Assessment of Wake Vortex Encounter Probabilities for Crosswind Departure Scenarios

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I. Introduction

Aircraft generated wake vortices pose a potential risk to following aircraft in various flight phases, whereas most wake vortex encounters are reported for approach and landing and for take-off and climb [1]. The ICAO wake-vortex aircraft separation standards [2] established in the 70's increasingly degrade aviation efficiency when traffic congestion limits airport capacity during landing and take-off.

Research has shown that the transport and persistence of wake vortices are highly dependent on meteorological conditions, so that in many cases the separation standards are over-conservative. For single-runway operations, analyses [3-5] suggest that, above a certain crosswind threshold, vortices are blown out of the flight corridor and pose no further threat to following aircraft. The EU-project CREDOS (Crosswind-Reduced Separations for Departure Operations) [6] intends to demonstrate the operational feasibility of a concept of operations that uses measures of the prevailing crosswind component to allow temporary suspension of the need to apply wake turbulence separations between successive departing aircraft.

The focus on the combination of crosswind and departures has significant advantages: (i) the follower aircraft is still on the ground when the controller schedules the separation. So the controller always has the possibility to extend the separation without requiring the pilot to make a manoeuvre. This beneficial situation also reduces the time horizon for which crosswind conditions must be anticipated. (ii) In contrast to arrival situations the leader aircraft is generally faster so that the actual separations tend to increase.

WakeScene-D (Wake Vortex Scenarios Simulation Package for Departure) [7] is an extension of WakeScene which has been developed for approach and landing and is described in detail in [8]. WakeScene-D estimates the probability to encounter wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation in a domain ranging from the runway to an altitude of 3000 ft above ground. In cases with potential wake encounters all relevant parameters can be provided to VESA (Vortex Encounter Severity Assessment) [9,10] which may subsequently perform detailed investigations of the severity of the encounter. WakeScene-D consists of elements that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area. The process and data flows are controlled and evaluated by the MATLAB-based environment MOPS (Multi Objective Parameter Synthesis) [11]. Within CREDOS WakeScene-D is used (i) to support the definition of suitable crosswind criteria that allow reducing aircraft separations, (ii) to identify critical parameter combinations, and (iii) to support risk analyses taking into account a broad range of variables which determine the probability and risk of a wake vortex encounter.

First, this manuscript briefly describes the operating sequence of WakeScene-D and the employed sub-models. For a detailed description of WakeScene-D including statements of the validation work performed for the employed sub-models and data bases we refer to [7]. Next, a reference scenario is introduced which shall represent the real current departure situation. Then the statistics achieved with reduced aircraft departure separations and different crosswind thresholds are discussed. Finally, the paper highlights a selection of the most interesting results found in the conducted comprehensive sensitivity analyses. The investigated parameters of these sensitivity analyses comprise sample size, aircraft type combination, take-off weight, departure route combination, flight path adherence, wind direction, wake vortex model, and a comparison to the arrival situation. On one hand, these sensitivity analyses help to increase the confidence in the software package and, on the other hand, they allow identifying the parameters that control encounter probabilities during takeoff and departure. In a next step the knowledge of these key parameters may enable the optimisation of CREDOS criteria for reduced aircraft separations.

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II. Survey on Operating Sequence and Employed Sub-Models

The flowchart depicted in **Figure 1** sketches the operating sequence of WakeScene-D. Via simulation control (MOPS) the types of the generator aircraft (A306, A310, A333, A343, B744 and B772) and follower aircraft (A320, AT45, B733 and CRJ), the departure routes (TOBAK2F, BIBOS6F, SOBRA1F, ANEKI5F, DKB2F, see **Figure 2**), and a number of aircraft and pilot parameters are selected. The traffic mix is modelled according to the statistics of Frankfurt airport in 2006 [12]. The Trajectory Model [13] provides time, speed, position, attitude, lift and mass of generator and follower aircraft along the flight paths. Based on vertical profiles of wind speed and direction, air density, virtual potential temperature, turbulent kinetic energy, and eddy dissipation rate (Meteorological Data Base) and aircraft position, speed, attitude, lift, and span (Trajectory Model) at one gate, the Deterministic Two-Phase wake-vortex decay model (D2P, [14,15]) simulates the development of wake vortex trajectories, circulation, vortex core radius, and attitude of wake vortex axes. The employed realistic one-year meteorological data base has been produced for the Frankfurt terminal area with the mesoscale weather-forecast model system NOWVIV (NOwcasting Wake Vortex Impact Variables, [16]). The Simplified Hazard Area Prediction model (SHAPe, [17]) computes the distance between wake vortex and follower aircraft within each gate and may discriminate between potentially critical cases and cases where safe and undisturbed flight is guaranteed. From all these data MOPS [11] computes defined criteria, like minimal distance between wake vortex and follower aircraft and the respective vortex circulation and height, which are interpolated between the gates and statistically analysed. Finally, data needed for further investigations with VESA are deduced and stored. The preselection of cases of interest within WakeScene-D reduces the computing effort for VESA significantly. The results are optionally visualised in graphs of the statistics, 2D and 3D views (see **Figure 4**) or animations of the departures of subsequent aircraft.

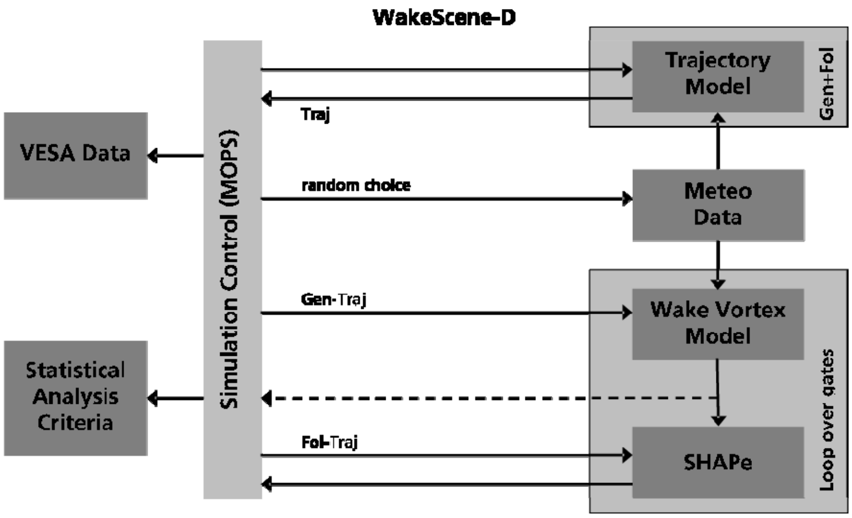

Figure 1: WakeScene-D flowchart. Arrows denote the data flow.

WakeScene-D simulates departures from runway 25R at Frankfurt international airport (see **Figure 2**). The selection of the configuration of the employed sub-models and parameters is always a trade-off between a realistic as possible set-up in order to include all relevant effects and a more generic set-up which enables transferring the results to other airports. In this investigation the aircraft employ the five different Standard Instrument Departure routes (SIDs) displayed in **Figure 2** with equal probability although in praxis the southerly departure routes are only used if strong northerly winds prevent the use of runway 18. Because WakeScene-D considers different standard departure routes also curved flight has to be taken into account. Therefore, wake vortex evolution is predicted within control gates which are released along the flight path of the wake vortex generator aircraft in predefined time increments of 5 s. The gates' orientations are perpendicular to the aircraft true heading and perpendicular to the flight path angle (see [7]).

