Simulating the Risk of Bird Strikes

Metz, Isabel; Ellerbroek, Joost; Muhlhausen, Thorsten; Kügler, D.; Hoekstra, Jacco

Publication date
2017

Document Version
Final published version

Published in
Proceedings of the Seventh SESAR Innovation Days, 28th – 30th November 2017

Citation (APA)
Metz, I., Ellerbroek, J., Muhlhausen, T., Kügler, D., & Hoekstra, J. (2017). Simulating the Risk of Bird Strikes. In *Proceedings of the Seventh SESAR Innovation Days, 28th – 30th November 2017: Belgrade, Serbia*

Simulating the Risk of Bird Strikes

Isabel C. Metz*, Joost Ellerbroek†, Thorsten Mühlhausen*, Dirk Kügler* and Jacco M. Hoekstra†
*German Aerospace Center
Institute of Flight Guidance
Braunschweig, Germany
†Delft University of Technology
Faculty of Aerospace Engineering
Delft, The Netherlands

***Abstract*—This paper presents a fast-time simulation environment for assessing the risk of bird strikes in aviation. An existing air traffic simulator was enhanced in order to simulate air and bird traffic simultaneously and to recognize collisions between birds and aircraft. Furthermore, a method was developed to generate bird movement information from different radar sources. The resulting set-up represents the first simulation environment to perform fast-time simulations including air traffic and bird movements. A verification with real data revealed that approximately thrice as many bird strikes occur in the simulation as in reality. When considering bird reaction to approaching aircraft, which is not covered in the simulation as well as unreported strikes, this implies an adequate result. For this reason, the simulator can serve as valuable tool to analyse the risk of bird strikes and to evaluate new Air Traffic Management concepts to reduce the number of these events.**

***Keywords*—Bird Strike, Safety, Capacity, BlueSky, Fast-Time Simulation, Air Traffic Management**

I. Introduction

Collisions between birds and aircraft, so called bird strikes, represent an ongoing threat to aviation safety [1]. To mitigate the risk for these events, airports maintain a bird / wildlife strike programme as required by the International Civil Aviation Organization (ICAO). These programmes aim at excluding wildlife in general and especially birds from the airport grounds, for example with habitat modification or harassment [2]. These measures have already led to a reduction of bird strikes at many airports [3]. However, bird strikes are not limited to the airport area. Aircraft taking off and landing have an increased risk of colliding with birds up to an altitude of 3000 ft (ca. 1000 m). Hence the endangered area spreads much wider than the airport perimeter where the wildlife strike programmes are effective. Concepts to further reduce the risks of bird strikes would involve the pilots and Air Traffic Control (ATC). [1], [4]. For example, based on bird movement information from the area, a take-off could be delayed to prevent a probable bird strike during departure (cf. e.g. [5]). The introduction of such a concept has the potential to prevent bird strikes that nowadays would be inevitable. However, delaying of traffic would lead to a reduced runway capacity which is especially critical for airports with high traffic loads. So far, the consequences on the safety and capacity of an airport when implementing such a bird strike prevention system for ATC and the pilots have not been studied. In the present work, a fast-time simulation environment which allows the analysis of these effects as well as the comparison of different options for the implementation of such a system is described. The applicability of the simulation environment as a research tool for assessing the risk for collisions between aircraft and birds was then verified with real bird and air traffic. This paper describes the generation of bird movement information for the simulation, the underlying model for the detection of bird strikes in the simulation as well as the resulting set-up. This is followed by an analysis of the simulation results.

II. Method

To develop a simulation environment for the analysis of bird strikes, an underlying simulation platform is required. This study relies on the BlueSky Open Air Traffic Simulator developed by Delft University of Technology. This simulator enables real- and fast-time simulation of air traffic [6]. A key advantage for the work presented here lies in the simulator's open character: BlueSky can freely be downloaded and modified. Thus, modules for bird traffic and collision detection between birds and aircraft could thus be integrated without any restrictions. The resulting simulator set-up facilitates the simultaneous simulation of bird movements and air traffic as well as the recognition of bird strike occurrences.

To run simulations in this set-up, input data for bird movements and air traffic is required. The following paragraphs describe, how these were obtained and processed for the simulation. Subsequently, the developed conflict-detection algorithm to identify bird strikes in the simulation is presented. Finally, the simulation set-up is summarized.

A. Bird Movements

For this study, bird movements in the extended airport area are relevant. This includes local movements at the airport itself as well as migrating patterns of birds in higher altitudes in the arrival and departure corridors. Avian radars offer high-resolution information about tracks of individual birds [7]. This seems ideal for this study. However, the range of the chosen avian radar is limited due to its range capability as well as radar shadowing from ground objects. Hence, an additional source for bird movements in the arrival and departure corridors was required for this study. Weather radar was selected for this purpose. Due to their ability to recognize birds, weather radars are widely used for the quantification of bird movements [8], [9].

By combining data from weather and avian radar, the full picture of bird movement in the extended airport environment can be visualized. While weather radar data has previously been used to visualize migration movements (cf. e.g. [10]), this work represents the first study to combine avian and weather radar data to gain movement information about local and migrating birds. Data was available for the area around Eindhoven airport in the Netherlands, namely from an avian radar stationed at that airport as well as from a weather radar in De Bilt. The avian radar serves as input for bird movements from ground to 200 m (ca. 660 ft), the weather radar covers the altitude band from 200 m to 1000 m (ca. 3000 ft). The lateral range of 25 km of the weather radar in De Bilt does not reach Eindhoven airport. However, the broad-fronted bird migration patterns over both location are strongly comparable (Hans van Gasteren, Royal Netherlands Air Force, personal communication, 4/12/2016). Hence, the bird densities recorded by the weather radar were projected to the airport area of Eindhoven. The following paragraphs describe, how information from the two radar sources was extracted and prepared for the simulation.

