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What is the Potential of a Bird Strike Advisory System?

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***Abstract*—This paper presents a collision avoidance algorithm to prevent bird strikes for aircraft departing from an airport. By using trajectory-information of aircraft and birds, the algorithm predicts potential collisions. Collision avoidance is performed by delaying departing aircraft until they can follow a collision-free trajectory. An implementation of this concept has the potential to increase aviation safety by preventing bird strikes but might reduce runway capacity due to delaying aircraft. As a precursor to the feasibility, this study investigates the maximum achievable safety effect at minimum delay costs of such a system by assuming a deterministic world. Therefore, no uncertainties regarding bird and aircraft positions were considered to enable the system to prevent all bird strikes for departing traffic while causing the smallest possible delay. The anticipated effects were studied by running fast-time simulations including three air traffic intensities at a single-runway airport and bird movements from all seasons. The results imply a high potential for the increase in safety at a reasonable reduction in runway capacity. An initial cost-estimate even revealed a strong saving potential for the airlines. Based on these results, a feasibility study of implementing a bird strike advisory system including uncertainties in bird movements as well as probabilistic effects will be performed.**

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

I. INTRODUCTION

Collisions between aircraft and birds have challenged the safety of air transportation since the beginning of aviation [1]. Most of these bird strikes occur below 1000 m [2]. Consequently, the highest risk for the majority of commercial aviation operations lies in the direct airport environment as well as the arrival and departure corridors. Traditional approaches to prevent bird strikes, as requested by the International Civil Aviation Organization (ICAO), aim at minimizing the number of birds at airports. They do not include the risk areas beyond the airport fences [3]. Over the past years, an increasing number of airports have implemented radars dedicated to tracking birds. [2]. This allows enhancing the horizon for risk-reducing measures to the arrival and departure corridors. As such, the visualization of bird movements could be used as real-time information or even as base for advisories for air traffic controllers and pilots [4]. The operational feasibility of such a concept has been studied by Hale and Stanley [5], revealing controller acceptance and potential workload reduction. The work presented here addresses the effects on an airport's safety and capacity when implementing such a bird strike advisory system. For this purpose, an algorithm determining potential collisions between aircraft and birds was developed. The algorithm focuses on departing aircraft. A bird strike during take-off, especially when one or multiple engines are hit, is most critical. The risk of substantial damage to engines is highest during this flight phase. Moreover, the aircraft needs thrust and controllability to return to the airfield, if required [4], [6]. A bird strike during approach is less dangerous, as the aircraft is already deliberately nearing the ground and consequently a safe state. Thus, the aviation authorities recommend to continue an approach when hitting birds [7] and collisions between birds and approaching aircraft are not considered in this study.

In case of a determined bird strike, the algorithm delays an aircraft's take-off until a collision-free trajectory is predicted. The algorithm was verified with fast-time simulations, including three air traffic volumes and bird movements from all seasons.

This study considers bird and aircraft movement as deterministic. No uncertainties regarding actual positions are included. Therefore, the algorithm is supposed to prevent all bird strikes by generating a minimum delay. The resulting impact on safety and capacity can serve as a reference for the maximum potential of a bird strike advisory system.

It was hypothesized that the implementation of the collision avoidance algorithm would cause critical delays during times with a high bird volume and high traffic intensity. Delays resulting in the loss of an assigned Air Traffic Flow Management (ATFM) slot [8] or a cancellation due to take-offs rescheduled after the designated opening hours were considered as critical. In scenarios with low to medium traffic volumes, the number and duration of caused delays for departing aircraft were expected to be acceptable.

II. METHOD

This work presents an algorithm for the prevention of collisions between birds and aircraft by delaying take-offs. By considering flight paths of aircraft and birds, the algorithm revises air traffic scenarios until all departing aircraft have a predicted collision-free trajectory. The algorithm was verified by simulating the resulting scenarios in fast-time. Subsequently, the output was analysed for the number of prevented bird strikes and the loss in runway capacity. Furthermore, airline-related costs saved through preventing bird strikes were compared to the expenses resulting from the introduced delays. The following paragraphs describe the set-up of the algorithm, the chosen specifications for this research, the applied verification procedure as well as the analysis method in detail.

A. *Collision Avoidance Algorithm*

The collision avoidance algorithm presented in this paper focuses on aircraft movement in the extended airport environment, where the risk of bird strikes is highest for civil aviation [2], [9]. The algorithm concentrates on potential collisions between birds and departing aircraft, as the risk of critical damages is highest in this phase [4], [6].

Within the algorithm, trajectories of scheduled departures are tested against the trajectories of birds present in the airport vicinity. In case of a critical overlap, the aircraft is delayed until its trajectory is predicted to be collision-free. This is performed per day for stored air traffic scenarios and bird trajectories.

