Abstract:
The present document contains the final report of CREDOS work package 3 "Risk Modelling & Risk Assessment" summarizing the main results from the different tasks and giving an overview on the produced documentation.

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Executive summary

In the CREDOS project the feasibility of a concept for reduced wake-turbulence related separations on departure under crosswind conditions was investigated. The project work was divided into five work packages (WP). The aim of CREDOS WP 3 titled “Risk Modelling & Risk Assessment” was to provide a simulation environment for the assessment of wake vortex hazard under different crosswind conditions and apply it to the departure situation used in the CREDOS concept. The simulation environment should address the probability of a wake encounter as well as the severity of it. A risk analysis consisting of suitable simulation scenarios should support the definition of safe reduced separation distances for crosswind departures.

All tasks in WP3 were successfully finished within the duration of the project. In sub-WP 3.1 the necessary additional models were developed, while in sub-WP 3.2 several weather scenarios were simulated that allowed discovering different effects of wind on wake encounter risk during departure and giving an indication of the crosswind needed to allow safe reduced spacing.

A trajectory generation model has been developed to generate realistic distributions of departing aircraft's flight paths for Monte Carlo simulations using the tool WakeScene-D. This trajectory model has been validated with aircraft track data delivered by DFS during the project. Piloted simulator tests of wake vortex encounters in two flight simulators were conducted with a number of licensed commercial pilots to gain experience about wake encounters during departure. Those tests generated a large database of simulated wake encounters flown with an A320 and an A330 flight simulator during departure that can be exploited for model development and validation. The data was used within CREDOS for development and validation of a pilot behaviour model for wake encounters during departure based on a Neural Net architecture and advanced severity criteria for assessment of the severity of wake encounters.

These additional models were integrated into the two simulation tools WakeScene and VESA providing a powerful simulation platform for risk assessment of wake encounters during take-off and departure. The new versions of these tools are referred to as WakeScene-D and VESA-D. They allow determining how many encounters are likely to happen in a certain scenario and how severe they are for the encountering aircraft. Relative assessments were made between a reference scenario and defined reduced separation scenarios.

Operational scenarios have been defined in WP 3 with input by the partners from other work packages
to determine the simulation scenarios that needed to be assessed. The wake encounter probability and severity was then computed using WakeScene-D and VESA-D. Extensive analyses have been conducted on the simulation results regarding the influence of parameters like wind direction and magnitude or aircraft routing on encounter frequency and severity.

The analyses revealed a significant effect of the veering of the wind with altitude, the so-called Ekman spiral, on encounter risk. This leads to the fact that crosswinds coming from the left of the departure runway on the ground generally lead to higher encounter probability above a certain altitude than crosswinds coming from the right (valid on the northern hemisphere). Furthermore, the simulations have shown that the routing of the aircraft in the departure corridor has a significant impact on wake encounter risk. Depending on how the departure routes are layed out, a crosswind with respect to the runway can become a headwind after a turn, increasing encounter probability, or it can transport vortices from one route into a neighboring one.

All results however indicate that for a scenario with straight-out departure routes a crosswind of 8 kt is needed to sufficiently reduce wake encounter risk when reducing the departure spacing between Heavy and Medium type aircraft from 120s to 60s. For a realistic departure route layout additional constraints are needed. For the Frankfurt example used in the simulations a crosswind of 6-8 kt could be sufficient if it is made sure it is coming from the right of the runway. Alternatively a restriction to using only the northerly departure routes would have a similar effect than departing straight-out, allowing a crosswind threshold of 8 kt as well.
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A Work Package 3 Deliverable Overview
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<th>Description</th>
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<td>BADA</td>
<td>Base of Aircraft Data</td>
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<tr>
<td>CREDOS</td>
<td>Crosswind Reduced Separations for Departure Operations</td>
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<td>CW</td>
<td>Crosswind</td>
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<td>D2P</td>
<td>Deterministic 2-Phase wake vortex decay and transport model</td>
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<td>DFS</td>
<td>Deutsche Flugsicherung</td>
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<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)</td>
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<td>DVM</td>
<td>Deterministic Wake Vortex Model</td>
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<td>FAA</td>
<td>Federal Aviation Administration</td>
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<td>MOPS</td>
<td>Multi-Objective Parameter Synthesis</td>
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<td>MTOW</td>
<td>Maximum Take-Off Weight</td>
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<td>NOWVIV</td>
<td>Nowcasting Wake Vortex Influence Variables</td>
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<td>SC</td>
<td>Severity Criterion value</td>
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<td>Simplified Hazard Area Prediction model</td>
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<td>SID</td>
<td>Standard Instrument Departure</td>
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<td>TOGA</td>
<td>Take-Off/Go-Around</td>
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<td>UCL</td>
<td>Université Catholique de Louvain</td>
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<td>VESA-D</td>
<td>Vortex Encounter Severity Assessment for Departures</td>
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Chapter 1