1) Avian Radar: The obtained avian radar data contains time-stamped positions of moving objects connected to tracks by a Kalman-Filter. Every track is assigned to an id as well as an object type. For this study, the data was filtered for the object types *small bird*, *medium bird*, *large bird* and *flock*. Moreover, to gain representative tracks, only birds with at least 20 timestamps were selected. Due to the radar's turning frequency of 0.75 Hz, this corresponds to a minimum track duration of ca. 27 seconds. This filtering reduces the number of tracks considered and thus is expected to slightly decrease the number of bird strikes in the simulation.

The avian radar at Eindhoven is a horizontal X-band radar providing latitude and longitude information of bird positions. Due to the low elevation resolution, the bird's altitude is not resolvable [7]. Because the beam size of the radar increases with distance, the range of potential vertical positions rises as well. When crossing a lateral distance of ca. one kilometre from the avian radar, the beam exceeds the altitude of 200 m. As weather radar data is used from 200 m upwards, an overlap of the two sources occurs as Figure 1 visualizes: Area 3 is considered by both radars. To avoid double counts, the number of birds tracked by the avian radar was set as follows: Assuming that birds fly at constant height once airborne, all birds flying within the range of area 1 during one time step at least were selected. For the outer range (areas 2 and 3), birds were filtered corresponding to altitude distributions determined by Shamoun-Baranes, van Gasteren and Ross-Smith [11]. They conclude that 48% of all birds fly below 200 m during daytime. At night, 35% fly below 200 m. Consequently, two out of three birds were removed from areas 2 and 3 to gain a conservative estimate of the number of birds. Area 5 is not covered by neither of the radars.

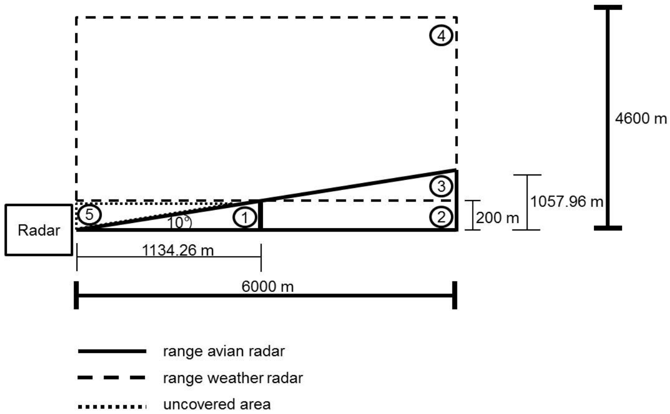


Figure 1: Areas covered by the avian and weather radar (not to scale). Area 1 and 2: avian radar. Area 3 and 4: weather radar. Area 5: no coverage

2) Weather Radar: The data of the chosen C-band weather radar in De Bilt contains information about bird reflectivity per km^2 and in altitude bins of 200 m. For this study, the altitude bands from 200 m to 1000 m were considered. To convert reflectivity to density in $\frac{birds}{km^3}$, the methodology described by Dokter et al. [12] was applied. Velocity and direction of birds was obtained from the Northern and Eastern speed components given in the weather radar data. As the study performed by van Gasteren et al. [13] revealed, recorded bird velocity is underestimated by the radar. Hence, it was increased by 3.44 $\frac{m}{s}$ as suggested by van Gasteren et al. [13]. To consider the standard deviations, individual birds were assigned to a velocity in a range of 12 $\frac{m}{s}$ around the average velocity. The applied standard deviation for bird direction amounts to 45° [13], (Hans van Gasteren, Royal Netherlands Air Force, personal communication, 11 October 2016). As for the avian radar data, altitude information was assigned randomly within the respective altitude band.

3) Processing of bird movements: After extracting bird movement information from the two radar sources, it was made available for the simulation by storing it in bird movement plans per simulated day. This reduces calculation effort during the simulation and allows a reproducibility of simulations. For birds covered by the avian radar, the bird movement plan contains all time-stamps and the corresponding track data. The last time-stamp is marked with a trigger for the simulation to remove the corresponding bird.

Birds covered by the weather radar are stored with information about their initialization and removal. The calculation of these steps is based on a preprocessing method described subsequently. In the first time-step covered by the weather radar, as many birds as represented in the input data's reflectivity are created at random positions in the designated airport area. In every subsequent update step, the birds' positions are extrapolated based on their speed and direction and compared to the boundaries of the airport area. Birds that left the area are marked to be deleted in the bird movement plan. They are replaced with new birds in order to keep the flow constant. As the weather radar birds mainly represent migrants, the general flight direction of individuals is very similar. For this reason, they leave the area in the same direction. As a consequence, the birds to replace the fly-outs are initialized at the opposite boundary. The number of these fly-ins is corrected for potential changes in reflectivity between time steps. Furthermore, the number of birds remaining in the area is kept corresponding to the reflectivity. If the reflectivity increases, birds are randomly generated over the entire area. In case of a decrease, birds are randomly deleted. Every initialization and every removal calculated in the preprocessing is stored in the flight movement plan. During the simulation, the bird's actual position is interpolated (avian radar) respectively extrapolated (weather radar) from the given data in the bird movement plan.