Depending on the season and location, thousands of birds are airborne in an airport's vicinity and should therefore be considered within the collision avoidance algorithm [10]. Moreover, when comparing trajectories of birds and aircraft for potential collisions, a high sampling resolution of intermediate positions is required to precisely rebuild the flight paths. This is relevant, as the range determining a collision is, especially in contrast to aircraft-aircraft collision avoidance as implemented in Traffic Collision Avoidance System (TCAS) [11], very small. To maintain runtime efficiency, it is therefore vital to perform as few comparisons of trajectory-pairs as possible. Hence, a two-step approach including an initial filtering phase, as proposed in [12], was chosen for the collision avoidance algorithm. In the algorithm's first step, the *filtering phase*, the considered airspace around the airport is divided into a four-dimensional grid consisting of tiles in the dimensions time, latitude, longitude and altitude. Every bird is stored in the tiles it crosses along its flight path. In the second step, the *narrow phase*, the tiles crossed by the individual aircraft are determined. Their trajectories are then only tested against birds present in the respective tiles as well as the neighbouring tiles. These are included to catch collisions between birds and aircraft flying at the boundaries of their tiles (cf. [12]). The comparison is performed for each aircraft. To enhance runtime efficiency, only the bird's and aircraft's trajectory segments within the time frame of the shared tiles are considered within the *narrow phase*. The comparison is performed for vertical separation first. If it is too small, the lateral separation is tested. If it is lost as well, it is finally evaluated, if the trajectories meet in the front area of the aircraft. The tail section of an aircraft experiences almost no bird strikes due to its small front surface [13], [14]. Hence, it is excluded from the protected zone.

Only if the three conditions of vertical and lateral separation as well as front area are met, the aircraft is delayed. The resulting trajectory is then also tested for potential collisions. Once a collision-free flight-path is predicted, the new take-off time is stored and the next aircraft tested. A schematic overview of this process per aircraft can be found in Fig. 1.

The delay applied in case of a predicted collision has two components. First, the aircraft receives a predefined delay to avoid the currently conflicting bird. Second, it is tested, whether the resulting take-off time interferes with scheduled arrivals. As the time-horizon of collision avoidance for bird-aircraft trajectories is relatively small, rescheduling a subsequent arrival would lead to a go-around which is considered as undesirable. Therefore, if the separation between a delayed take-off and the subsequent arrival is lost, the departure is shifted to the next slot providing sufficient separation to the surrounding arrivals. This can lead to a domino-effect for following departures, which might also need to be shifted to maintain runway separation.

The output of the collision avoidance algorithm consists of two components. First, the bird-aircraft pairs predicted to experience a collision are saved. Second, the intended and effective take-off time for every departure is stored. For delayed take-offs, the delaying cause, i.e. a prevented bird strike or a transferred delay, is stored. This departure information serves as base for generating the revised, collision-free flight plan.

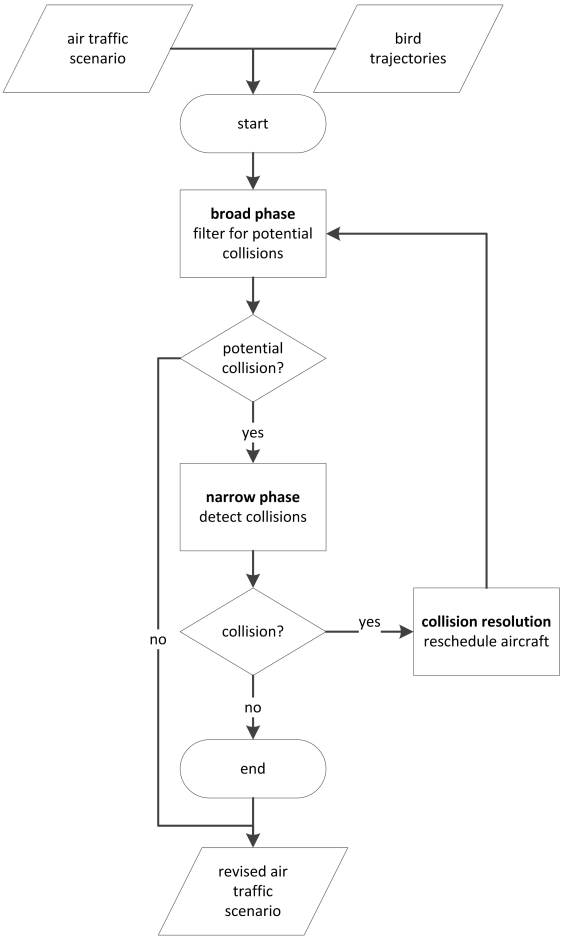

Fig. 1: Collision detection and resolution process per aircraft

Furthermore, the output was used to analyse the delays resulting from the collision avoidance intervention.