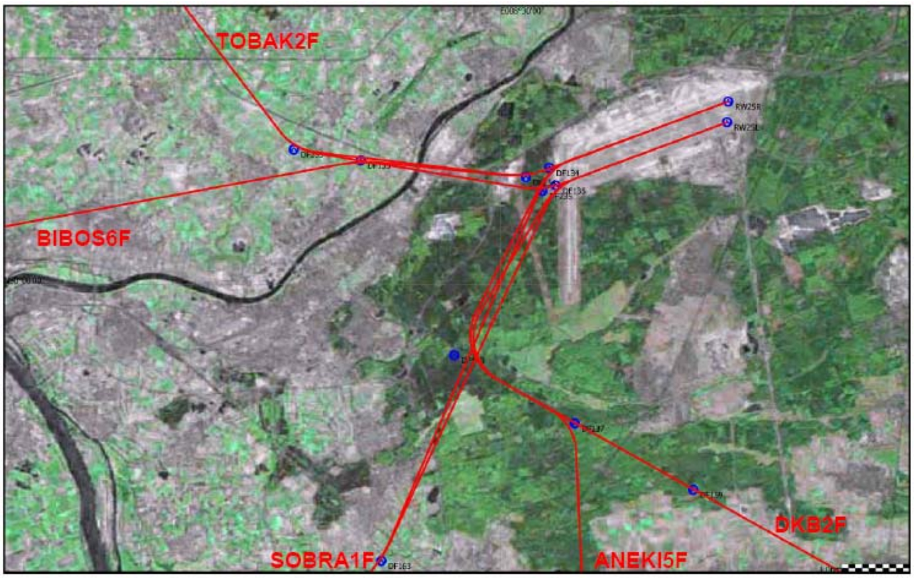

Figure 2: Standard instrument departure routes (SIDS) modelled in WakeScene-D [SeeYou, free software].

III. Reference Scenario

The described scenario serves as a reference which shall represent the real current departure situation. The working hypothesis assumes that the encounter frequencies estimated for reduced separations under appropriate crosswind conditions shall not be higher than in the reference scenario.

The reference scenario employs a sample size of 1,000,000 aircraft pairings. All follower aircraft obey the 120 s ICAO separation. The following parameters of the generator and the follower aircraft are randomly distributed: start point, take-off weight, thrust mode, departure route combination, trajectory deviation, and pilot delay parameter. We employ meteorological data of the NOWVIV one-year data base within the operational hours of Frankfurt airport (6:00 – 23:00). Furthermore, cases with tailwinds above 5 knots are excluded. The constraints regarding operational hours and tailwind are also applied for all other investigated cases.

Figure 3 singles out the fraction of departures (70,167 cases or 7.0%) in which the follower aircraft approach the vortices closer than 50 m and the vortices still have at least a circulation of 100 m^2/s. These cases potentially correspond to an encounter and should be understood as cases of interest or potential encounters. Detailed investigations with VESA are necessary to identify the risks related to such potential encounters. For convenience we call these cases simply encounters without regard to the real connected risks.

Remarkably, 66% of these “encounters” are restricted to heights below 300 ft above ground (see **Figure 3a**). Within this altitude range clearance of the flight corridor by descent and advection of the vortices is restricted: stalling or rebounding vortices may not clear the flight path vertically and weak crosswinds may be compensated by vortex-induced lateral transport [15]. This culmination of vortex encounters at low altitudes indicates that the crosswind criterion sought in CREDOS could possibly be limited to this height range, which would substantially facilitate the implementation of an operational system.

Further, minor peaks at 1300 ft and at 1800 ft occur in **Figure 3a**. These minor peaks can be attributed to flight path changes which increase the encounter risk compared to approximately parallel flight of the leader and follower aircraft. **Figure 4** exemplifies a typical situation: At about 1500 ft the leading aircraft reduces thrust and thus the climb rate; at the same time it initiates a turn towards a southerly direction. The combination of this flight path diversion with a strong headwind component which counteracts the vortex descent and a southerly wind direction leads to the displayed encounter at 1250 ft. The second cluster of encounters at 1800 ft is related to the resumption of climb when the aircraft reach the final climb speed. A number of other combinations of flight path diversions and adverse wind directions have been identified, both for identical and different departure routes of the leader and follower aircraft.

Figure 3b reveals that within the 50 m distance the encounter frequency depends only weakly on the separation between aircraft and wake vortices. **Figure 3c** and **d** indicate a considerable range of vortex ages between 80 s and 150 s corresponding to vortex strengths between 100 and 430 m^2/s. The irregular circulation distribution in **Figure 3d** is mostly related to differing vortex decay characteristics of the different generator

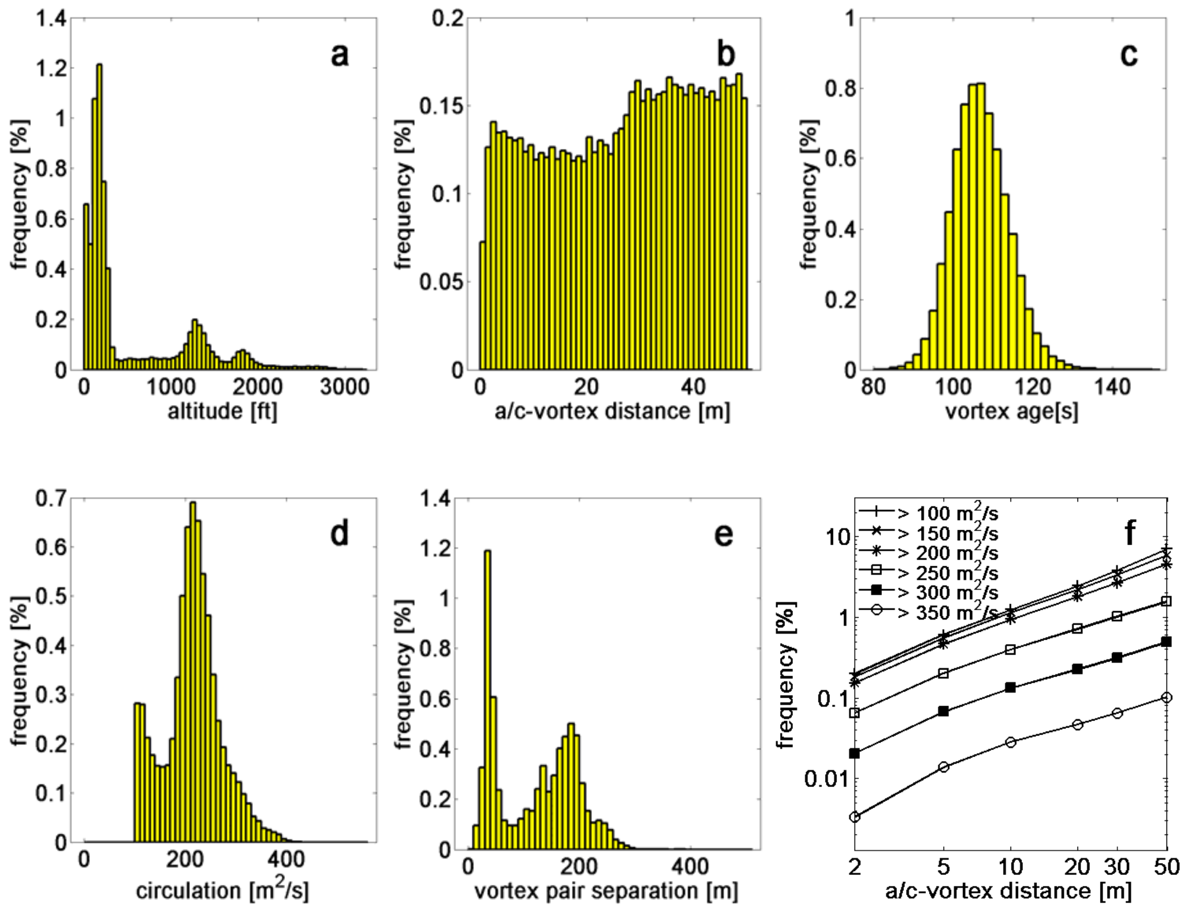

Figure 3: Statistics of the reference scenario where the displayed 70,167 cases meet two criteria: the aircraft approach the vortices closer than 50 m and the vortices still have at least a circulation of 100 m^2/s. a) Aircraft altitude, b) distance between follower aircraft and wake vortex, c) vortex age, d) vortex circulation, e) vortex pair separation, and f) encounter frequency dependent on maximum follower aircraft distance to the vortex and minimum circulation.