Introduction

In the CREDOS project the feasibility of a concept for reduced wake-turbulence related separations on departure under crosswind conditions was investigated. The work was performed in five work packages (WP). This document summarizes the achievements made in CREDOS WP 3 titled "Risk Modelling & Risk Assessment". The aim of WP 3 was to provide a simulation environment for the assessment of wake vortex hazard under different crosswind conditions that can be used for risk assessment underlying the safety case of the CREDOS concept and apply it to the departure situation. The work package was organized in two phases. The first phase of the work package was concerned with updating the existing simulation models to cover the departure situation. In the second phase operational scenarios were defined representing the full range of situations and the upgraded simulation tools were used to determine the quantitative risk associated with different separation minima. This was leading to recommendations for the separations to be used under certain crosswind strengths.

WP 3 used inputs from WP 2, mainly in form of updated and validated wake vortex behaviour models to simulate wake evolution and decay in and out of ground effect. Analysis in WP 2 of the wake and weather measurements acquired during the project delivered a first indication of the required crosswind when reducing departure spacing. These should be confirmed by the risk assessment done in WP 3. The conducted risk assessment provided safety arguments to WP 4 to support the Safety Case for the CREDOS concept. Additionally, recorded data from the piloted simulator tests performed in subtask 3.1.5 were delivered to WP 2 for validation of the WAVENDA algorithm.

The main results of the subtasks in WP 3 are compiled in the following. Most of the subtasks produced a report on their work that is referenced in the corresponding section and summarized in App. A which also contains the responsible partner for each document. The work done in each subtask is covered in detail in these reports. Additional to these several publications external to the project have been prepared. At the time of writing this report these are references [5], [6], [14], [15] and [16].
The project partners involved in WP 3 were DLR, TU Berlin, UCL and Airbus. Valuable inputs helping in the definition of the scenarios to be assessed in the risk assessment have been provided by Eurocontrol, FAA and NLR. Data for validation of the trajectory model developed in subtask 3.1.1 was provided by DFS.
Chapter 2

Summary of main results

The following sections summarize the main results of the different subtasks of WP 3. The detailed results of each of these subtasks can be found in associated deliverables that are referenced in the sections. A complete overview over all deliverables produced in the work package with a mapping to the associated tasks is given in App. A.

2.1 Subtask 3.1.1 - Development of aircraft trajectory models for take-off and departure

Subtask 3.1.1 was concerned with developing an aircraft trajectory model able to generate realistic tracks of departing aircraft to be included in the WakeScene-D simulation environment for Monte Carlo simulations. For this purpose real measured departure tracks from Frankfurt airport were analysed and a 3-degree-of-freedom point-mass model was developed.

The aircraft trajectories are modelled for departure, beginning on the runway along a standard departure route until approx. 3000 ft above ground level. Many environment and aircraft specific parameters influence an aircraft trajectory. The model can simulate sensitivities depending on parameters of main influence. These factors can be varied in between defined boundaries with given probability distributions in Monte Carlo simulations to generate a set of trajectories for different aircraft types and departure conditions. To describe an aircraft trajectory, in contrast to the full aircraft dynamics, a point-mass model for the three translational degrees of freedom of the aircraft rigid body motion is sufficient (3 degrees-of-freedom).

Fig. 2.1 shows the submodels of the trajectory model developed in subtask 3.1.1. The pilot model included is a simplified modelling of real pilot behaviour, split into thrust, azimuth and altitude control to follow the desired flight path. The aircraft database used to obtain aircraft performance parameters that are necessary for the model is the Eurocontrol BADA database, version 3.6 [8]. For environmental parameters the NOWVIV database generated by DLR is used [9]. The definitions of the departure
routes are taken from the Jeppesen Navigation Database [17].

The parameters that can be varied as inputs to the trajectory model are the departure SID route, the weather data file from the NOWVIV database, the aircraft type, weight and thrust mode (TOGA or Flex), start point on the runway and random deviations from the nominal route in lateral and longitudinal direction.

For validation of the model extensive real-life position and performance data of departing aircraft at Frankfurt International airport has been provided by DFS. In total data of about 20,000 departures was available, including several different Heavy and Medium aircraft types. Validation of the model was performed for the most frequent aircraft types in the dataset, in particular for the A320, A330-300, A340-300, A300-600, B747-400 and B737-300. Figures 2.2 and 2.3 show an example result of the validation of the trajectory model with respect to the recorded data.