Birds do not always fly alone but also in flocks [14]. Therefore, every bird in the simulation represents one or multiple individuals. This is relevant for later evaluations of the risk for damage resulting from bird strikes. Birds from the avian radar are already grouped in individuals and flocks. However, no information about the flock sizes is available from the input data. From the weather radar data, information about the total number of birds, but not about their distribution in birds flying individually and birds flying in flocks can be obtained. To generate this missing information for the bird movement plans, data from a multi-year-study on bird migration over the Netherlands was used [15]. Despite its age – the report dates from 1985 – this is the most complete source available, including data about the flock and altitude distribution of the most representative bird species in the Netherlands. Furthermore, it contains detailed information for birds flying below and above 200 m which perfectly corresponds to the boundary between avian and weather radar in this study.

Two flock-size distributions were calculated: The distribution for the avian radar birds includes birds flying in flocks. The distribution for weather radar birds also considers the data of individual flying birds per species to receive information about the share between individual and group flyers.

To gain flock information about birds within the avian radar range, the top 15 species reported to fly below 200 m were chosen, representing 89% of all birds in this category. Regarding birds flying above 200 m, 14 species representing 97% of all birds of this category were considered. From the mean flock size per species obtained from the study by Lensink and Kwak [15], weighted flock size averages were calculated for the two radar sources. For the weather radar birds, the distribution between birds flying alone and in groups was calculated in addition. The flock sizes were finally determined by applying a Poisson distribution as suggested by Lensink and Kwak [15] by using the weighted average as expected number. Poisson distributed values include one and zero. To obtain valid flock sizes with a minimum of two members, results smaller than two were increased accordingly.

Bird migration patterns differ significantly between day and night. During daytime, birds mainly migrate in groups, while they fly individually or with large distances between flock neighbours during the night [14], [16], [17]. Hence, the described distributions are only valid for diurnal migration. For nocturnal migration, which the study of Lensink and Kwak [15] does not cover, the flock size distribution was obtained from Hüppop et al. [18] and assigned to the species Lensink and Kwak [15] had observed. The designator for applying the flock distributions for nocturnal or diurnal migration in the bird movement plan is civil twilight.

Next to the number, also the size of birds involved in a bird strike influences the risk of aircraft damage [2]. The avian radar data only contains size information for birds flying individually, but not for flocks. From the weather radar data, this information cannot be retrieved at all. To assign birds to a size, the chosen species from the study of Lensink and Kwak [15] were categorized based on their weight into the classes *small*, *medium* or *large* as defined by the aviation authorities [19]. Corresponding to the species distributions, these size classes were assigned to the birds in the movement plans.

B. Air Traffic

To get realistic flight plans for air traffic, scenarios based on real traffic were generated. The availability of bird movement information set the simulation area to Eindhoven airport in the Netherlands. This airport has a very low traffic volume [20]. To evaluate the impact of various traffic intensities on the risk of bird strikes, flight plans from additional airports were generated and transferred to the airport of Eindhoven to cover high, medium and low traffic volumes as well. For comparability and to facilitate the integration into the simulated airport area – Eindhoven has one runway – traffic from airports with one operational runway were selected. With regard to their ranking considering number of flights in the 2015 Airports Council International (ACI) traffic report, London Gatwick (UK) for high, Geneva (CH) for medium and Birmingham (UK) for low intensity were chosen. In addition, a scenario covering Eindhoven traffic was generated. The flight plans were generated based on data from one representative day per airport in 2016 (source: European Organization for the Safety of Air Navigation (EUROCONTROL) database, accessed via Bruno Nicolas, Statistics Specialist, Eurocontrol, personal communication 5 April 2017 & 4 August 2017). Figure 2 visualizes the selected traffic volumes.

The dataset obtained from EUROCONTROL contains trajectories per aircraft. Every trajectory consists of time-stamped three-dimensional positions which allow to reproduce an aircraft's flight path. For landing aircraft, the time stamp of their last recorded position within the trajectory was used as initialization time in the flight plan. Departing traffic was initialized at the time of their first recorded position. Due to variances in the input-data, air traffic generated based on these time stamps could overlap and thus collide in the simulation. To exclude the risk for aircraft collisions, a minimum separation time between the initialization of two aircraft was introduced. Based on the known maximum capacity of an airport with single runway operation – London Gatwick with 55 movements per hour – this parameter was set to 1.09 minutes [21]. Depending on the traffic sequence within the simulation, aircraft could still lose their separation in the simulation. However, the main goal