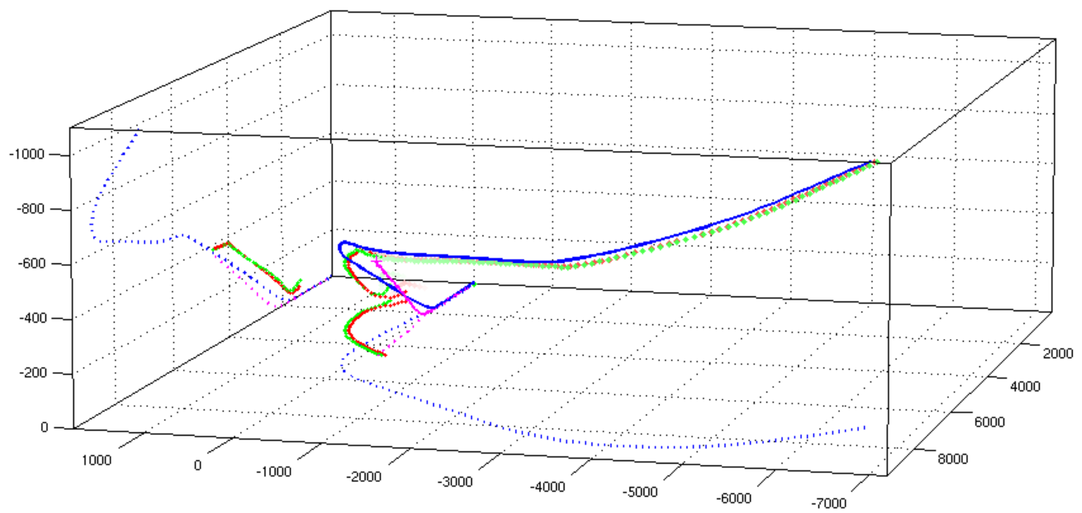

Figure 4: Perspective view of trajectories of wake-generating aircraft (blue) and follower aircraft (magenta) together with wake vortex positions (starboard vortex green, port vortex red). Projections of aircraft and vortex positions on vertical and horizontal planes are added for convenience. Dimensions in meters, not in scale.

aircraft types in combination with different decay rates in ground proximity and aloft. **Figure 3e** illustrates that in 19% of the encounters the vortices still approximately retain their initial vortex spacings ranging from 34.5 m to 50.6 m for the selected vortex generator aircraft types. The cluster of vortex separations beyond 100 m represents the range typically occurring after vortex rebound in ground proximity.

Figure 3f displays encounter frequencies dependent on the distance between the follower aircraft and the vortex and the respective circulation, Γ. The frequency of encounters with $\Gamma > 100$ m^2/s reduces from 7.0% for vortex distances below 50 m to 0.20% for distances below 2 m. For circulations stronger than 350 m^2/s the encounter frequencies are 0.10% for vortex distances below 50 m and reduce to 0.0037% (37 cases of 1,000,000 departures) for distances below 2 m.

The considered range of distances to the vortex and circulation strengths was chosen such that, on one hand, no cases of interest are missed and, on the other hand, the rarest strong encounters are captured. Note that the weakest potential encounters ($\Gamma > 100$ m^2/s, $d < 50$ m) in many cases may not lead to any perceptible interference. On the other hand, close encounters on the order of 2 m to 5 m are almost not feasible because they are impeded by wake vortex induced aircraft reactions. Also other factors like encounter angles, flight attitude and altitude of the follower aircraft are not considered. Therefore, only VESA which fully considers the encounter situation including the interaction of aircraft and wake vortex may really evaluate the related risks. However, VESA investigations are out of the scope of this manuscript and thus the metrics of **Figure 3f** are used to relatively compare the risks of the different scenarios.

IV. Crosswind Dependency

Statistics of encounter frequencies and encounter conditions have been produced for 60 s and 90 s departure separations and minimum crosswinds from 0 to 10 knots in 2 knot increments, respectively. All other parameters correspond to the reference scenario. The crosswind criterion is met when the crosswind at 10 m height above ground exceeds a predefined threshold. This crosswind criterion has been selected because (i) 10 m is the standard height for surface wind measurements and thus constitutes the operationally simplest approach for crosswind dependent reduced separations. (ii) Most encounters are restricted to heights below 300 ft above ground. (iii) An investigation of wind conditions at Frankfurt airport [18] reports a 95%-correlation of the crosswind at 100 m height with the 10 m wind measurement.

Three independent analyses of field measurement data of wake vortices generated by departing aircraft in an altitude range from 0 to 400 m at Frankfurt airport have been performed within the CREDOS project to determine crosswind thresholds which ensure that the wake vortices have left a safety corridor at certain aircraft separations [18-20]. Although the three analyses employ different assumptions on the safety corridor definition and size, the employed confidence levels, and the crosswind measurement sources and definitions, they consistently yield crosswind thresholds on the order of 4 m/s to make sure that the wake vortices have escaped a safety corridor at a vortex age of 60 s with a high probability based on good quality wind measurements. Note that such studies do not allow quantifying the related risks and setting the risks into relation to the current ICAO operations.

The corresponding WakeScene-D results for aircraft separations of 60 s and crosswinds above 8 knots (4.1 m/s) are displayed in **Figure 5**. The overall frequency of encounters of 3.1% (31,239 cases) is clearly below the corresponding frequency of 7.0% of the reference scenario. **Figure 5** shows in agreement with the experimental results that the strong crosswind in ground proximity is outmost effective. The remaining 56 encounters below 300 ft can be almost neglected compared to the corresponding 45,962 encounters in the reference scenario. Now the peak at 1800 ft related to flight path diversions clearly dominates the scenario.

The encounter synopsis in **Figure 5f** indicates that despite of the reduction of the overall encounter frequencies the encounters with circulations stronger than 350 m^2/s are still 2 to 4 times more frequent than in the reference scenario in **Figure 3f**. This can be explained by the halved time for vortex transport and decay. Two facts may potentially reduce the hazard of the current encounters compared to the reference scenario. i) The encounters occur at sufficiently high altitudes to provide ample time for pilots to recover. ii) The encounter angles are increased which could potentially reduce adverse effects for the follower aircraft.

Figure 6 and **Figure 7** depict the so-called encounter angles γ and ψ which denote the inclination angle and the azimuth angle between vortex axis and flight path of the follower aircraft, respectively. Negative inclination angles γ denote situations where the aircraft approach the vortex from below. Negative azimuth angles ψ refer to encounters from the left, i.e. the aircraft hit in general the port vortex.