For the complete documentation of the model and its validation see [1], excerpts have been published in [6].
2.2 Subtask 3.1.2 - Airspace simulation for take-off and departure

Subtask 3.1.2 was to extend the airspace simulation tool WakeScene to also cover departures. The corresponding version of the tool is named WakeScene-D (described also in [15] and [16]). The package consists of modules that model the traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution and potential hazard area. It supports the definition of suitable crosswind criteria that allow reducing aircraft separations, enable to identify critical parameter combinations and allow performing risk analyses taking into account a broad range of variables which determine the probability and risk of a wake vortex encounter. WakeScene-D estimates the probability to encounter wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation. The severity of the identified encounters can then be evaluated with VESA-D (Vortex Encounter Severity Assessment for Departure), which has been developed within subtask 3.1.8 in parallel.

WakeScene-D incorporates the trajectory model developed earlier in subtask 3.1.1 and uses the same NOWVIV weather database to simulate realistic wind and weather conditions for the prediction of wake vortex behaviour. Two wake vortex prediction models are included, the Deterministic Two-Phase wake vortex and transport model D2P by DLR and the Deterministic Wake Vortex Model DVM by UCL. For identification of wake encounters the Simplified Hazard Area Prediction model SHAPe by DLR is included as well [10, 11].

Adaptations of the simulation platform included the orientation of the computational gates for simulation of the wake vortex behaviour, which now also account for turns and for the climb angle of the departing aircraft (Fig. 2.4). Furthermore the bank angle of the aircraft during turns (modelled also in the trajectory model from subtask 3.1.1) is taken into account in the wake vortex evolution models. The wake vortex prediction models have been adapted to account for the tilted gates during departure.

Figure 2.4: Simulated airspace with computational gates in WakeScene-D

The hazard areas used in the Simplified Hazard Area Prediction model SHAPe that is used to determine potential encounters have been adapted to the departure situation by comparing it to the approach case for which SHAPe is validated. A specific validation of SHAPe for departure has how-
ever not been performed in CREDOS.

WakeScene-D was used for large-scale fast-time simulations under variation of several input parameters influencing the aircraft tracks, meteorological situation and wake vortex behaviour (Fig. 2.5). It also provides extensive statistical analysis tools via the software environment MOPS also developed by DLR [18]. An example of an evaluation result from WakeScene-D showing frequencies of relevant wake encounter parameters is contained in Fig. 2.6.

The adaptation work performed in subtask 3.1.2 is described completely in [12].

Figure 2.5: Simulated aircraft trajectories with wake evolution using WakeScene-D

Figure 2.6: Example of statistics derived from Monte Carlo simulations in WakeScene-D: cases with potential encounter situations for the reference scenario.
2.3 Subtask 3.1.3 - Definition of relevant scenarios

In subtask 3.1.3 possible relevant scenarios for the assessment in flight simulator tests were identified regarding the air traffic scenarios, aircraft combinations and meteorological conditions. For wake vortex encounters during takeoff the parameters of influence were identified and offline wake vortex encounter simulations were performed to derive tendencies for the impact of different parameters.

A survey on the aircraft traffic mixes, the departure route layouts and departure altitude profiles has been performed. Data was taken from the EuroBen study as well as readily available navigation data. Based on the traffic mix and basic aircraft parameters the most relevant aircraft pairings have been identified, which have been taken into account in the WP 3 encounter risk assessment (see Fig. 2.7).

Furthermore a simple wake vortex encounter parameter study has been done to identify the likely main influence parameters on wake encounter severity during departure. Results are similar to earlier investigations during approach.

For the complete report see [21].

Figure 2.7: Wing span vs. MTOW for representative Heavy and Medium class aircraft selected for assessment
2.4 Subtask 3.1.4/3.1.5 - Piloted simulator tests

Subtasks 3.1.4 and 3.1.5 were concerned with preparation and realization of piloted simulator tests of wake encounters during take-off. Subtask 3.1.4 was the preparation of these tests in two simulators, a certified A330 training simulator operated by the Zentrum für Flugsimulation Berlin (ZFB), and an A320 development simulator (THOR) at Airbus in Hamburg (see Fig. 2.8).

The preparation included the adaptation of simulator software to generate wake encounters during the take-off phase, the setup of a test procedure and determination of suitable test cases. Pilot questionnaires used to capture the pilots subjective hazard rating of each encounter were developed for the tests. The three-dimensional wake vortex velocity flow fields provided by UCL's DVM model were integrated into the simulator software as well. However they were finally not used in the actual piloted tests, as a simpler wake vortex representation was chosen.