B. Specifications

This section describes the specifications of the above described collision avoidance algorithm applied for the verification and analysis performed within this work. To represent aircraft movements, flight plans from three airports with single-runway mode and different traffic intensity were obtained from the Demand Data Repository (DDR) 2 database of the European Organization for the Safety of Air Navigation (EUROCONTROL) [15]. The selected scenarios represented the daily traffic intensities *high* (954 movements), *medium* (501 movements) and *low* (305 movements). To generate the aircraft trajectories, the flight plans were simulated and the trajectories were logged in the BlueSky Open Air Traffic Simulator developed by TU Delft (cf. [16], [17]). With increasing logging frequency, trajectories can be rebuilt more precisely for analysis. On the other hand, this results in larger datasets and thus higher memory requirements for the processing within the collision avoidance algorithm. Therefore, a logging frequency with sufficient precision at minimum cost of memory was searched. Initial evaluations revealed that a higher sampling rate is necessary during the lift-off phase between 0 m and 15 m to account for the rapid changes in vertical speed in this phase. During the remaining flight, a smaller sampling rate is sufficient. Within the collision avoidance algorithm, linear interpolation was applied between recorded aircraft positions. The collision avoidance algorithm was executed for three combinations of logging frequencies. These can be found in Table I. Bird movement information was obtained from the avian radar located at Eindhoven airport and the weather radar in De Bilt, both in the Netherlands. The data was processed into trajectories as described in [18]. As shown in that study and confirmed in [19], this procedure leads to an overestimate in number of bird strikes between factor 2.5 and 3.3. This has to be taken into account when evaluating the effect on runway safety and capacity in the present work.

Bird movement derived from the weather radar data is represented by the start and end of the birds trajectories. The avian radar logged individual bird trajectories with a frequency of one Hertz. The resulting bird-objects from both radars represent individuals as well as flocks of birds. Birds present in the airspace around the arrival and departure corridors up to 1000 m, where bird strike risk is highest [2], were included. To evaluate the potential effects of the collision avoidance depending on the number of birds present during the different seasons, bird data from one week per month within a year was used as proposed in [18]. By combining the resulting 84 days of bird data with the three different flight plans, 252 scenarios resulted. Due to the season-dependent variability in bird movements [10], the sample size seems rather small. However, the Monte-Carlo study performed in [19] demonstrated reproducibility of the number of bird strikes. Thus, the sample size is seen as sufficient. Identical airport opening hours from 05:00 to 22:00 Coordinated Universal Time (UTC) were used in all scenarios.

TABLE I: Logging frequencies of aircraft trajectories

Iteration Identifier	Logging Frequency Lift-Off (Hz)	Logging Frequency Other Flight Phases (Hz)
I	10	2
II	20	1
III	20	2

In this initial application of the collision avoidance algorithm, the maximum potential of its effects in terms of maximum number of prevented strikes at a minimum delay cost should be evaluated. Therefore, bird and aircraft trajectories are given and do not include uncertainties.

The tile-widths of the considered grid-dimensions used for filtering relevant bird trajectories are summarized in Table II. Birds were filled into the grid based on their trajectory information. Between the given positions, linear interpolation was applied. This was defined as appropriate, as the differences to distances calculated with a more sophisticated definition including e.g. the haversine function [20], are small.

To determine a potential collision between aircraft and bird in the *narrow phase*, protected zones around the opponents were defined. A penetration of these protected zones is considered as a collision. In aircraft-aircraft collision avoidance as implemented in the TCAS, the protected zones consist of a caution, warning and collision area [21]. The here presented implementation aims at preventing all bird strikes at a minimum cost of delays. Therefore, only the collision area is included in the opponent's protected zones. The zones of both opponents are disc-shaped, as visualized in Fig. 2. The protected zones of birds do not have a height, as this dimension is considered negligible for birds (cf. [18]). For the aircraft, only the front part of the disc, determined by the aircraft's sweep, is considered. The

TABLE II: Grid and tile sizes

Tile Dimension	Tile Width	Grid Width	Number of Tiles
time	10 s	61,200 s	6120
latitude	1,000 m	29,910 m	30
longitude	1,000 m	25,450 m	26
altitude	100 m	1,000 m	10

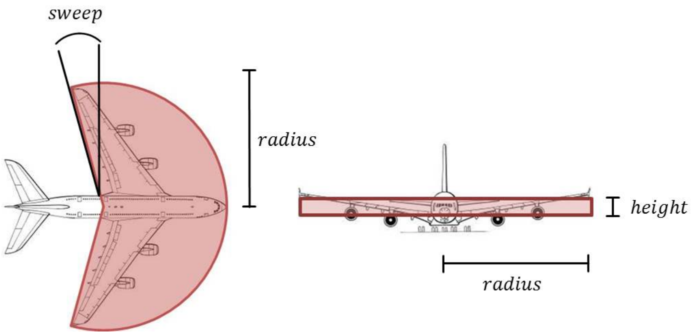

Fig. 2: Protected zone aircraft. Left: top view. Right: front view (source: [18])

height is an average from all aircraft components except the tail section and gear (cf. Fig. 2). The definitions for the protected zones were obtained from [18]. Table III summarizes them for birds, Table IV for aircraft. Regarding birds, the size of the protected zones depend on the weight classification and, in case of a flock, the number of birds. For the aircraft, the size category determines the protected zone's extent. These specifications were selected to be comparable with the collision-detection implemented in the BlueSky Open Air Traffic simulator, which was used for verifying the algorithm (cf. [18]).