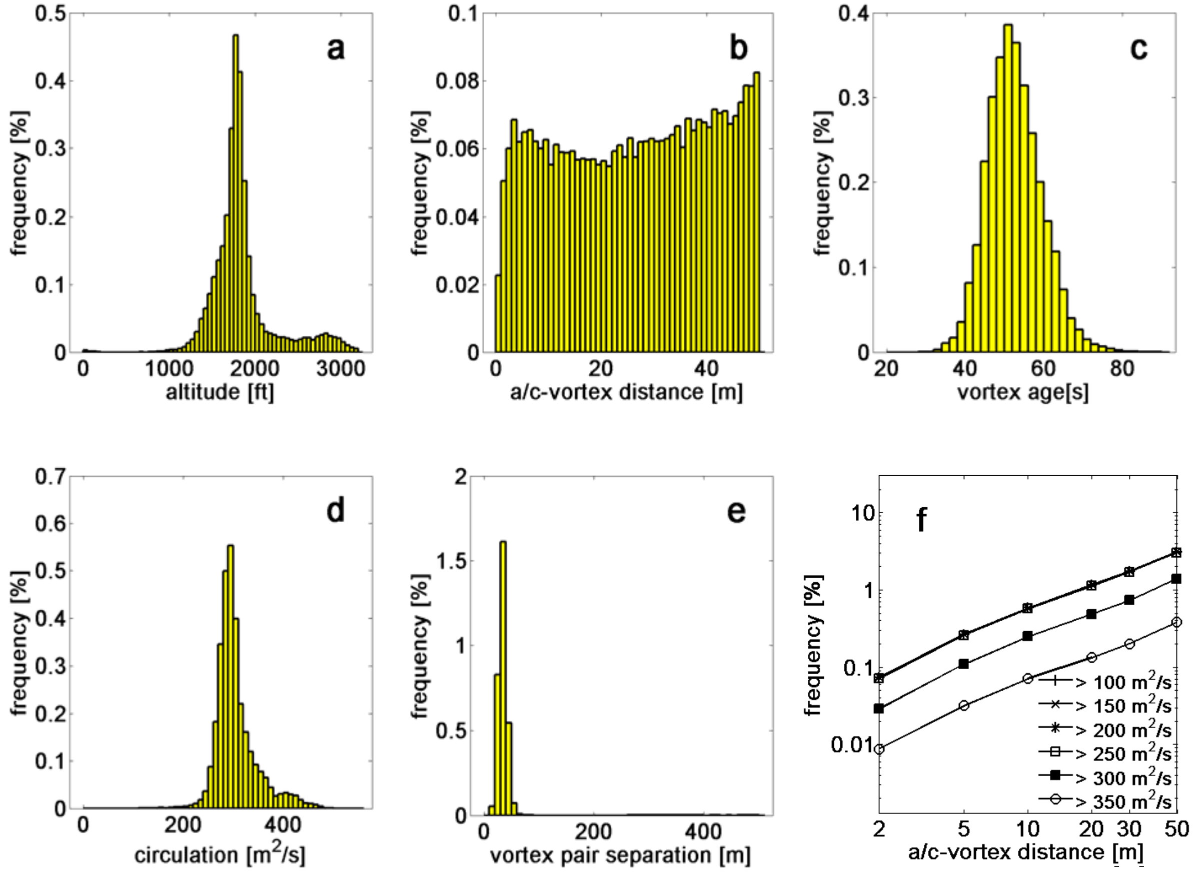

Figure 5: Statistics of 1,000,000 departures for aircraft separations of 60 s and a crosswind threshold of 8 knots from which the displayed 31,239 cases meet two criteria: the aircraft approach the vortices closer than 50 m and the vortices still have at least a circulation of 100 m^2/s. f) encounter frequency dependent on maximum follower aircraft distance to the vortex and minimum circulation.

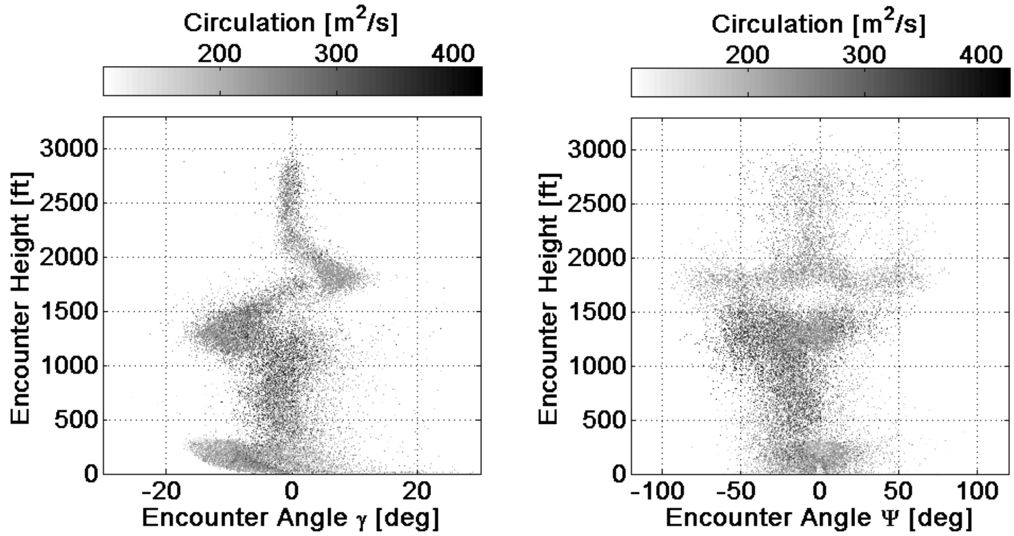

Figure 6: Encounter angles γ (inclination angle) and ψ (azimuth angle) dependent on altitude with grey-scale-coded circulation for the reference scenario.

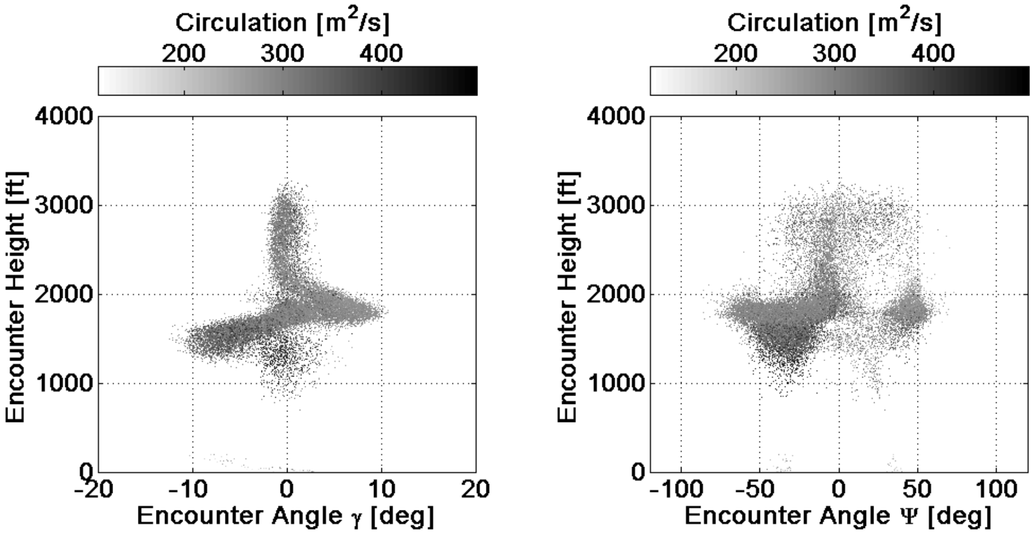

Figure 7: Encounter angles γ (inclination angle) and ψ (azimuth angle) dependent on altitude with grey-scale-coded circulation for 60 s aircraft separations with crosswinds above 8 knots.

Figure 6 shows the encounter angles with grey-scale-coded circulation values for the reference scenario. The predominantly negative inclination angles γ below 300 ft correspond to cases where the aircraft approach the wake vortices from below after the vortex rebound. Due to the ground induced decay the corresponding circulation values are relatively low.