Subtask 3.1.5 was the actual performance of the tests with several licensed airline pilots in both simulators. The simulations were conducted by placing a wake vortex pair of varying circulation, span and orientation in front of the departing aircraft (Fig. 2.9), invisible to the pilots. The reaction of the pilot in countering the sudden reaction of the aircraft to the wake was recorded for each departure flown. Additional to that the pilots gave their subjective severity rating for each wake encounter in a specific questionnaire.

In total 576 wake encounters have been flown with 14 different pilots in the A320 simulator and 691 encounters with 11 different pilots in the A330 simulator, producing an extensive database of piloted wake encounter simulations during departure for subsequent model development and validation (see ch. 2.5 and 2.6). Some sample data recorded during the tests was delivered to NLR for validation of the Wake Vortex Encounter Detection Algorithm WAVENDA within WP 2.
2.5 Subtask 3.1.6 - Development of WVE severity criteria

In subtask 3.1.6 advanced severity criteria were developed to be applied to encounters during take-off and departure. The approach is based on a multi-parameter criterion proposed in [22] that was adapted and modified for wake encounters. Four envelopes were defined combining two dynamic aircraft parameters respectively which are typical to a specific safety hazard. These four envelopes are:

- Aircraft Attitude Envelope (AAE), taking into account bank and pitch angle attitude
- Cabin Acceleration Envelope (CAE), taking into account the maximum lateral and vertical accelerations in the cabin
- Attitude Control Envelope (ACE), taking into account the necessary control inputs (side stick roll and pitch) to recover the aircraft with respect to the actual aircraft motion in the corresponding axis
- Air Flow Envelope (AFE), taking into account the angle of attack and sideslip

Limits have been defined to distinguish normal operation from non-normal operation. The general shape of the envelopes is shown in Fig. 2.10.
For each parameter a “green” boundary has been determined within which normal operation can be assumed, and a “red” boundary beyond which the situation is regarded as unacceptable, with a transition region in between. A visualization of each encounter is possible by plotting the time histories of the corresponding parameters into the envelopes, which shows if one of the boundaries is violated during the encounter (see Fig. 2.11). To quantify the severity, a value is computed for each envelope ranging between 0 below the green limit and 1 at or above the red limit. These are added up to give the final Severity Criterion value $SC$, which is also limited to 1. This takes into account that either a strong excursion in only one of the envelopes or a moderate excursion in several envelopes at the same time can present a hazard to the encountering aircraft.

The criteria were validated with the data recorded during the simulator tests in subtask 3.1.5. The six Hazard Rating categories defined in the questionnaire used during the piloted simulator tests were compared to the model rating category applied to the same recorded wake encounters. Here model rating category 1 corresponds to a criterion value of $SC = 0$, category 2 corresponds to $0 < SC < 1$ and category 3 corresponds to $SC = 1$. The validation plot in Fig. 2.12 shows a correct prediction rate of $p = 45.7\%$ (green) while only $p = 7.5\%$ of encounters are predicted wrongly by the model (red), where wrong is defined as predicted too low or more then one category too high by the model. Conservative predictions of one category too high are accepted as the pilots can usually not judge all the parameters taken into account in the model and thus are assumed to underestimate the hazard on average. On average the ratings of the severity criteria model are conservative.

This severity criterion model has been implemented in the VESA-D simulation platform to assess wake encounter risk developed in subtask 3.1.8. The complete development and validation of the severity criterion model is described in [4].
2.5 Subtask 3.1.6 - Development of WVE severity criteria

Figure 2.11: Example of severity rating for one encounter

Figure 2.12: Prediction quality of severity criterion with respect to pilot ratings
2.6 Subtask 3.1.7 - Development of a pilot model for take-off and departure

In subtask 3.1.7 a pilot model was developed that is able to handle the take-off and additionally recover from wake encounters during take-off. It was developed and validated using the extensive simulator data acquired in subtask 3.1.5. The model is based on a Neural Network architecture for sidestick inputs applied by the pilot, with extensions based on simple control schemes for the operation of throttle lever, flaps and slats, landing gear and the pedal on ground (Fig. 2.13). It can simulate the whole take-off run from brake release at the threshold up to following a defined departure route (SID). Additionally a decision model for manual Autopilot disconnection during an encounter was implemented, although the data basis used for validation of this model is limited.