Due to the high aircraft speeds and the small sizes of the protected zones, trajectory comparison should be performed with a high sampling rate to catch all strikes. Considering runtime and memory requirements, a sampling rate enabling to detect strikes with high risk of damage at least should be implemented. Highest risk of damage occurs at high velocities and close to the aircraft's core [6], [14]. Therefore, a minimum sampling frequency to detect head-on collision between aircraft of the smallest category and birds of all sizes at the highest observed speed at half of the aircraft's wingspan as visualized in 1 was defined as minimum.

$$f_s = \frac{v_{ac} + v_b}{r_{ac} - r_b} \tag{1}$$

where f_s refers to the sampling rate in Hertz, r_{ac} to the aircraft radius in meter, r_b to the bird radius in meter, v_{ac} to the aircraft velocity and v_b to the bird velocity, both in meter per second.

By applying the smallest aircraft radius of 14.2 m, the smallest bird radius of 0.32 m, the largest velocity of 113.18 m/s as defined in the flight plans and a maximum bird velocity of 16.22 m/s, a sampling rate of 9.32 Hz results. Distance measures were performed using the local flat earth approximation [20]. For compatibility with the reference used for the algorithm's verification, the rate was increased to 20 Hz.

In case of a detected collision, the aircraft is delayed in five-second increments. If this leads to the loss of separation to an arriving aircraft, the departure is further delayed until it has a minimum separation to the previous and following arriving aircraft . Occurring delays are transferred to subsequent departures. For simplicity, an average minimum separation of 66 seconds was applied between all aircraft in all scenarios. This separation corresponds to 55 take-offs per hour which is achieved at Europe's most frequented single-runway operated airport of London Gatwick [22], [23].

TABLE III: Protected zones birds (source: [18])

Bird Group	**Wingspan (m)**	**Flock Size Radius (m,** n_{birds}: number of birds)
small	0.32	$\sqrt{n_{birds}} \cdot \frac{0.32}{2} + 0.06$
medium	0.68	$\sqrt{n_{birds}} \cdot \frac{0.68}{2} + 0.16$
large	1.40	$\sqrt{n_{birds}} \cdot \frac{1.40}{2} + 0.41$

TABLE IV: Protected zones aircraft (source: [18])

Aircraft Category	**Radius (m)**	**Height (m)**	**Sweep (°)**
Widebody	39.88	1.99	33.50
Narrowbody	19.00	1.01	25.00
Regional	14.20	1.35	0.00

C. Verification

The determining criteria for a correct implementation of the collision avoidance algorithm were defined as the number of false warnings as well as the number of strikes still taking place after revising the flight plans. As aircraft and bird trajectories are defined as deterministic within the collision avoidance, all collisions of departing traffic should be prevented and no false warnings generated. However, due to the chosen sampling rate of the trajectories, the collision avoidance is defined as correctly implemented if at least 95% of all bird strikes are detected and a maximum of 5% false alarms caused.

To analyse the collision avoidance algorithm's output for undetected strikes, the revised air traffic scenarios were simulated in fast-time alongside the bird movements considered for the collision avoidance. The BlueSky Open Air Traffic Simulator was chosen as simulation platform. It was selected as it contains modules to simulate air traffic and bird movements simultaneously and records bird strikes [18]. After the simulation, the number of remaining strikes occurring to departing traffic was counted. For the evaluation of false warnings, the bird movements and the initial air traffic scenarios were simulated in BlueSky as a reference and the occurring collisions logged. These were then compared to the collisions prevented by the algorithm. Prevented collisions which did not occur in the initial scenarios were counted as false warnings. Within the comparison, only collisions of aircraft without a transferred delay were considered in order to ensure the comparability between the outputs. Fig. 3 visualizes the verification process.

D. Impacts of the Collision Avoidance Algorithm

The expected increase of safety by reducing number of bird strikes was tested within the verification process as described in the previous section. The consequences on runway capacity were expected to increase with traffic intensity. It was hypothesized that the collision avoidance would not lead to critical delays in the *low* and *medium* traffic intensity scenarios. In the *high* intensity scenarios, critical delays were expected during peak times. Critical delays were defined as time losses larger than ten minutes. These result in missing of an assigned ATFM slot as defined by EUROCONTROL [8]. Furthermore, delays leading to take-offs after the dedicated opening hours of the respective airport were considered as critical.