Aloft the inclination angles on average are slightly negative. This can be explained to some extent by the steeper climb rates of the follower aircraft and to some extent by reduced descent rates of aged wake vortices. At about 1500 ft the aircraft reduce the climb rate and start to accelerate. Below that altitude range the aircraft with higher climb rates encounter less inclined vortices (γ < 0, see **Figure 4**). Inversely, positive inclination angles (encounter from above) occur in the altitude range where the follower aircraft with lower climb rates encounter wake vortices which were generated by aircraft which have already resumed climb when they have reached the final climb speed.

The azimuth angles ψ are on average negative. This can probably be attributed to the more frequent south-westerly winds. Crosswinds directed from port to starboard are tilting the vortices in azimuthal direction because the longer residence times of older vortex segments lead to larger transport distances. The turns around 1500 ft and 2000 ft (see **Figure 2**) lead to increased encounter azimuth angles with positive and negative signs depending on the departure route combinations and the wind direction (see **Figure 4**).

Figure 7 shows the encounter angles for 60 s aircraft separations with crosswinds above 8 knots. Now encounters at low altitudes have almost completely disappeared. Most of the remaining encounters are occurring above 1000 ft and can be explained by the flight path changes discussed above.

A remarkable concentration of encounters with strong vortices between 1000 ft and 1700 ft occurs with inclination angles centred on zero and azimuthal angles around 30 deg. These strong encounters mainly occur if the leading aircraft follows a southerly departure route. In these cases the leading aircraft have already initiated a turn without reducing the climb rate and south-westerly winds compensate vortex induced descent.

Table 1 provides a synopsis of the encounter frequencies for the investigated crosswind and departure separation scenarios. The crosswind threshold and aircraft separation combinations where the encounter frequencies are similar to or fall below the reference scenario (highlighted in dark grey) are highlighted in light grey. The total encounter frequency of the reference scenario of 7% is almost doubled when the aircraft separation is reduced by 30 s and it is almost tripled when the aircraft separation is halved from 120 s to 60 s. For crosswinds stronger than 4 knots (6 knots) the total encounter frequency of the 90 s (60 s) aircraft separations is reduced again to almost 50% of the reference scenario. Further increased crosswinds only marginally reduce the encounter frequencies. This can be explained by the fact that for aircraft separations of 60 s (90 s) already for 6 knots (4 knots) crosswind thresholds only less than 3% (1.5%) of the encounters occur below 300 ft. Stronger 10 m crosswinds are not effective in reducing the encounter frequencies at altitudes above 300 ft.

scenario	120 s all CWs	90 s 60 s all CWs	90 s 60 s CW > 2kts	90 s 60 s CW > 4kts	90 s 60 s CW > 6kts	90 s 60 s CW > 8kts	90 s 60 s CW > 10kts
total encounter frequency	7.0%	12.8% 19.9%	7.5% 17.7%	3.7% 8.3%	2.6% 3.8%	2.2% 3.1%	1.9% 2.7%
encounter frequency below 300 ft	4.6%	9.4% 15.8%	2.9% 13.1%	0.057% 3.5%	0.0003% 0.10%	0.0002% 0.0056%	0.0% 0.0044%
worst case encounter frequency	0.0037%	0.023% 0.11%	0.011% 0.056%	0.0073% 0.020%	0.0041% 0.010%	0.0026% 0.0086%	0.0017% 0.0025%

Table 1 Encounter frequencies for different aircraft separations and crosswind scenarios. Encounters correspond to cases where the distance between the follower aircraft and the vortex is smaller than 50 m and the circulation is larger than 100 m^2/s. For worst case encounters the vortex distance is smaller than 2 m and the circulation is larger than 350 m^2/s.

Encounter frequencies at 90 s (60 s) aircraft separation below 300 ft fall below the frequencies of the reference scenario already for crosswinds above 2 knots (4 knots). At 4 knots (6 knots) crosswinds and 90 s (60 s) aircraft separations encounter frequencies are reduced to only about 1.2% (2.2%) of the reference scenario. Another strong reduction to 3 (56) encounters below 300 ft is obtained with crosswinds above 6 knots (8 knots) at the 90 s (60 s) aircraft separations. Further reductions due to increased crosswinds are negligible.

For worst case encounters (vortex distance smaller than 2 m and circulation larger than 350 m^2/s) the frequency is increased by a factor of 6 (30) when the aircraft separation is reduced from 120 s to 90 s (60 s). Encounter frequencies below the reference scenario at 90 s (60 s) aircraft separations are only achieved with crosswinds stronger than 8 knots (10 knots).

In conclusion crosswinds are very effective to reduce encounter frequencies close to the ground already for crosswinds stronger than 4 knots (6 knots) at 90 s (60 s) aircraft separations. As a consequence, the encounters at higher altitudes become more prominent. Due to the reduced time for vortex decay worst case encounter frequencies aloft are not reduced very effectively by increasing crosswinds.

Figure 8 shows encounter frequencies versus crosswind speed in 0.5 knot increments for different aircraft separations. The left plot displays absolute encounter frequencies where the term “all” in the inset denotes the frequencies of the crosswind increments of all simulated departures with or without encounters. For the relative encounter frequencies shown on the right the frequencies of the crosswind situations are normalized.

Figure 8 indicates that the highest encounter frequencies are not observed for zero crosswinds. They occur instead for the reference scenario 120 s and the 90 s departure separations around crosswinds of $\pm$ 1 to $\pm$1.5 knots. If the aircraft separation is reduced to 60 s the most critical crosswinds amount to $\pm$ 2.5 knots. This is due to the fact that weak crosswinds may compensate the vortex-induced lateral propagation speed of wake vortices generated in ground proximity such that the luff vortex is hovering above the runway [15]. For the 60 s separation the critical crosswind magnitude is higher because the crosswind has less time to transport the vortices out of the flight corridor.

Figure 8 right indicates that for the 120 s separation crosswinds above 2.5 knots do not significantly reduce the relative encounter frequencies. For the 90 s separation this is the case above about 4 knots and for the 60 s separation the corresponding threshold is at about 6 knots. Beyond these thresholds the encounters at high altitudes related to flight path diversions constitute the dominant risks.

Somewhat surprisingly the histograms are not symmetric. Note that already at -5 to -5.5 knots the relative encounter frequency for 60 s separations is lower than the encounter frequency for 5 to 5.5 knots for the 120 s reference scenario. Several reasons for the asymmetry can be identified: (i) the realistic meteorological data base contains distributions of wind speed and direction which are not only the result of predominant synoptic patterns but are also influenced by the orography in the vicinity of the airport, in particular the Taunus mountain ridge. (ii) The winds aloft generally deviate from the winds at 10 m altitude and (iii) the departure routes are not symmetric with respect to the runway. (iv) The most important and fundamental effect, however, is related to the turning of the wind direction to the right with increasing height (Ekman Spiral). This effect is described in more detail in section VB.