Figure 2.13: Block diagram of pilot-aircraft system with the pilot model for take-off and departure

The weights and biases of the different nodes of the neural net were optimised by training the model with a part of the recorded simulator data generated by real pilots. This optimisation was performed open-loop, i.e. with fixed input data and without interaction between pilot model and aircraft dynamics. The resulting weight and bias matrices are specific to the aircraft for which they were produced, however as far as validation data is available a corresponding weighting can easily be produced also for other aircraft.

To validate the parameter sets for the neural net, the pilot model was tested in the VESA-D A320 simulation in the loop. The resulting response of the aircraft as well as the actual stick commands of the pilot model were compared to those from the simulator tests with pilots. Fig. 2.14 shows an example of the pilot model compared to the real pilots by means of the bank angle of the aircraft. This kind of validation has been performed for several different parameters in the lateral and longitudinal axes, showing in general a very good agreement.

The main work concentrated on the development of a deterministic version of the pilot model. This means the outputs of the pilot model (which are the inputs to the different control elements) are exactly the same as long as the input to the model is the same. This version was validated and used for the risk assessment performed in sub-WP 3.2. In addition a probabilistic add-on has been developed, which can be optionally activated, and which provides varying outputs with the same
2.6 Subtask 3.1.7 - Development of a pilot model for take-off and departure

Figure 2.14: Example of pilot model output compared to recorded pilot data

inputs. The range of variation of the models outputs has been determined by statistical evaluation of the recorded data from the piloted simulator tests.

In its present version the pilot model is applicable to Airbus-type aircraft with a Fly-By-Wire flight control system using a sidestick to control the aircraft, as it has been validated with data recorded on these types of aircraft. During the project an attempt was made as well to adapt the model to an aircraft model similar to a Saab 340 which was available at Airbus for the VESA-D simulation environment. Similar piloted simulator data was available from an Airbus-internal project to be used for the training of the neural net, although not in the same quality as from the A320 simulator. The adaptation worked quite well and the model produced realistic outputs when compared with simulator data. Due to limitations in the Saab simulation model however it was finally not used in the VESA-D risk assessment. A simple neural net based pilot model for encounters with the Saab 340-like aircraft model in stationary climb however is available.

The complete documentation of development and validation of the deterministic and probabilistic pilot model can be found in [3], extracts are also available in [5].
2.7 Subtask 3.1.8 - Advanced WVE offline simulation for take-off and departure

The objective of subtask 3.1.8 was to develop an offline simulation tool for wake encounters during departure based on the available VESA tool by Airbus that takes into account the dynamic reactions of an aircraft to a wake encounter. The new version of the simulation extended to departures is termed VESA-D. This tool allows the assessment of the severity of encounters and subsequently the estimation of the associated risk when simulating a large number of departures. The core of the VESA tool is a 6 degree-of-freedom flight simulation that allows a realistic simulation of the dynamic reactions of an aircraft during a wake vortex encounter. For this purpose an Airbus A320 aircraft simulation was used, along with a so-called Aerodynamic Interaction Model (AIM) that allows computing the induced forces and moments of a wake vortex on the simulated aircraft.

This tool was extended with sub-models developed within subtasks 3.1.6 and 3.1.7, namely the pilot model and severity criteria. The pilot model was integrated into the VESA-D simulation and already provided results for validation of the model in subtask 3.1.7. For the risk assessment to be performed for CREDOS the deterministic version of the model was used. The severity criterion developed in subtask 3.1.6 was implemented in the simulation platform as a post-processing of the data provided by the A320 wake encounter simulation. It computes the severity using the different dynamic aircraft parameters which are recorded during the simulation.

The simulation runs in fast-time under the MOPS environment similar to WakeScene-D. It can be run in two different ways. One is using it stand-alone, using parametric analytical vortex models and allowing variation of several parameters influencing the aircraft performance and characteristics of the vortices. This is useful for sensitivity analyses and Worst-Case searches. The second way is to use it coupled to WakeScene-D, to process those departures in a severity assessment which have been identified by WakeScene-D as potential encounters, using the output of the wake vortex behaviour models D2P or DVM and the associated weather profiles that were used to compute the vortex evolution. This allows the assessment of complete scenarios in a highly realistic way taking into account all impact parameters on wake encounter risk.

Both tools can be run independently from each other, with the necessary data transferred from WakeScene-D to VESA-D in a specified format. This allows simulating several different scenarios in parallel and in different locations. One of the main efforts was to develop the interface between WakeScene-D and VESA-D to allow exchange of the necessary data and ensure continuity between both tools when transferring data from previous WakeScene-D computations to VESA-D for further assessment. This also includes some corrections made in VESA-D to account for differences in the follower aircrafts flight path between the simpler WakeScene-D representation and the full 6-degree-of-freedom simulation in VESA-D. This interfacing is described in detail in [20].