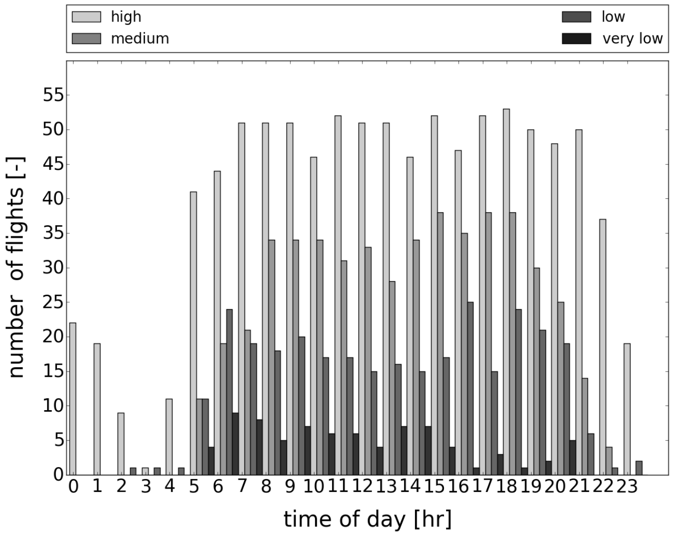


Figure 2: Daytime distribution of flights for the chosen traffic intensities

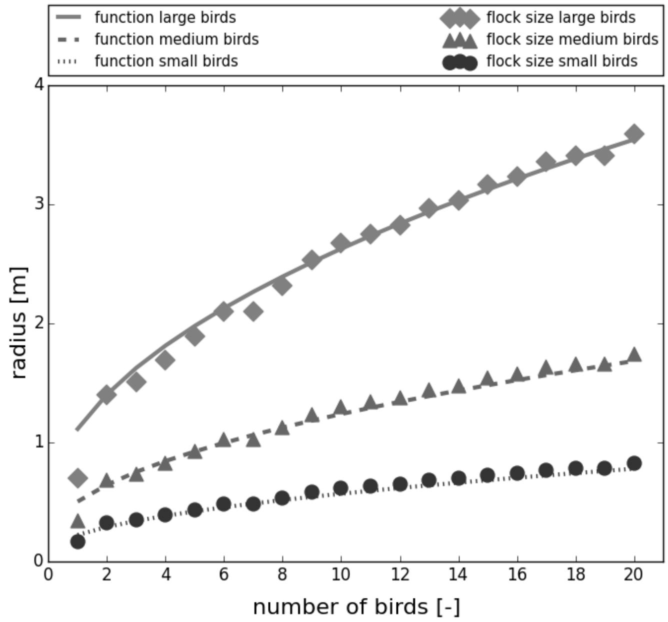


Figure 3: Increase in flock size radius with rising number of flock members

to avoid collisions while changing the input data as little as possible was fulfilled with this measure.

The flights of the considered traffic intensities were mapped to Eindhoven airport. For all simulations, runway 03 was active. Landing aircraft were initialized at 3000 ft at one of the initial approach fixes MITSA or RUSAL and performed Instrument Landing System (ILS) approaches. Departing aircraft used the Standard Instrument Departures (SID) and were deleted once reaching 3000 ft.

C. Conflict Detection Algorithm

To detect bird strikes in the simulation protected zones were defined around birds and aircraft. A bird strike occurs, when a bird and an aircraft penetrate each other's protected area. The definition of the protected zones is described subsequently.

1) Protected Zone Birds: The protected zone of birds depends on two parameters: The bird's size and the number of birds represented by one bird object. The protected zone around individual and flocks of birds was modelled as disc to minimize the impairment of the collision detection algorithm on the simulation's runtime performance. The shape of flocks, which varies amongst different species [22], was thus simplified. Due to the small height of birds, especially in comparison to the height of aircraft, it was decided to disregard this parameter and keep the protected zone of birds two-dimensional. The diameter of the protected zone of individual birds directly refers to the wingspan of the category it belongs to. For each of the bird categories *small*, *medium* and *large*, a weighted average for the wing span was calculated based on the species considered from [15] and their distribution.

To model the protected zone for flocks, the theory of dense packings of congruent circles in a circle [23] was used as a base. This theory describes how the radius of a circle increases with rising number of circles within that circle. Considering comprising circles, corresponding to protected zones of flocks, containing up to 20 circles which represent

TABLE I: RADII FOR DIFFERENT FLOCK SIZES

Bird Categotry	Wingspan [m]	Flock Radius	Standard Deviation from Flock Size [m] in [23]
small	0.32	$\sqrt{n_{birds}} \cdot \frac{0.32}{2} + 0.06$	0.030
medium	0.68	$\sqrt{n_{birds}} \cdot \frac{0.68}{2} + 0.16$	0.038
large	1.40	$\sqrt{n_{birds}} \cdot \frac{1.40}{2} + 0.41$	0.050

birds within the flock, functions for the radii of the protected zone for each bird category were developed. Thereby, the neighbouring distance between the individual birds was not considered. These distances have so far only been analysed for some species (cf. e.g. [16]). Moreover, for migrating birds, which are mostly relevant in context of this study, it is most efficient to fly adjacent or even with slightly overlapping wing tips [24]. Hence, this parameter was set to zero. Table I summarises the developed functions. Figure 3 visualizes them.

2) Protected Zone Aircraft: The basic shape of the protected zone of aircraft corresponds to an upright cylinder. To consider the major aircraft types, the aircraft from the flight plans were categorized into the groups *wide body*, *narrow body* and *regional*. The parameters required for the definition of the protected zone per category were obtained for the aircraft with the largest wingspan in each group: The Airbus A380-800 represents *wide bodies*, the Boeing B757-300 *narrow bodies* and the Bombardier Dash 8-400 *regional aircraft*.

The protected zone's diameter corresponds to the aircraft's wing span. Because of their small front surface, an aircraft's rudder and elevator experience almost no bird strikes [25],

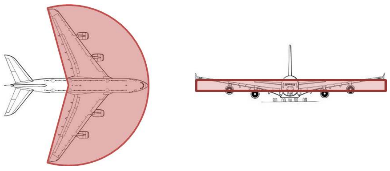


Figure 4: Top and front view of an aircraft's protected zone (Airbus A380-800)

TABLE II: PARAMETERS DEFINING AN AIRCRAFT'S PROTECTED ZONE

Aircraft Category	Reference Aircraft Type	Radius $[m]$	Height $[m]$	Sweep $[°]$
Widebody	Airbus A380-800	79.75	1.99	33.5
Narrowbody	Boeing 757-200	38.0	1.01	25.0
Regional	Bombardier Dash 8-400	28.4	1.35	0.0

[26]. Thus, the tail section is cut from the protected area. Its arc length depends on the wing's sweep.

