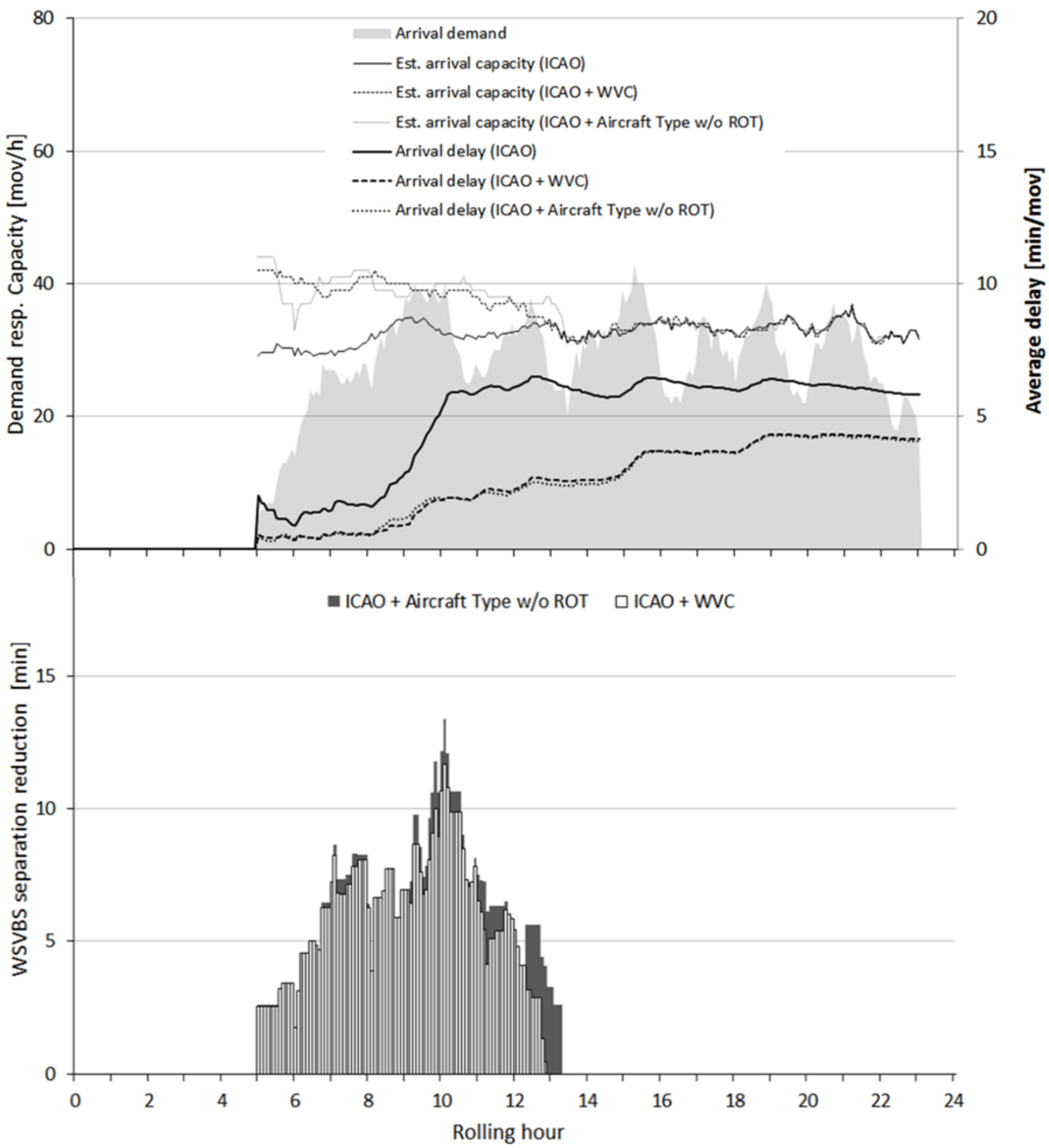

Figure 7. Daily characteristics of the single runway system Above: *Average delay and arrival capacity. Below: Separation reduction. Both depicted in a 5-min-rolling-hour interval.*