Figure 2.15 shows schematically the interaction of both tools.
2.8 Subtask 3.2.1 - Definition of operational scenarios

The scenarios to be assessed with the combined WakeScene-D/VESA-D simulation platform for the risk assessment in subtasks 3.2.2 and 3.2.3 have been defined in this task.

A list of scenarios of interest for sensitivity studies has been produced and a ranking of importance established with input of the different CREDOS partners, as the amount of simulation scenarios seemed to exceed the available resources. Finally almost all of the defined scenarios could be investigated.

Furthermore the reference scenario was defined in this task, which should reflect as close as possible the current situation without reduced wake-related separations. The operational scenarios have also been defined, representing cases with reduced separation and a corresponding minimum crosswind. The targeted crosswind thresholds range from 2 to 10 kt in 2 kt increments, measured at 10 m height at the airport, which would be the operationally most simple solution. Separations of 120s, 90s and 60s have been investigated in combination with these crosswind thresholds.

2.9 Subtasks 3.2.2/3.2.3 - Quantitative safety assessment

These last two tasks had the goal to perform a risk assessment for the reduction of wake-related separation distances under crosswind conditions using the tools developed in the previous tasks. The assessment was divided into two parts. WakeScene-only studies were performed by DLR for sensitivity analyses of several parameters on the simulation results and first insight into the influence of different separation distance and crosswind combinations on encounter frequency. The results of these studies are contained in [13], extracts are also described in [14]. Simulations using WakeScene-D and
VESA-D in combination were aimed at assessing the risk of wake encounters for the different crosswind/separation scenarios taking into account also the severity of each encounter. The results of this risk assessment are available in [19]. With the help of the results a possible crosswind threshold was determined which would allow a safe reduction of separations during take-off.

The WakeScene studies presented in [13] were split into four parts, which are summarized here. A reference scenario was set up to represent the current departure situation as good as possible. It employs separations of 120s with all possible wind conditions except tailwinds of more than 5 kt. 1 Million departures were simulated in this scenario to get solid statistical results. Six Heavy generator aircraft types and four Medium follower aircraft types were simulated in random combinations and in proportions based on the traffic mix of Frankfurt airport to cover the weight range of both Heavy and Medium wake turbulence aircraft categories (see also ch. 2.3). Statistical analysis is presented regarding frequency of potential encounters, distributions of minimum distance to the vortices, vortex strength and encounter altitude.

The operational target scenarios differ from the reference in their applied separation of 60s or 90s together with varying crosswind thresholds between 0 and 10 kts in 2 kt increments, while all other parameters correspond to the reference scenario. The same statistical analysis is performed as for the reference scenario and the results compared. A synopsis of the results is given in Tab. 2.1. It shows in yellow for which crosswind thresholds the encounter frequency is approximately at or below the level in the reference scenario (green). The results suggest that for a reduction of the separation down to 60s a crosswind threshold of 6 kt might be sufficient when the whole of the encounters is regarded. To also reduce the number of potential worst-case encounters (here defined as those events with the highest vortex circulation and smallest minimum distance to the vortices) below the reference level however crosswinds of 10 kt or higher would be needed. This assessment however does not yet take into account the actual severity of those identified encounters.

The table also shows already that with increasing crosswind the number of encounters below 300 ft altitude is very quickly reduced, which means in turn that the encounters above this altitude gain significantly in proportion.

**Table 2.1:** Encounter frequencies for different aircraft separations and crosswind scenarios (see [13])

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<tr>
<th>Scenario</th>
<th>120s All CWs</th>
<th>90s 60s All CWs</th>
<th>90s 60s CW&gt;2kts</th>
<th>90s 60s CW&gt;4kts</th>
<th>90s 60s CW&gt;6kts</th>
<th>90s 60s CW&gt;8kts</th>
<th>90s 60s CW&gt;10kts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total encounter frequency</td>
<td>7.0%</td>
<td>12.8%</td>
<td>7.5%</td>
<td>3.7%</td>
<td>2.6%</td>
<td>2.2%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Encounter freq. below 300 ft</td>
<td>4.6%</td>
<td>9.4%</td>
<td>2.9%</td>
<td>0.057%</td>
<td>0.003%</td>
<td>0.002%</td>
<td>0%</td>
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<tr>
<td>Worst case encounter freq.</td>
<td>0.0037%</td>
<td>0.023%</td>
<td>0.011%</td>
<td>0.0073%</td>
<td>0.0041%</td>
<td>0.0026%</td>
<td>0.0017%</td>
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</tbody>
</table>

16
Furthermore, in sensitivity analyses the effect of a number of input parameters like sample size, flight path adherence or combinations of SID routes on the results of different scenarios have been investigated. This provides a good view over the major impact factors on wake encounter probability on take-off. Finally, wake vortex simulations in WakeScene-D were compared to real measured vortex wakes at Frankfurt airport during the CREDOS EDDF-2 campaign to validate the global wake vortex behaviour in the simulation, showing a very good agreement between both. The detailed results of all these studies can be found in [13].