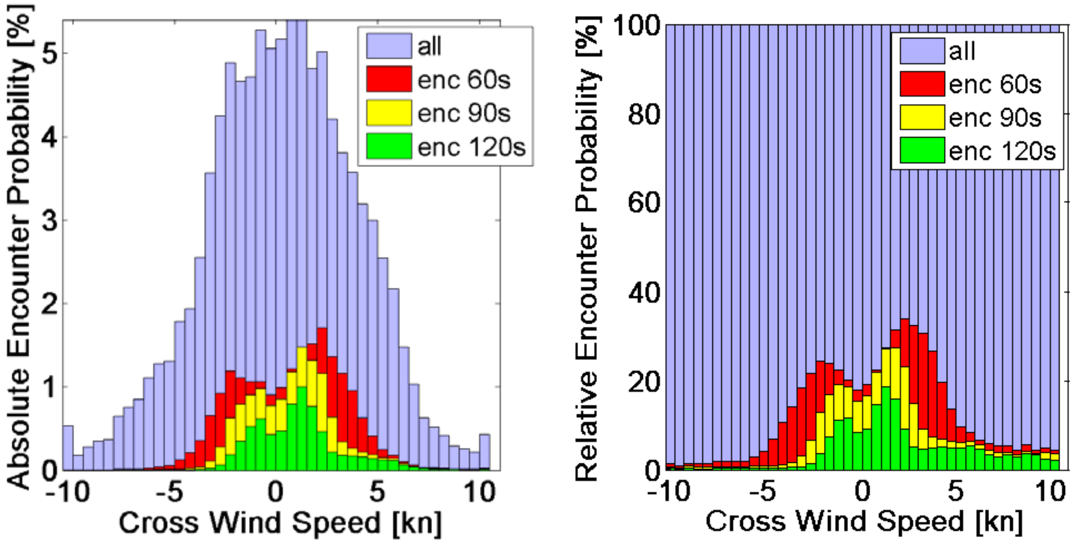

Figure 8: Encounter frequencies (aircraft vortex distance smaller than 50 m and circulation larger than 100 m^2/s) versus crosswind speed in 0.5 knot increments for different aircraft separations. Left: Absolute encounter frequencies where "all" denotes the frequencies of the crosswind increments. Right: Relative encounter frequencies. Winds blowing from the port side are positive.

V. Sensitivity Studies

Comprehensive sensitivity analyses regarding the impact of various sub-models and parameter selections have been performed. First, a selection of the most interesting results is discussed. Then a survey on the key results of the remaining sensitivity studies is provided.

A. Departure Routes

In order to investigate effects of different departure route combinations (see **Figure 2**) the SIDS BIBOS6F and TOBAK2F are combined and termed Northern routes (N). The combination of the Southerly routes ANEKI5F, DKB2F, and SOBRA1F is termed (S). In contrast to the actual use of the SIDs at Frankfurt airport here every SID is used with equal probabilities and the departure route combinations are varied randomly. The SID route combinations NN, NS, SN, and SS are filtered from the calculated scenarios. The respective sample sizes amount to 160,000, 240,000, 240,000, and 360,000 pairings of departing aircraft. Although sample sizes of 160,000 scenarios do not guarantee completely converged results, the observed trends should be sufficiently robust.

For the encounter statistics with crosswinds above 8 knots displayed in **Figure 9** the differences between the SID combinations are quite prominent because the encounters in ground proximity (which are independent from SID combinations) are already quite rare (see **Figure 5**) and many encounters aloft are related to flight path diversions. All encounter frequencies of the NS departure route combination are smaller than in the reference scenario. For the SN SID combination the encounter frequencies are consistently higher. This can be attributed to the more frequent south-westerly winds which transport the vortices from the S to the N routes. As a consequence for the SN SID combination only the close encounters are less frequent than in the reference scenario.

Note that the SS SID combinations feature significantly higher encounter frequencies than the other SID combinations. This again can be explained by the predominant south-westerly winds which are headwinds with respect to the aircraft and which compensate the vortex induced descent speed. The effect may be exacerbated by the resumption of climb when the aircraft reach the final climb speed at about 1800 ft.

The NN SID combination which is used by default at Frankfurt airport features consistently lower encounter frequencies compared to the reference scenario with the sole exception of the frequency of $\Gamma > 350\ m^2/s$ and $d < 2$ m.

As a result for a generic airport the SID combination study indicates that reduced departure separations could be supported by crosswinds above 8 knots which significantly reduce encounter frequencies close to the ground and by using diverging departure route combinations which reduce encounter frequencies at higher altitudes. The procedure could be refined by using only SID combinations where the leading aircraft is flying on the downwind SID.

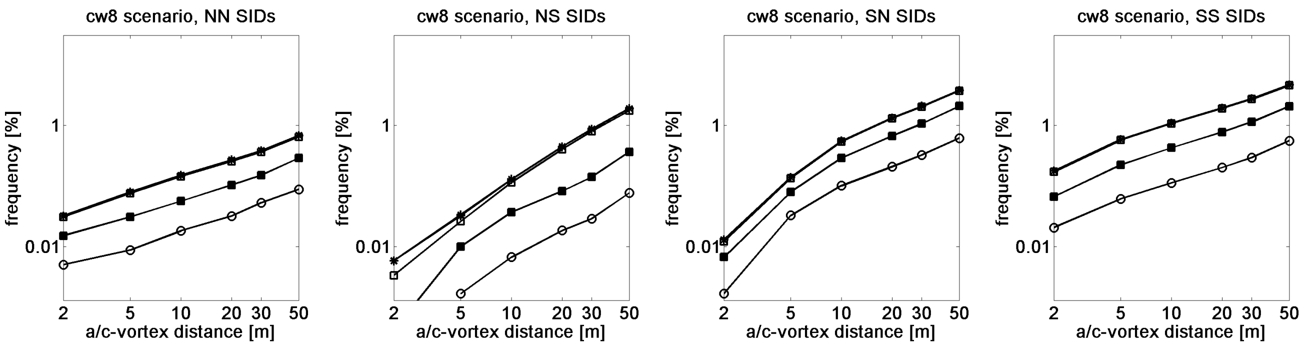

Figure 9: Encounter frequency dependent on follower aircraft distance to the vortex and circulation. Statistics of four different departure route combinations for aircraft separations of 60 s and crosswinds above 8 knots.

B. Wind Directions

This section considers effects of wind directions on the encounter frequencies. Four different wind direction sectors are distinguished: headwind, tailwind, crosswind from port side, and crosswind from starboard side. Here the wind directions are defined with respect to the runway direction. So headwinds are blowing from 315° > RWA > 45° where RWA denotes the relative wind angle with respect to the runway direction. Winds from the starboard side correspond to the wind direction range 45° > RWA > 135°.

SID-comb. wind dir.	all	N-N (16.0 %)	N-S (24.0 %)	S-N (24.0 %)	S-S (36.0 %)
CW port (20.9 %)	5.2%	4.6%	4.3%	5.3%	6.1%
CW starb. (18.9 %)	1.7%	1.6%	1.6%	1.5%	1.9%
tailwind (22.4 %)	2.5%	2.3%	2.1%	2.4%	2.9%
headwind (37.8 %)	13.3%	13.4%	13.3%	13.0%	13.4%

Table 2: Encounter frequencies dependent on four different 90° wind direction sectors for the reference scenario. Wind sector icon assumes a flight direction from right to left.

Table 2 lists the encounter frequencies dependent on the four different wind direction sectors for the reference scenario. Headwind situations lead to the highest encounter probabilities because headwind transport of the wake vortices may compensate wake vortex descent or even lead to rising wake vortices with respect to the generator aircraft trajectory. This effect increases encounter frequencies because the medium weight class followers usually take off earlier than the leader and climb steeper than the leading aircraft and therefore usually fly above the wake vortices. In contrast, the encounter frequencies for tailwind situations are much lower (more than a factor of five), because tailwinds support wake vortex descent.

However, the smallest encounter frequencies are observed for crosswinds from the starboard side. Here the crosswinds close to the ground reduce encounter frequencies. With increasing height the wind direction turns on average to the right (Ekman spiral[2]). Consequentially, a tailwind component is added to the crosswind which supports vortex descent and thus reduces encounter frequencies aloft.

Due to the same mechanism crosswinds from port side receive a headwind component with increasing height. As a consequence, the port crosswind situation leads to three times more encounters than the starboard side crosswinds. Additionally, crosswinds from the port side also support encounters for departures of the leading aircraft on the southerly departure routes. There is also some weak trend that the strongest circulation values occur for the headwind encounters (not shown).