Apparent from Figure 7 the WSVBS provides usable separations essentially before noon regardless of the mode actually operated (A/C or WVC). The average delay in the first arrival peak with up to 40 hourly movements around 9:00 am reaches a level of approximately two minutes per movement benefiting from a sufficient arrival capacity at this time. Having this rather low level of delay for a single runway with this number of requested movements seems to be an indication that separations infringe runway occupancy time constraints. The situation returns to 'normal' in the afternoon, when conventional separations are applied and delay consolidates at a four minutes level applying WSVBS separations at both separation modes. As already implied before, results regarding these modes do not reveal a significant difference in terms of delay or capacity. Compared to WVC mode, only 3.4 separation minutes more can be saved applying individual A/C based separations (w/o ROT) at this day (compared to the ICAO base case).

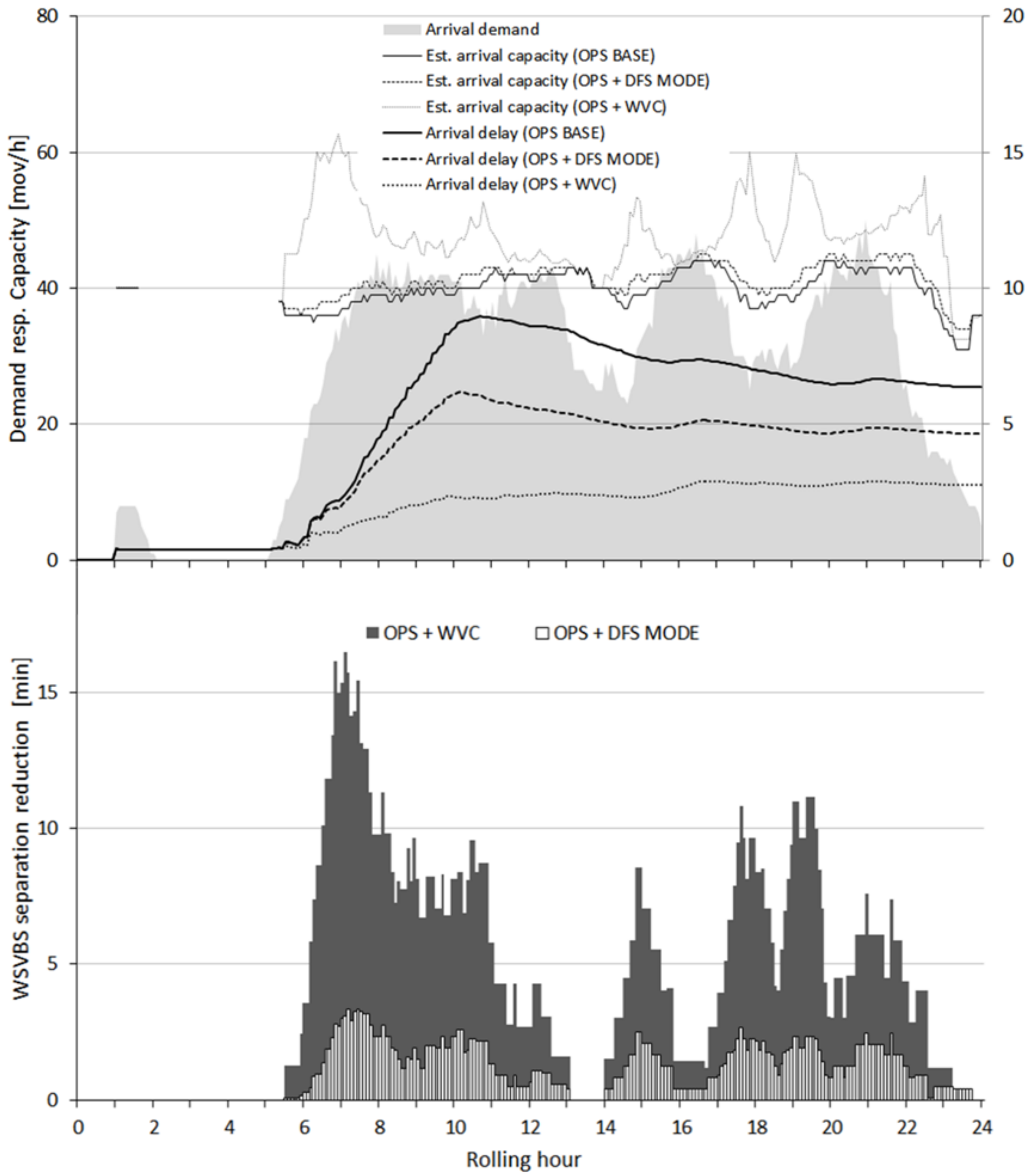

Figure 8. Daily characteristics of the dual dependent runway system Above: *Average delay and arrival capacity. Below: Separation reduction. Both depicted in a 5-min-rolling-hour interval.*

Figure 8 shows the comparison of the recently introduced operational base case with two modes of WSVBS operation (WVC and DFS) on the dual dependent runway system. Following the first morning demand peak around 7:00 am, average delay is rapidly increasing up to almost 9 minutes per movement in the base case caused by a capacity barely accommodating the actual demand. This situation eases in DFS mode through slightly increased capacity values reducing the average delay by more than 2 minutes. Using the WVC mode the system provides a notable number of applicable separations with an average hourly reduction up to 15 minutes maximum. The available capacity of this mode seems to be sufficient for all situations of the analyzed day resulting in an average delay of not even three minutes per movement. Compared to DFS mode, 78 separation minutes more can be saved applying the WVC mode at this day (compared to the OPS base case).

VI. Conclusion and Outlook

The impact of individual wake vortex separations regarding capacity and delay on a single and a dual dependent runway system has been investigated. These separation minima are generated by the described Wake Vortex Prediction and Monitoring System WSVBS and are used accounting for existing operational separation concepts. A delay model which is capable to process pairwise dynamic separation minima was applied to generate average and cumulated delay rates for defined scenarios. To compare these estimates to the appropriate capacity values, runway capacity was calculated for the rolling hour horizon of the considered weather days. These days were selected out of a sample of 66 weather days during winter 2006/2007 at Frankfurt/Main airport whereas the selection was driven by promoting a representative share of consistent periods of favorable weather conditions in which the WSVBS generated separations below conservative ICAO values. A representative traffic sample each for the single and the dual dependent runway system representing a high demand level was applied. 12 scenarios are investigated including base case scenarios.