The second report from these two tasks [19] contains a risk assessment using VESA-D in conjunction with WakeScene-D for the possible operational scenarios. The assessment is performed with a departure route layout using all SIDs of runway 25R in Frankfurt, as well as with only using the northerly routes (as is usually the case with runway 18 in use) and a comparison with the same scenarios but with a straight-out departure route. For all scenarios it could be shown that close to ground, up to an altitude of approx. 300ft, the crosswind is very effective in reducing encounter risk. Here a crosswind component as low as 6 kt is generally sufficient to reduce the encounter risk to almost zero.

One major effect identified was that of the veering wind with altitude (called Ekman spiral), which causes a maximum in encounter risk above a certain altitude for crosswinds of about 4-6 kt magnitude coming from the left of the runway. Fig. 2.16 shows the distribution of the probabilities to encounter a vortex of a certain severity (by means of the Severity Criterion value $SC$) versus crosswind magnitude, split into low and high encounter altitude, for straight-out departures. Consequently there is no influence of the SID routing. Even if the encounter probability aloft increases first with crosswind, above a crosswind of 8 kt the probability at 60s separation is below that at 120s and low crosswinds. As the high-crosswind condition is much less frequent than the low-crosswind one, and thus contributes much less to the overall wake encounter probability, this could be considered a sufficiently safe situation. When ensuring that the crosswind on ground is coming only from the right of the departure runway, the threshold could even be reduced to 6 kt as the encounter probability and risk is then considerably lower, caused by the Ekman spiral effect. The same conclusions could be drawn when considering the encounter risk, also taking into account the severity of each single encounter, as well as using only the northerly departure routes of runway 25R instead of a strictly straight departure (Fig. 2.17).

The comparisons of the different scenarios however showed a significant influence on wake encounter risk at higher altitudes when all SID routes of runway 25R are used equally (see Fig. 2.18). Depending on how the departure routes turn with respect to the wind direction, a considerable headwind component with respect to the heading can be added, which increases wake encounter probability significantly during departure. Therefore additional consideration is needed regarding the actual departure route layout at an airport where the concept should be implemented. In the Frankfurt example, restricting the reduction of aircraft separation to situations when the crosswind is coming from the right of the runway reduces the wake encounter risk according to Fig. 2.19, driven by the Ekman spiral effect.
Finally sensitivity analyses have also been added to increase the confidence in the results that are described in deliverable D3-10 [19].

Figure 2.16: Encounter probability for SC>0, straight-out departures

Figure 2.17: Encounter probability for SC>0, departures only on northerly routes
Figure 2.18: Encounter probability for SC>0, using all SIDs of RWY 25R (incl. 90s separation)

Figure 2.19: Encounter probability for SC>0, all SIDs of RWY 25R, crosswind only from the right
Chapter 3

Conclusions and recommendations

3.1 Conclusions

The aim of CREDOS WP 3 was to develop and apply wake vortex encounter simulations for the de-
parture phase and perform risk assessments to support the safety case for introducing the CREDOS
concept from a wake encounter risk point of view. A major part of the work package was dedicated
to model development and validation. Advanced models have been produced and combined with
wake vortex behaviour and weather models into two powerful simulation platforms, WakeScene-D
and VESA-D, which are able to provide wake encounter risk assessments for departure under vary-
ing weather conditions.

A trajectory generation model has been developed to generate realistic distributions of departing
aircraft’s flight paths for Monte Carlo simulations using the tool WakeScene-D. This trajectory model
has been validated with aircraft track data delivered by DFS during the project.

Piloted simulator tests of wake vortex encounters in two flight simulators were conducted with a
number of licensed commercial pilots to gain experience about wake encounters during departure.
Those tests generated a large database of simulated wake encounters flown with an A320 and an
A330 simulator during departure that can be exploited for model development and validation.