An additional parameter to be considered is the economic impact. Bird strikes cause substantial costs to the aviation industry [24], [25]. On the other hand, the take-off delays generated by the collision avoidance algorithm cause costs as well [26]. Direct costs resulting from a bird strike mainly concern the operator of the affected aircraft. However, the economic impact caused by the impairs in operations also influence the other parties involved in the Air Traffic Management (ATM) process [27]. For this study, Federal Aviation Administration (FAA) data considering bird strike related costs

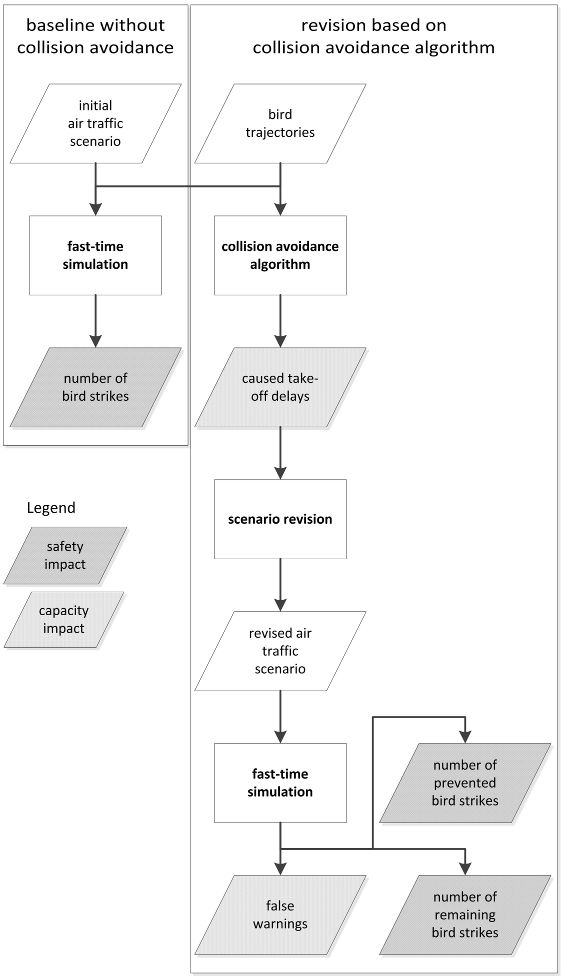

Fig. 3: Verification process and outputs

for airlines in the US could be obtained [25]. Based on reports from 1990 to 2015, average repair costs of US \$ 164,595 (3,945 reports) and average indirect costs of US \$ 27,599 (2,962 reports) per bird strike were determined. Indirect costs include expenses resulting from lost revenues, passenger costs, rescheduling of aircraft and flight cancellations. The resulting costs of US \$ 192,194 represent average costs per strike, where an adverse effect on the flight was reported (24,473 reports). When mapping them to all 169,856 reported strikes, average costs of US \$ 27,691 (ca. €24,947 [1]) per strike result. These are inflation-adjusted to 2015. Due to incomplete reporting, the authors of [25] consider these costs as minimum estimates. The effective costs are estimated to be two to three times higher.

Regarding delay costs, data is available for Europe. In [26], reference values are presented for the year 2014. Airline costs are calculated for different phases of flight and include the costs of fuel, maintenance, fleet, crew, passengers and reactionary delays. By considering all aircraft types for the taxi phase (cf. [26], Table 27, p.12), average delay costs of €175 per five minutes, respective €35 per minute result.

The presented cost factors for bird strikes and delay minutes originate from different countries. Furthermore, the costs of bird strikes are expected to represent minimum costs because of incomplete reporting. Therefore, the monetary consequences for the airlines calculated within this work should be regarded as an initial cost approximate.

III. RESULTS

Within this work, a collision avoidance algorithm to prevent collisions between aircraft departing from an airport and birds by delaying departures was developed. It was analysed regarding the effect on the airport's safety, runway capacity and monetary consequences for the airlines. This section presents the results from the verification of the collision avoidance algorithm, which also illustrate the algorithm's potential safety benefit. Subsequently, the outcomes of the delay-analysis and the estimate of resulting airline-costs are described.

A. *Verification*

The correct implementation of the collision avoidance algorithm was tested in two steps. First, the flight plans resulting from the algorithm were simulated alongside the initial bird movements in the BlueSky Open Air Traffic Simulator. The results were compared against a baseline in which the initial flight plans serving as input for the collision avoidance algorithm were simulated with the identical bird movements. Strikes occurring with the revised flight plans served as verification criterion. To account for inaccuracies resulting from the chosen resolution, a tolerance of 5% of the strikes taking place in the baseline was defined as acceptable. Second, the algorithm's output was evaluated regarding false warnings. These warn of collisions which did not take place in the initial scenarios and are therefore superfluous. To evaluate the false warning rate, the collisions prevented by the algorithm were compared to the collisions that took place in the baseline. For comparability, only aircraft with identical take-off times in the baseline- and revision-scenarios were considered. This applied to 75 of 149 strikes in the *high*, 53 of 68 strikes in the *medium* and all strikes in the *low* traffic intensity. Aircraft which already had an initial delay in the revised scenario were excluded. A tolerance of 5% of false warnings related to all warnings was applied.