An aircraft's height strongly varies along its wingspan. Hence, if setting the protected zone's height to the aircraft's largest vertical expanse, the number of bird strikes would be strongly overestimated. Therefore, an average height was determined from the heights of the aircraft's front surfaces prone to bird strikes: the wings, engines and the fuselage [27]. This average height represents the height required to be multiplied with the aircraft's wingspan to obtain a rectangle corresponding to the aircraft's relevant front surface. It is calculated by adding the front surfaces of the aircraft's components given in Equation 1. The resulting protected zone is visualized in Figure 4. The key parameters to determine the dimensions of the protected zone per aircraft category are given in Table II.

$$S_{front} = \underbrace{(b - 2 \cdot r_f) * h_w}_{\text{front surface wings}} + \underbrace{n_e \cdot r_e^2 \cdot \pi}_{\text{front surface engines}} + \underbrace{r_f^2 \cdot \pi}_{\text{front surface fuselage}} \quad (1)$$

where b represents the wingspan, r the radius of the respective components and h the height, all in metre. n_e is the number of engines.

3) Conflict Detection: During simulation, the protected zones of birds and aircraft are constantly tested for overlaps. Every overlap of a bird's and an aircraft's protected zone leads to a bird strike. As a consequence, the bird hit is removed from the simulation and a bird strike is counted.

D. Simulation Set-Up

After describing the relevant input parameters for the simulation, the resulting set-up is summarized here. The number of bird strikes occurring at an airport strongly depends on the season: During migration as well as in summer, when many young and inexperienced birds fly, more strikes take place than in winter [1], [2]. To include seasonal effects within this study, bird movement plans were created for an entire year. It was decided to simulate one week per month in the period from October 2015 to September 2016 where radar data was available. This allowed to keep the simulation effort at a reasonable level while all seasons were covered and the number of days (n = 84 per airport) was representative. The weeks were chosen based on radar availability and weather. The reason for the latter criteria lies in the radar's decreasing tracking ability with increasing precipitation [7]. By choosing weeks with little precipitation, a high detection rate and as such representative bird movement information was ensured.

Every bird movement plan was combined with the flight plans representing high, medium, low and very low traffic volume to study the effect of different traffic intensities on the bird strike risk. Depending on the airport, the traffic volume varies throughout the year [20]. This variation is implicitly considered by providing flight plans for different traffic intensities. The combination of bird data from 84 days and flight plans covering the four traffic intensities led to a total of 336 simulated traffic days.

By simulating the described scenarios, two goals were pursued. First, a verification, if the developed simulation environment appropriately reflects the risk of bird strikes at an airport, took place. Here, it was expected that more bird strikes would be counted in simulation than in reality. The main reason is, that the simulated birds are not modelled to show reactions to aircraft whereas in reality, birds often manage to perform last-minute escapes when an aircraft approaches. Furthermore, not all bird strikes are recognized or reported, especially ones with very small birds or strikes that did not damage the aircraft involved. Even with the slight reduction of simulated bird strikes due to the filtering of the avian radar data (cf. section II-A1), the number of bird strikes within the simulation should be higher than in reality. The second goal of the simulation campaign is to acquire data for a baseline scenario for further research involving new Air Traffic Management (ATM) procedures to avoid bird strikes.

III. Results and Discussion

The goal of this work was to develop a simulation environment to model the risk of bird strikes. The resulting set-up enables fast-time simulations of bird and air traffic movements. Collisions between birds and aircraft are registered and counted as bird strike occurrences. To verify the set-up and to generate a baseline-scenario for further simulations, 336 days were simulated for the airport of Eindhoven, where the input data for bird movements originates from.

To evaluate the outcomes of the simulations, the bird strike rates were calculated for the four considered traffic intensities high, medium, low and very low. Additionally, the bird strikes occurrences were categorized by altitude band as well as by month of occurrence. Finally, the correlation between bird volume and number of bird strikes per season was determined.

The bird strike rate of an airport is generally given in number of bird strikes per 10.000 flights [28]. The average ratio of all bird strikes at Eindhoven airport amounted to 12.33 between 2007 and 2016 (source: Bird Strike Database, Royal Netherlands Air Force. Hans van Gasteren, 3/8/2017, personal communication). The bird strike rates resulting from

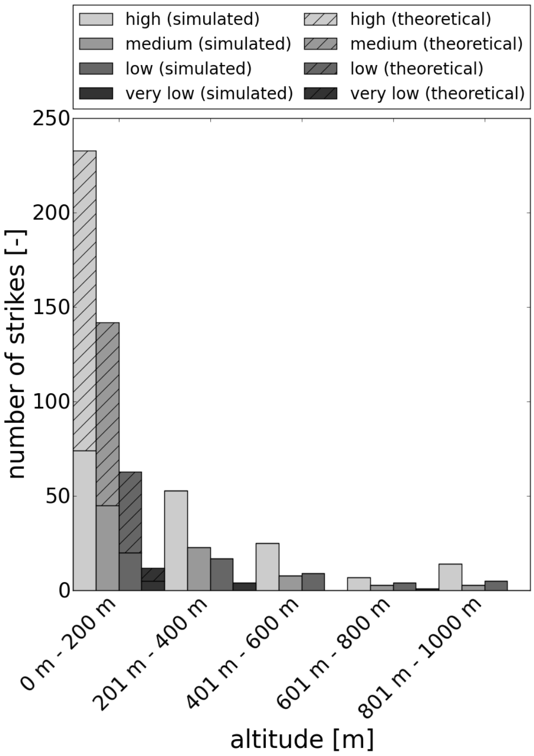


Figure 5: Bird strike altitude distribution (0-200 m: avian radar, 200 - 1000m: weather radar) for the chosen traffic volumes