Table 3 lists the wind direction effects for 60 s aircraft separations and crosswinds above 6 knots. Because cases with tailwinds above 5 knots are excluded from operations, the wind sector for tailwinds has no contributions. The encounter frequencies for headwinds and for crosswinds from the port side are now almost identical. Considerable differences occur between the different departure route combinations. Small encounter frequencies are observed for headwinds and crosswinds from the port side (southerly winds) for leading aircraft on the northern departure routes and, conversely, for crosswinds from the starboard (northerly winds) side for leading aircraft on the southern departure routes. Hence, encounters can be avoided if the crosswind after the turn transports the vortices away from the former flight track, i.e. southerly crosswinds are favourable for turns to the north.

The smallest encounter frequencies occur for crosswinds from the starboard side combined with the S-N SID combination. Here two favourable effects are combined: the turning of the crosswind to a tailwind at increasing altitudes and the fact that the vortex generating aircraft uses the downwind departure route. Crosswinds above 8 knots show similar characteristics with further reduced encounter frequencies.

SID-comb. wind dir.	all	N-N (16.0 %)	N-S (24.0 %)	S-N (24.0 %)	S-S (36.0 %)
CW port (38.0 %)	5.5%	1.8%	1.4%	7.7%	8.5%
CW starb. (44.7 %)	1.5%	0.9%	3.5%	0.2%	1.3%
tailwind (0 %)	–	–	–	–	–
headwind (17.2 %)	5.8%	1.6%	2.7%	7.9%	8.3%

Table 3: Encounter frequencies and corresponding circulation strengths dependent on four different 90° wind direction sectors for 60 s aircraft separations and crosswinds above 6 knots. Wind sector icon assumes a flight direction from right to left.

The wind sector definition of 90° used in this section can not be used in combination with the crosswind thresholds used otherwise in this study. Therefore, we also tested the classical crosswind thresholds with a discrimination of the direction of the crosswind. For crosswinds above 6 knots and 8 knots this more practical definition of 180° wind sectors leads to similar encounter frequencies as the 90° definition; i.e. starboard crosswinds lead to fewer encounters than port crosswinds. This simplified definition has the advantage that the crosswind criteria used otherwise can still be used and only the sign of the crosswind direction must be considered. Further, slightly higher periods of use are possible.

[2] Above the atmospheric boundary layer with a thickness on the order of 1 km the wind direction is mainly controlled by the equilibrium of the driving pressure gradient force and the Coriolis force. In the atmospheric boundary layer the friction force causes a deviation of the wind direction to the left (on the northern hemisphere).

C. Key Results of Remaining Studies

Sample size: It must be guaranteed that the sample size of the Monte Carlo simulations is sufficiently large to provide converged simulation results also for rare events. For this purpose statistics of encounter frequencies derived from sample sizes of 10^4, $5{\cdot}10^4$, 10^5, $2{\cdot}10^5$, $5{\cdot}10^5$, and 10^6 departures of aircraft pairings have been analysed for different scenarios. It was found that a reasonable representation of the frequencies of the most critical and rare encounters requires sample sizes of 500,000 departures of aircraft pairings. Therefore, the one million sample size used for the current investigations guarantees well converged statistics.

Flight path adherence: Deviations of the A320 from its nominal flight tracks in vertical and horizontal direction have been determined being on the order of 100 m. Therefore, the sensitivity of encounter frequencies of the standard flight path deviation model has been compared to a version in which these deviations were deactivated. The study indicates that the deactivation of aircraft trajectory deviations only slightly reduces the encounter frequencies.

Wake vortex model: Wake vortex modelling constitutes a very important element of WakeScene-D. Therefore, the statistics achieved with the D2P wake vortex model have been compared to results of the Deterministic Vortex Model (DVM) [21]. The two wake vortex models deliver very similar characteristics of encounter altitude, the distance between follower aircraft and wake vortex, and vortex age. The circulation distributions exhibit different characteristics but almost identical ranges. In ground proximity the D2P model predicts more pronounced vortex spreading. For the statistics of encounter strength and distance between aircraft and vortex similar characteristics are found. The corresponding deviations are naturally more pronounced for the rare encounters and reside typically within a range of 5% to 30%. Because the encounter frequencies of equal strength vary between the different scenarios by up to almost two orders of magnitude, the agreement between the encounter statistics of the two wake vortex models is considered as good. In particular, the conclusions derived from the synopsis of the encounter frequencies in **Table 1** would be identical with the DVM wake vortex predictions.

Aircraft type combinations: The encounter frequencies of the considered scenarios have been filtered to attribute the encounters to the 24 possible leader/follower combinations. As expected encounters are avoided if the leading aircraft take off late and climb slowly whereas the follower aircraft take off early with a steep climb rate. Thereby, the respective flight tracks are well separated. In contrast, if the leading aircraft take off early and climb steeply whereas the follower aircraft take off relatively late, the resulting flight tracks may be close to each other leading to high encounter probabilities.

Take-off weight: The general observation "if the leading aircraft take off early and climb steeply whereas the follower aircraft take off late and climb slowly, the resulting flight tracks may be close to each other leading to high encounter probabilities" is not only true for aircraft type combinations. It also applies to the take-off-weight distributions (which correlate with take-off positions and climb rates) within specific aircraft type combinations.

Comparison to arrival situation: The comparison of the current reference scenario (see **Figure 3f**) to WakeScene results for arrivals obeying the ICAO minimum separation of 5 NM between heavy and medium aircraft in [7] indicates that encounters ($\Gamma > 100$ m^2/s and distances to the vortices below 30 m) are 5.6 times more frequent for arrivals (21.5%) than for departures (3.8%). For approaches the accumulation of encounters within a height range below 300 ft is with about 95% even more pronounced. The reason for these differences can mainly be attributed to the much more pronounced spreading of aircraft trajectories for the departure situation which is caused by e.g. large variations of rotation point and climb rate. Note that the considered departure and arrival scenarios can not be directly compared due to differences regarding sample size and traffic mix. So the comparison rather allows deriving general trends but does not allow for precise comparison.

VI. Conclusions

WakeScene-D is a software package to determine wake vortex encounter probabilities for departures. The severity of encounters identified by WakeScene-D can subsequently be evaluated with VESA (Vortex Encounter Severity Assessment) [9,10]. In this manuscript first the components of WakeScene-D which model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area are briefly described. Then applications of WakeScene-D are discussed which shall support the identification of suitable crosswind criteria that allow reducing aircraft separations for departures.

Monte Carlo simulations of the Frankfurt traffic mix with a sample size of 1,000,000 cases indicate that for current operations 66% of the potential encounters are restricted to heights below 300 ft above ground. Within this altitude range clearance of the flight corridor by descent and advection of the vortices is restricted: stalling or rebounding vortices may not clear the flight path vertically and weak crosswinds may be compensated by vortex-induced lateral transport [15]. Further, minor peaks at altitudes of 1300 ft and at 1800 ft occur which can be attributed to flight path diversions (change of climb rate and heading) in combination with adverse wind conditions (headwind and crosswind) which increase the encounter risk compared to approximately parallel flight of the leader and follower aircraft. For example, increased encounter frequencies are observed when the leading aircraft conducts a turn towards the main wind direction. The resulting headwind component may compensate wake vortex descent and may advect the vortex trail into the flight path of the follower aircraft.

Statistics of encounter frequencies and encounter conditions have been established for 60 s and 90 s departure separations and minimum crosswinds from 0 to 10 knots in 2 knot increments, respectively. The reduction of aircraft separations from 120 s to 60 s approximately triples the number of encounters, whereas the fraction of strong encounters increases due to the reduced time for vortex decay.