The collision avoidance algorithm was executed with aircraft trajectories being recorded at three combinations of sampling frequencies (cf. Table I). The outcome from simulating the resulting scenarios is shown in Table V. Slight variations in number of remaining strikes and false warnings are present for the *high* and *low* traffic intensities. When applying the tolerance for remaining collisions and false warnings restrictively by rounding them off, only iteration III fulfils all requirements. Therefore, this iteration was selected to be evaluated regarding the algorithm's impact on runway capacity and airline costs.

B. *Impact on Runway Capacity*

Based on the verification results, iteration III was used for further analysis of the algorithm's output. The respective results

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[1] based on the exchange rate of 1.11 from 2015 [28]

TABLE V: Verification results for the collision avoidance algorithm for different sampling rates of aircraft trajectories for the three traffic intensities

Traffic Intensity	**Number Strikes Baseline (-)**	**Tolerated Strikes and False Warnings (-)**	**Remaining Strikes (-)**			**False Warnings (-)**		
			iteration I	***iteration II***	***iteration III***	***iteration I***	***iteration II***	***iteration III***
high	155	7.75	9	6	6	3	3	3
medium	70	3.5	2	2	2	1	1	1
low	54	2.7	1	1	1	2	3	2

TABLE VI: Analysed delay parameters for the three traffic intensities

Traffic Intensity	**Affected Flights (%)**	**Number Transferred Delays per Prevented Strike (-)**	**Number all Delays per Prevented Strike (-)**	**Average Delay per Strike (s)**	**Average Delay per Day (s)**	**Potentially Lost Departure Slots per Day (-)**
high	3.14	6.77	7.77	120.1	1753.57	14
medium	0.58	0.64	1.64	76.10	106.91	1
low	0.48	0.11	1.11	2.50	13.79	1

are presented in this section. If not stated differently, they represent the total of the 84 simulated days per traffic intensity.

The impact on runway capacity was assessed by evaluating the departure delays caused by the algorithm. Delays resulting from the algorithm's intervention to prevent a potential strike (initial delay) as well as delays transferred to subsequent departures (transferred delay) were considered. Fig. 4 summarises the boxplot values of the delay distribution for the three traffic intensities *high*, *medium* and *low*. Next to the range of initial and transferred delays, also the distribution of their combination is presented here. In all traffic intensities, the average delay is higher for transferred than for initial delays. Based on the number of occurrences, the distribution of the sum of both delays is mainly influenced by the transferred delays for the *high* intensity. Regarding the other intensities, more initial delays take place. This leads to a smaller average when considering all delays. The maximum observed delay amounted to 396 seconds (*high* intensity). This lies well below the defined critical delay of 600 seconds (10 minutes). Moreover, all aircraft could depart within the airport opening hours in all scenarios.

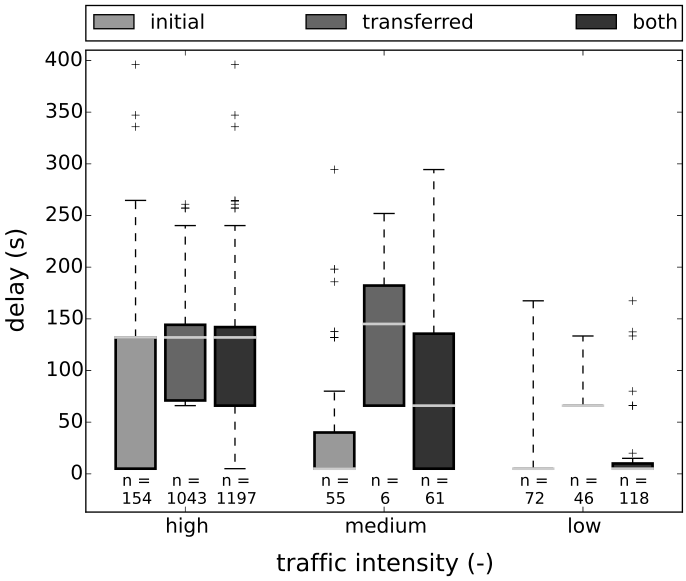
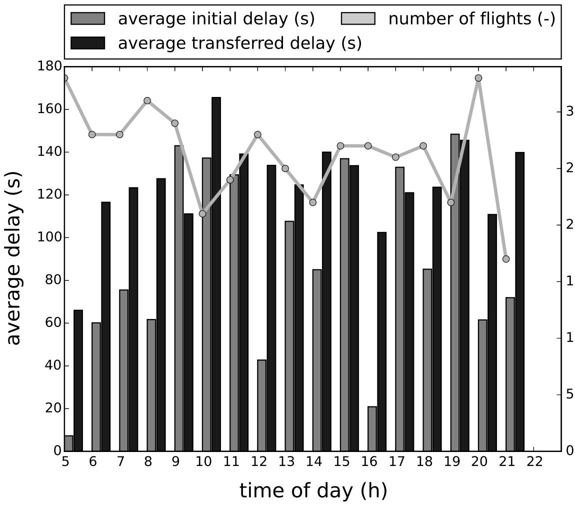