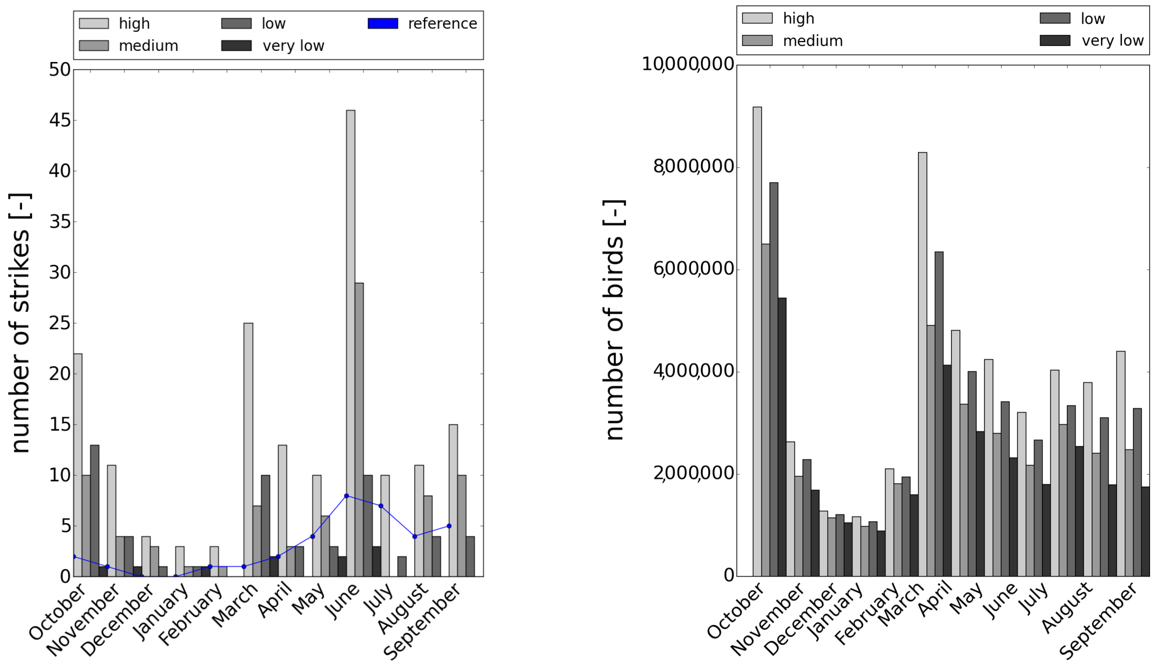
the simulations are a little higher: They amount to 21.59 for high, to 19.48 for medium, to 21.78 for low and 15.07 for very low traffic volume. Due to last-minute escapes in reality which are not modelled in the simulation as well as because of unreported strikes, a larger offset would be expected. However, birds were filtered for duration of stay in the altitude band covered by the avian radar (cf. section II-A1). For this reason, the risk for bird strikes is reduced in this altitude band. This is reflected in the altitude distribution of strikes in the simulation as visualized in Figure 5. As statistics from across the world consistently suggest, the number of bird strikes decreases exponentially with increasing altitude [26], [29], [27]. With regard to the simulation results visualized in Figure 5, a significant decrease can only be found from 201 m on – the altitude from which the weather radar data serves as source for bird movements. Between zero and 200 m, where the data from the avian radar was used, the number of bird strikes is only slightly higher than in the altitude band above. By comparing the number of all birds including the ones filtered out to the number of birds considered for the simulation, the theoretical sum of bird strike occurrences was calculated. To ensure the accuracy of scales, the number of birds was weighted with their average duration of stay. The determined values (top bars in Figure 5) increase the bird strike rate to a reasonable level. Table III presents the comparison between the simulated and theoretical bird strike rates. In contrast to the other scenarios, the rise of the bird strike rate when considering all birds present is relatively small in the very low-scenario. The main reason is that the offset between the number of all birds present within the opening hours and the number of birds selected for the simulation is much smaller than in the other scenarios.

TABLE III: SIMULATED AND THEORETICAL BIRD STRIKE RATES [NUMBER OF STRIKES PER 10.000 FLIGHTS]

Airport	Simulated Bird Strike Rate	Theoretical Bird Strike Rate
High	21.59	41.43
Medium	19.48	42.53
Low	21.78	38.25
Very low	15.07	25.62
Eindhoven (reference)	12.33	

Figure 6 visualizes the seasonal distribution of bird strikes (Figure 6(a)) and number of birds (Figure 6(b)). Additionally to the number of strikes in the chosen scenarios, the average number of strikes per month for the period 2007 - 2016 is given for the reference airport in Eindhoven. It has to be noted that the data from Eindhoven reflects all strikes that happened within one month. In contrast, the simulation results cover the number of strikes for one week per month. These numbers differ between the scenarios. This is mostly correlating with the air traffic volume. However, in five months, at least the same number of strikes occurred in the low-scenario as in the medium-scenario. This can be explained by the temporal distribution of flights: Between 6 and 7 a.m., where internationally most bird strikes are recorded [25], [29], more flights depart in the low-scenario (cf. Figure 2). In this period, 24% of all strikes happen in the low-scenario with 8% of the daily air traffic movements. In the medium-scenario, only 2% of all strikes occur with 4% of the daily traffic.