The data was used within CREDOS for development of a pilot behaviour model for wake encounters
during departure based on a Neural Net architecture. The model consists of a number of sub-models
and is able to perform all necessary control actions for take-off and departure from the start of the
take-off roll, and it is able to realistically recover from a wake encounter. It is validated with the
simulator data recorded during the piloted encounters and mimics pilot control behaviour considerably
well. Efforts to extend the model architecture to other flight phases are underway.

Furthermore the simulator data was used to develop advanced severity criteria for assessment of the
severity of wake encounters. The recorded data and results from pilot questionnaires were used to
verify the severity predictions of the model. Significant progress was made on these criteria during the CREDOS project, but further improvement seems to be possible.

These additional models were integrated into the two simulation tools WakeScene-D and VESA-D. The results generated within the work package applying both of these tools independently and in conjunction are robust and conclusive and allow giving recommendations for crosswind thresholds needed for reduction of departure take-off separations. These results confirm initial estimations on the minimum required crosswind obtained from pure evaluation of wake vortex measurements at Frankfurt airport also conducted during the project [7]. They also point out the major impact factors on wake encounter risk on departure that could be exploited in follow-on activities.

As long as only straight-out departures are considered, a crosswind threshold of 8 kt seems to be necessary to sufficiently reduce the wake encounter risk up to an altitude of 3000 ft when the separation shall be reduced down to 60s. For altitudes up to only 300 ft a crosswind of 6 kt or more is already sufficient. The main cause for the difference between low and high altitude risk was identified to be the change of wind direction with altitude (Ekman spiral).

When considering a realistic departure route layout like the one of Frankfurt International airport runway 25R, which was used exemplarily in the risk assessment, the specific routing of the different SIDs can lead to increased encounter risk under certain circumstances. The risk assessment results however suggest that a crosswind threshold of 6-8 kt could here also be sufficient (for the whole considered altitude domain up to 3000 ft), provided the wind is coming from the right of the runway, due to the Ekman spiral effect. As the Ekman spiral is driven by Coriolis forces, this effect is inverted on the southern hemisphere. This result is however also specific to the Frankfurt SID layout that was used. Finally, when restricting all departures to the northerly routes from runway 25R in Frankfurt, a crosswind threshold of 8 kt could also be sufficient, as this scenario is similar to the straight-out case.

3.2 Recommendations

Recommendations for possible future work have been identified in several areas and are explained in the respective deliverables. They are summarized here, while some additional recommendations shall be given from an overall work package viewpoint.

Regarding the pilot model it is desirable that the model is applied and verified for other flight phases than departure as well. The validation for the longitudinal axis could be strengthened, as the available data from the CREDOS simulator sessions contains mainly roll-dominant wake encounters.

Similarly the severity criterion developed within CREDOS should be applied and verified also for other flight phases. The methodology and the chosen parameter limits need to be validated by experts including pilots as well as handling qualities, aerodynamics and flight physics specialists.

Concerning the simulation tools WakeScene-D and VESA-D one main issue is the comparability
between the trajectories of the encountering aircraft between both tools. As the simulation of the single departure is much more accurate in VESA than in the WakeScene trajectory model, differences in the aircraft position and attitude appear which have to be corrected appropriately. While this was taken care of as good as possible for the CREDOS simulations, a more accurate simulation of the single departure tracks in the trajectory model is expected to result in a more accurate reproduction of the encounter scenario in VESA. The goal of the trajectory model achieved so far was to provide realistic distributions of departure tracks for a probabilistic assessment.

Regarding the simulations themselves the assessment should be extended to other aircraft than the A320 used in the combined WakeScene-D/VESA-D risk assessment to cover a larger part of the traffic mix. Also, before implementing the concept at a specific airport, local assessments should be conducted taking into account the local departure route structure and weather conditions.

So far the wake encounter risk assessment assumed winds measured at 10m height above ground, which is an operationally simple solution, as the information is available at every airport. Also evaluations in WP 2 have shown that for crosswinds above a certain threshold the crosswind on the ground correlates quite well with the crosswind up to 1000ft altitude. A risk assessment should however also be conducted assuring a certain crosswind (or crosswind/tailwind combination) up to an altitude that can typically be covered by modern wind measurement equipment. This is assumed to reduce the overall wake encounter risk in crosswind conditions.

Furthermore no constraints on the SID combinations of leading and following aircraft have been assumed, although some results have been evaluated also for the fractions of departures with a specific leader/follower SID combination. It is assumed that by additionally ensuring the following aircraft is departing on an upwind route, the encounter risk is significantly further reduced. Simulations explicitly taking this constraint into account should confirm this assumption.
References


## Appendix A

### Work Package 3 Deliverable Overview

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¹ CO: Confidential - PU: Public