If aircraft separations are reduced from 120 s to 60 s and crosswinds at 10 m height above ground exceed a threshold of 8 knots, the overall frequency of potential encounters of 3.1% clearly is falling below the corresponding frequency of 7.0% of the reference scenario. The strong crosswind in ground proximity very efficiently reduces the encounters below 300 ft to 0.0056%. Unfortunately, the crosswind is not beneficial for encounters which are related to flight path diversions along the departure routes. Due to the by 50% reduced time for vortex transport and decay, encounters with circulations stronger than 350 m^2/s are still 2 to 4 times more frequent than in the reference scenario.

In this study the aircraft employ five different Standard Instrument Departure routes (SIDs) with equal probability although in Frankfurt operations the southerly departure routes are only used if strong northerly winds prevent the use of runway 18. For the 60 s departure separations and the 8 knots crosswind threshold the northerly departure routes used by default at Frankfurt airport feature consistently lower encounter frequencies compared to the reference scenario with a single exception.

As a result for a generic airport the SID combination study indicates that reduced departure separations could be supported by crosswinds above 8 knots which significantly reduce encounter frequencies close to the ground and by using diverging departure route combinations which reduce encounter risks at higher altitudes. The procedure could be refined by using only SID combinations where the leading aircraft is flying on the downwind SID.

An investigation of wind direction effects on the encounter frequencies reveals an intriguing phenomenon: Headwind situations lead to the highest encounter probabilities because headwind transport of the wake vortices may compensate wake vortex descent or even lead to rising wake vortices with respect to the generator aircraft trajectory. This effect increases encounter frequencies because the medium weight class followers usually take off earlier than the leader and climb steeper than the leading aircraft and therefore usually fly above the wake vortices. In contrast, the encounter frequencies for tailwind situations are much lower because tailwinds support wake vortex descent.

However, the beneficial effects of crosswinds are not symmetric. The smallest encounter frequencies are observed for crosswinds from the starboard side. Here the crosswinds close to the ground reduce encounter frequencies. With increasing height the wind direction turns on average to the right. Consequentially, a tailwind component is added to the crosswind which supports relative vortex descent and thus reduces encounter frequencies aloft. This turning of the wind direction with height is related to the concept of the Ekman spiral which describes the resulting wind direction in the atmospheric boundary layer by equilibrium of the driving pressure gradient force, the Coriolis force, and the friction force.

Due to the same mechanism crosswinds from port side receive a headwind component with increasing height. As a consequence, the port crosswind situation leads to significantly more encounters than the starboard side crosswinds. This crosswind direction sensitivity suggests establishing separate crosswind thresholds for crosswinds from left and right side of the runway.

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References

[1] "Wake Vortex Research Needs for Improved Wake Vortex Separation Ruling and Reduced Wake Signatures", Final Report of the Thematik Network 'WakeNet2-Europe', 6th Framework Programme, National Aerospace Laboratory, NLR-CR-2006-171, Amsterdam, Mar. 2006.

[2] ICAO, Procedures for Air Navigation Services - Air Traffic Management, Doc 4444, ATM/501, 2001.

[3] de Bruin, A.C., Speijker, L.J.P., Moet, H., Krag, B., Luckner, R., and Mason, S., "S-Wake – Assessment of Wake Vortex Safety," Publishable Summary Report, National Aerospace Laboratory, NLR-TP-2003-243, Amsterdam, 2003.

[4] Frech, M., and Zinner, T., "Concept of Wake Vortex Behavior Classes," *Journal of Aircraft*, Vol. 41, No. 3, 2004, pp. 564–570.

[5] Frech, M., and Holzäpfel, F., "Skill of an Aircraft Wake-Vortex Model Using Weather Prediction and Observation," *Journal of Aircraft*, Vol. 45, No. 2, 2008, pp. 461-470.

[6] CREDOS, www.eurocontrol.int/eec/credos/

[7] Holzäpfel F., Kladetzke J., Amelsberg S., Lenz H., Schwarz C., De Visscher I., "Aircraft Wake Vortex Scenarios Simulation Package for Takeoff and Departure," *Journal of Aircraft*, Vol. 46, No. 2, 2009, pp. 713–717, also AIAA Paper 2008-8921.

[8] Holzäpfel, F., Frech, M., Gerz, T., Tafferner, A., Hahn, K.-U., Schwarz, C., Joos, H.-D., Korn, B., Lenz, H., Luckner, R., and Höhne, G., "Aircraft Wake Vortex Scenarios Simulation Package - WakeScene," *Aerospace Science and Technology*, Vol. 13, No. 1, 2009, pp. 1-11, doi:10.1016/j.ast.2007.09.008.

[9] Höhne, G., Luckner, R., and Fuhrmann, M., "Critical Wake Vortex Encounter Scenarios,"*Aerospace Science and Technology*, Vol. 8, No. 8, 2004, pp. 689-701.

[10] Luckner, R., Höhne, G., Fuhrmann, M., "Hazard criteria for wake vortex encounters during approach," *Aerospace Science and Technology*, Vol. 8, No. 8, 2004, pp. 673-687.

[11] Joos, H.-D., Bals, J., Looye, G., Schnepper, K., and Varga, A., "A multi-objective optimisation based software environment for control systems design," Proceedings of 2002 IEEE International Conference on Control Applications and International Symposium on Computer Aided Control Systems Design, CCA/CACSD, Glasgow, Scotland, U.K., 2002.

[12] Anon., „Frankfurt Airport Luftverkehrsstatistik 2006," Fraport AG, Frankfurt am Main, Germany, 2007.

[13] Amelsberg, S., and Luckner, R., "Parametric Aircraft Trajectory Model for Takeoff and Departure," 1st CEAS European Air and Space Conference, CEAS-2007-273, Berlin, Germany, Sept. 2007, pp. 785-795.

[14] Holzäpfel, F., "Probabilistic Two-Phase Wake Vortex Decay and Transport Model," *Journal of Aircraft*, Vol. 40, No. 2, 2003, pp. 323-331.

[15] Holzäpfel, F., and Steen, M., "Aircraft Wake-Vortex Evolution in Ground Proximity: Analysis and Parameterization," *AIAA Journal*, Vol. 45, No. 1, 2007, pp. 218- 227.

[16] Frech, M., Holzäpfel, F., Tafferner, A., and Gerz, T., "High-Resolution Weather Data Base for the Terminal Area of Frankfurt Airport," *Journal of Applied Meteorology and Climatology*, Vol. 46, No. 11, 2007, pp. 1913-1932.

[17] Schwarz, C.W., and Hahn, K.-U., "Full-flight simulator study for wake vortex hazard area investigation," *Aerospace Science and Technology*, Vol. 10, No. 2, 2006, pp. 136-143.

[18] Dengler K., Wiegele A., "EDDF-1 Data Collection Campaign Report," CREDOS, D2-1, 25 November 2008, 51 pages.

[19] De Visscher, I., L. Bricteux, S. Karampelas, G. Winckelmans, F. Holzäpfel, R. Baumann, Y. Roblin, K. Schröder, "EDDF-2 database analysis and performance assessment of the Wake Vortex Models on the EDDF-1 and EDDF-2 databases," CREDOS D2-5, 2009.

[20] Konopka J., Fischer H., "EDDF-2 Data Collection Campaign Report," CREDOS, D2-4, 30 April 2008, 58 pages.

[21] Winckelmans G., Duquesne T., Treve V., Desenfans O., and Bricteux L., "Summary description of the models used in the Vortex Forecast System (VFS)," Univ. Catholique de Louvain, Louvain-la Neuve, Belgium, Apr. 2005.