The comparison of the number of strikes in the simulation with real data reveals two main differences: First, in the summer months, the number of strikes at Eindhoven are relatively high in comparison to the simulation results. This could be related to increased flight activity in Eindhoven during the summer months, while the scenarios consider average traffic volumes. The second deviation can be found in the month of March, where the simulation results increase significantly, while the number of bird strikes remains at a relatively low level at Eindhoven airport. When comparing the bird strike occurrences in the simulated scenarios with the number of birds (cf. Figure (6(b))), the peak in March is reflected in both statistics. Obviously the majority of spring migration took place in March in the year considered for the simulations. In contrast, the data from Eindhoven is averaged over ten years. In this period, the exact timing of spring migration could have shifted between the years. This probably led to a wider distribution of bird movements – and thus bird strikes – over the spring months. Overall, when comparing the seasonal trends between the simulation and reality, a high similarity can be found: In autumn, the number of bird strikes is relatively high. During the winter months, fewer bird strikes occur. In spring, the number increases again and has a maximum in



(a) Number of strikes per month for the simulated traffic volumes and at the reference airport

(b) Number of birds per month for the simulated traffic volumes

Figure 6: Number of strikes and number of birds per month

June when many inexperienced juvenile birds fledge. With the named exception of March, the seasonal trends seem to be well reflected within the simulation. This is supported by the number of birds present in the simulation as shown in Figure 6(b). Most birds fly during migration in autumn and spring. In winter, there is very small bird activity while more birds fly in summer. The only offset between number of birds and number of strikes can be found in June: With regards to the number of birds flying, a large number of bird strikes occurred. This could be attributed to very high activity of juvenile birds. Due to a lack of experience, they cause significantly more strikes than adult birds. [30]. The peak in bird strike occurrences at Eindhoven airport in this month supports this assumption. The correlation between number of strikes and number of birds in the simulation was calculated for all months and for all months excluding June. The Spearman correlation was applied for this purpose as not all of the considered values are normally distributed. Table IV summarizes the results. It becomes clear that the exclusion of the values for June, where the high number of bird strikes is not related to a rise in number of birds, notably increases the correlations. Regarding these values, the high-scenario shows a strong significant correlation ($r(10)$=0.89, $p < .001$) the low-scenario a moderate significant correlation ($r(10) = .71, p < .01$). The medium and very low scenarios do not correlate significantly ($r(10) = .44, p = .088$; $r(10) = .26, p = .281$). This is most likely connected to the opening hours of the airports where the scenarios originate from: Scenarios with longer airport opening times

TABLE IV: SPEARMAN CORRELATION BETWEEN NUMBER OF BIRDS AND BIRD STRIKE OCCURRENCES (N = 12 MONTHS)

Airport	r_s All Months	$p - value$ (One-Tailed) All Months	r_s w/o June	$p - value$ (One-Tailed) w/o June
High	.70	$<$ .001	.89	$<$ .001
Medium	.33	.144	.44	.088
Low	.62	$<$ .001	.71	$<$ .001
Very low	.26	.204	.26	.218

have higher correlations between number of birds and bird strike occurrences (cf. Figure 2). Moreover, scenarios with longer opening times have a higher simulated bird strike rate (cf. Table III) . The different opening hours also cause the higher number of birds in the low scenario compared to the medium scenario (cf. Figure 6(b)). The sample size for all the airports was twelve simulated months, which is very small for statistical evaluation. To gain more robust correlation results, Monte-Carlo experiments will be performed. The analysis of these simulations will include a detailed evaluation of the coherence between time of day and number of bird strikes.

With regard to the discussed results considering bird strike rate, altitude distribution as well as the seasonal course of bird strikes, the risk for collisions between birds and aircraft is modelled adequately in the developed simulation set-up.

IV. Conclusions

The aim of the presented work was to develop and verify a fast-time simulation environment to analyse the risk of bird strikes in the arrival and departure corridors of an airport. For this purpose, information from two radars was merged for the first time to generate bird movement information and to receive the full picture of birds flying in the extended airport area. By combining these bird movements with air traffic, the risk of bird strikes can be simulated in fast-time. Up to the author's knowledge, this simulation set-up is unique. The verification of the set-up revealed that the simulated bird strike rate is 2 to 3.5 times higher than in reality. Due to last-minutes escapes often occurring in reality but not modelled within the simulation, this conforms to the expectations. The correlation between number of bird strikes and number of birds seems to depend on airport opening hours and has to be addressed in future research. Especially if respecting all birds present in the lowest altitude band, the altitude distribution of bird strikes reflects international statistics appropriately. The seasonal effects on the bird strike risk are covered adequately as the comparison to real data from Eindhoven airport visualizes. In conclusion, the verification with real data demonstrates that the developed simulation environment reflects the risk for bird strikes decently. For this reason, the simulation environment and the results from the simulated scenarios are suitable to serve as baseline for future research evaluating ATM concepts for reducing the bird strike risk.

Acknowledgements

We thank the Royal Netherlands Air Force, the Royal Netherlands Meteorological Institute, Robin Radar and Eurocontrol for providing radar data and flight plan data. We are grateful to Hans van Gasteren for constructive discussions and valuable advice. We appreciate his and three anonymous reviewer's feedback on this paper.