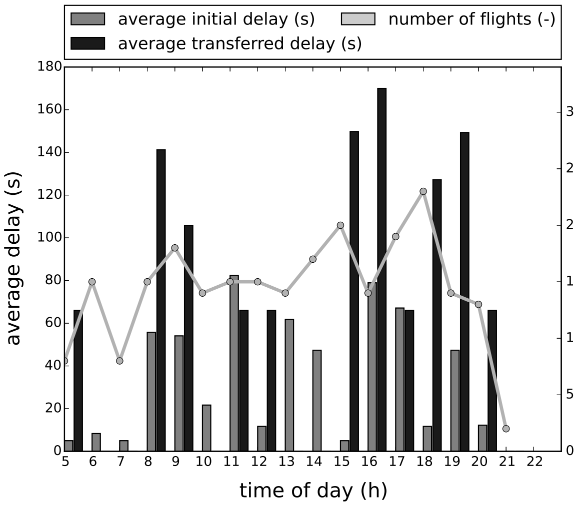
Fig. 4: Boxplot values for initial, transferred and all delays for the three traffic intensities. n: number of occurrences.

The number of flights affected by the algorithm is very small in all traffic intensities, with a maximum of 3.14% in the *high* intensity, as shown in Table VI. Only in this intensity, more transferred delays than initial delays were generated. With decreasing traffic intensity, the collision avoidance algorithm's effect decreases as well for all considered parameters. This becomes especially visible when considering the average delay per day and consequently potentially lost departure slots per day, composed of twice the implemented minimum separation of 66 seconds. While 14 departure slots get lost in the *high* traffic intensity scenario, the reduction only amounts to one slot in the *medium* and the *low* traffic intensity respectively.

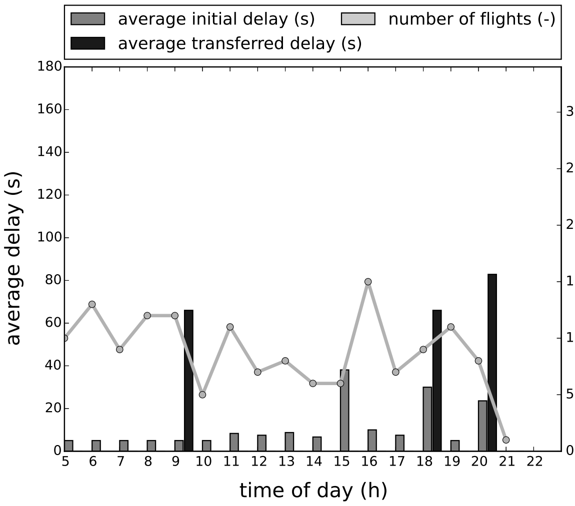
Fig. 5 visualizes the number of flights as well as the generated delays per hour for the three traffic intensities. As for the entire dataset considered in Table VI, the sum of generated delays as well as the ratio of transferred to initial delays decreases with decreasing traffic intensity. The coherence between the number of flights and the sum of delays per hour varies among the traffic intensities. The corresponding Spearman correlation r_s is weak for the *high* traffic intensity ($r_s = 0.59, p-value < 0.01$). In the *medium* intensity, number of flights and delays correlate strongly ($r_s = 0.82, p-value < 0.01$) and moderately ($r_s = 0.66, p - value < 0.01$) in the *low* intensity. In all cases, the results are significant. The number of strikes is a slightly better predictor for generated sum of delays per hour. Here, stronger correlations, all of them significant, were observed for all traffic intensities (*high*: $r_s = 0.68, p - value < 0.01$, *medium*: $r_s = 0.93, p - value < 0.01$, *low*: $r_s = 0.89, p - value < 0.01$).



(a) high traffic intensity



(b) medium traffic intensity



(c) low traffic intensity

Fig. 5: Initial and transferred delays as well as number of flights per hour

C. *Effect on Airline Costs*

The monetary quantification of the costs and benefits of implementing a collision avoidance concept as presented here has to be performed carefully, as the sources for the costs of bird strikes and delay minutes originate from different countries. Furthermore, the dataset serving as input for the costs of bird strikes is considered as incomplete and the resulting costs are expected to underestimate the effective expenses. Therefore, the numbers presented here serve as an initial estimate of the monetary impact on the airlines. Table VII summarizes the potential savings due to the prevention of strikes and costs resulting from the applied delays when regarding bird- and aircraft movements as deterministic. In all traffic intensities, the monetary benefits outnumber the costs considerably. Thereby, the ratio between benefits and expenses strongly increases with decreasing traffic intensity.

IV. DISCUSSION

A system preventing bird strikes by delaying departing aircraft has the potential to increase an airport's safety at the cost of a decreased runway capacity. This work presents a collision avoidance algorithm on which such a system could base. By performing fast-time simulations including the resulting flight plans, the potential impact on safety, capacity and economic consequences on airlines was evaluated. All aircraft- and bird-movements were set as deterministic. This allowed to analyse the maximum effect or the potential of the concept in terms of preventing all delays at a minimum delay cost. The results can serve as baseline for further investigations taking into account uncertainties in the predictability of bird movements.