In summary the use of WSVBS separations on a single runway system promises a potential separation benefit in between actual wake vortex separation and radar separation minima, which could be utilized without substantial operational changes in ATC. Concerning the dual dependent runway system WSVBS separations might be easily used to enable separations under instrumental weather conditions which are present in favorable visibility today providing a noticeable delay and capacity benefit. It is found that a separation reduction scheme based on 1 s time increments clearly outperforms approaches that support only either ICAO or radar separation. On the other hand, the use of aircraft type dependent separations does not deliver substantial benefits compared to aircraft weight class combinations in the defined scenario setup.

Apart from the fact that WSVBS predictions are conservative enough to fulfill the safety requirements, the focus of future work regarding the WSVBS itself will be put on the operational integration as well as a methodology for a comprehensive risk analysis. Procedures are needed to provide time based WSVBS separations to the controller generally separating approaching aircraft by lateral minimum *distances*. Moreover, studies need to be conducted to examine the impact of dynamic pairwise separations on the strategic planning process of the controller, like e.g. aircraft sequencing. Real time simulations have been conducted by DLR (Gerling, 2008), but did not focus on the single runway system yet. A methodology of a comprehensive risk analysis will enable to adjust all WSVBS components to appropriate and consistent confidence levels. This may enable relaxing the current safety allowances leading to increased periods of time with reduced separations. The WSVBS may also be further developed to provide warning in situations where the routinely applied aircraft separations may not be sufficient in order to further increase safety during approach and landing.

Quantifying delay and capacity impacts on different runway systems, the effect of stochastic demand behavior needs to be introduced. Individual delay already built up before arriving at the respective airport leads to arrival sequences and times, which are not corresponding to scheduled slot times contained in the applied schedules of this work. This yields more realistic benefit quantifications in terms of combining stochastic elements of both, the traffic patterns and the weather behavior. Assuming the functionality to process individual time based separations, fast time simulation tools provide this ability.

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