References

[1] J. McKee, P. Shaw, A. Dekker, and K. Patrick, "Approaches to Wildlife Management in Aviation," in *Problematic Wildlife. A Cross-Disciplinary Approach*, 2016, ch. 22, pp. 465–488.
[2] B. MacKinnon, *Sharing the Skies. An Aviation Industry Guide to the Management of Wildlife Hazards*. Transport Canada, 2004.
[3] R. A. Dolbeer, "Height Distribution of Birds Recorded by Collisions with Civil Aircraft," *Journal of Wildlife Management*, vol. 70, no. 5, pp. 1345–1350, 2006.
[4] ——, "Increasing Trend of damaging bird strikes with aircraft outside the airport boundary: implications for mitigation measures," *Human-Wildlife Interactions*, vol. 5, no. 2, pp. 1235–248, 2011.
[5] I. Metz, T. Mühlhausen, J. Ellerbroek, D. Kügler, and J. M. Hoekstra, "Evaluating the Effects of a Bird Strike Advisory System," in *Bird/Wildlife Strike Prevention Conference*, Amsterdam, the Netherlands, December 2016.
[6] J. M. Hoekstra and J. Ellerbroek, "BlueSky ATC Simulator Project: an Open Data and Open Source Approach," in *7th International Conference on Research in Air Transportation*, Philadelphia, PA, USA, June 2016.
[7] R. C. Beason, T. J. Nohara, and P. Weber, "Beware the Boojum: caveats and strengths of avian radar," *Human-Wildlife Interactions*, vol. 7, no. 1, pp. 16–46, 2013.
[8] E. Eastwood, *Radar Ornithology*. London, UK: Methuen, 1967.
[9] S. J. Gauthreaux, D. Mizrahi, and C. Belser, "Bird Migration and Bias of WSR-88D Wind Estimates," *Weather Forecast*, vol. 70, no. 13, pp. 465 – 481, 1998.
[10] J. Shamoun-Baranes *et al.*, "Innovative visualizations shed light on avian nocturnal migration," *PloS one*, vol. 11, no. 8, 2016.
[11] J. Shamoun-Baranes, H. van Gasteren, and V. Ross-Smith, "Sharing the Aerosphare: Conflicts and Potential Solutions," in *Aeroecology*, P. B. Chilson, W. F. Frick, J. F. Kelly, and F. Liechti, Eds., 2017.
[12] A. M. Dokter, F. Liechti, H. Stark, L. Delobbe, P. Tabary, and I. Holleman, "Bird migration flight altitudes studied by a network of operational weather radars," *Journal of the Royal Society Interface*, vol. 8, 2011.
[13] H. van Gasteren, I. Holleman, W. Bouten, E. van Loon, and J. Shamoun-Baranes, "Extracting bird migration information from C-band Doppler weather radars," *Ibis*, vol. 150, pp. 674–686, 2008.
[14] I. Newton, *The Migration Ecology of Birds*. Academic press, 2010.
[15] R. Lensink and R. Kwak, "Vogeltrek over Arnhem in 1983 met een samenvatting over de periode 1981-1983 en methodieken voor het bewerken van telmateriall ," 1985, deel I en II.
[16] B. Zuur, "Nearest neighbour distances in day and night migrating birds. A study using stereophotography," *Vogelwarte*, vol. 32, pp. 206–218, 1984.
[17] R. P. Larkin and R. E. Szafoni, "Evidence for widely dispersed birds migrating together at night," *Integrative and comparative biology*, vol. 48, no. 1, pp. 40–49, 2008.
[18] O. Hüppop, J. Dierschke, K.-M. Exo, E. Fredrich, and R. Hill, "Bird migration studies and potential collision risk with offshore wind turbines," *Ibis*, vol. 148, pp. 90–109, 2006.
[19] Federal Aviation Administration, "14 CFR 33.76 - Bird Ingestion," 2011, volume 1.
[20] ACI Europe, "Airport Traffic Report," 2016, December, Q4 and Full Year 2015.
[21] Amadeus IT Group SA, "London Gatwick Airport increases runway capacity to 55 flights per hour and estimates an additional 2 million passengers on a single runway assisted by Amadeus A-CDM Portal," 2014, http://www.amadeus.com/web/amadeus/en_1A-corporate/Amadeus-Home/Newsroom/Archive/2014_12_16_London-Gatwick-Airport-increases-runway-capacity/1319658626891-Page-AMAD_DetailPpal?assetid̄1319614321235&assettypeP̄ressRelease_C. Online: accessed 17 July 2017.
[22] C. K. Hemelrijk and H. Hildenbrandt, "Some causes of the variable shape of flocks of birds," *PloS one*, vol. 6, no. 8, 2011.
[23] R. L. Graham, B. D. Lubachevsky, K. J. Nurmela, and P. R. Östergård, "Dense packings of congruent circles in a circle," *Discrete Mathematics*, vol. 181, no. 1-3, pp. 139–154, 1998.
[24] P. Lissaman and C. A. Shollenberger, "Formation flight of birds," *Science*, vol. 168, no. 3934, pp. 1003–1005, 1970.
[25] Australian Transport Safety Bureau, "Australian aviation wildlife strike statistics 2006 to 2015," Canberra, ACT, Australia, 2017.
[26] R. A. Dolbeer, J. R. Weller, A. L. Anderson, and M. J. Begier, "Wildlife strikes to civil aircraft in the United States 1990 - 2015," 2016, Federal Aviation Administration National Wildlife Strike Database. Serial Report Number 22.
[27] EASA, "Bird population trends and their impact on Aviation safety 1999-2008," 2009, Safety Report.
[28] ICAO, "Airports services manual," 2012, doc 9137 Part 3 Wildlife Control and Reduction.
[29] D. Harris, "Wildlife Strikes at Canadian Airports: A 2016 Annual Report," 2017, transport Canada.
[30] van Gasteren, Hans and Both, Inge and Shamoun-Baranes, Judy and Laloë and Bouten, Willem, "GPS logger onderzoek aan Buizerds helpt vogelaanvaringen op militaire vliegvelden te voorkomen," *Limosa*, vol. 87, no. 87, pp. 107 – 116, 2014.