The correct implementation of the collision avoidance algorithm was verified by considering aircraft-bird collisions still occurring and false warnings being generated. Thereby, three combinations of logging frequencies for aircraft trajectories were tested. It was found that the combination of 20 Hz during lift-off and 2 Hz during the remaining flight phases fulfils the verification requirements. Hence, the corresponding iteration III was selected for further evaluation of the algorithm's outcome. Thereby, aircraft flight plans of high, medium and low traffic intensities as well as bird movements from all seasons were considered. A safety benefit in terms of prevented collisions of 96% to 98% of prevented bird strikes resulted, while 1%-4% of false warnings were generated.

TABLE VII: Savings and costs when implementing the bird strike advisory system as presented in this work

Traffic Intensity	**Number Prevented Strikes[a] (-)**	**Costs Saved[b] (€)**	**Sum Delay (min)**	**Delay Costs[c] (€)**	**Saved Costs per Caused Costs (-)**
high	149	3,717,103	2,454.72	85,924.93	43.26
medium	68	1,696,396	149.67	5,238.59	323.83
low	53	1,322,191	19.31	675.71	1956.74

[a] number of strikes in initial scenarios minus remaining strikes iteration III

[b] € 24,947 per strike

[c] € 35 per minute

To assess the impact on runway capacity, the delays resulting caused by the collision avoidance algorithm were analysed. Delays above 10 minutes, leading to a loss of an ATFM slot were defined as critical as well as delays causing departures to be shifted after the airport opening hours. Against the hypothesis, no critical delay took place in any of the scenarios. Even in the *high* traffic intensity scenarios containing 954 flights in 17 hours, the resulting delays and the loss of 27 departure slots could be compensated for. The maximum delay amounted to just above six minutes and all flights could depart within the airport opening hours. Moreover, the amount of flights which were influenced by the algorithm was extremely small with a maximum of 3.14% in the *high* traffic scenario.

The generated delays and consequently the impact on the runway capacity decrease with decreasing traffic intensity. Fewer flights lead to smaller numbers in transferred delays and fewer departure slots are lost. The correlations between number of flights and generated delays vary among the air traffic intensities. A stronger coherence is observed between number of strikes and generated delays. However, predicting the duration of generated delays based on number of flights or strikes per hour should be performed carefully. For a more reliable estimate, the number of birds present in the airspace and their behaviour would need to be taken into account too.

The initial cost estimation revealed a strong potential to save direct costs for the airlines when implementing a collision avoidance algorithm. In all scenarios, airlines would profit from the implementation. The benefit increases with decreasing traffic intensity. The simulation overestimates the number of bird strikes. Therefore, also the number of interventions and thus the impact of the collision avoidance algorithm should be interpreted as a maximum estimate. Still, when assuming a linear coherence between prevented bird strikes and caused delays as a first approximate, the ratio between savings and costs remains strongly beneficial. The cost-analysis focused on the aircraft operators. To receive a more elaborate picture of the economic consequences for all parties involved in the ATM process, more complete data is required.

Within the here presented algorithm, all bird and aircraft trajectories were known in advance. Therefore, the results represent the effects of an optimum system, preventing all bird-aircraft collisions while generating minimum delays. When including uncertainty, especially in bird movements, the effects of a bird strike advisory system algorithm will decrease. Depending on the chosen system settings, two potential outcomes are expected. Warning on every bird which might potentially collide with an aircraft, will increase the number of (false) alerts and therefore increase the number and duration of induced delays. On the other hand, when generating warnings of birds with a high chance for collision only, the number of correctly prevented strikes decreases. The outcome strongly depends on the achievable accuracy of bird movement prediction which is studied in ongoing research. Nevertheless, this study shows the strong potential of implementing a bird strike advisory system based on a collision avoidance algorithm preventing bird strikes for departing aircraft. When applying suitable settings in an implementation including uncertainties in bird movements, the benefits might still outnumber the downsides, even for airports operating at high traffic intensities.

V. CONCLUSIONS

Within this work, a collision avoidance algorithm for the prevention of bird strikes by delaying aircraft departing from an airport was verified and its impact on the airport's safety and capacity as well as the economic consequences for the airlines evaluated. The analysis revealed strong safety benefits in terms of prevented bird strikes at a reasonable number of generated delays for departing aircraft in all scenarios. A rough cost-estimate even implied the potential for cost-savings for the airlines. However, the here presented algorithm represents an ideal system, assuming that bird movement is deterministic. Hence, the bird strikes are prevented at a minimum delay costs, as no uncertainties are considered. Therefore, this system can be interpreted as a reference for further research including the limited predictability of bird movements to evaluate the feasibility of a bird strike advisory system.

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