Reduzierung des Vogelschlagrisikos für Tiefflüge

Reducing the Risk of Bird Strikes for Low-Level Flight Operations

Isabel C. Metz, German Aerospace Center DLR, Institute of Flight Guidance,
Markus Schwendener, FCS Flight Calibration Services GmbH

2022

Zusammenfassung

Abstrakt: Das Vogelschlagrisiko ist bei Operationen unter 3000 ft am höchsten. Daher sind Flugzeuge, die Flugoperationen in niedrigen Höhen durchführen, besonders anfällig für Kollisionen mit Vögeln. Die FCS Flight Calibration Services GmbH bietet Flugvermessungs- und Flugvalidierungsdienste an. Aus diesem Grund fliegen die Flugzeuge des Unternehmens hauptsächlich in niedrigen Höhen und damit im Hochrisikobereich. Aufgrund der steigenden Anzahl von Streiks bei FCS-Flugzeugen in den letzten Jahren hat das Unternehmen ein Forschungsprojekt initiiert, um mögliche Gegenmaßnahmen zu evaluieren. Zur Ermittlung von Risikofaktoren wurden die Vogelschlagmeldungen des Unternehmens auf Trends hinsichtlich Jahreszeit, Tageszeit, betroffene Flugzeuge und Standort analysiert. Um mögliche Gegenmaßnahmen zu finden, wurde eine Literaturrecherche zu Optionen zur Verringerung des Vogelschlagrisikos durchgeführt. Basierend auf den Ergebnissen wurden betriebliche Maßnahmen sowie Anpassungen am Flugzeug umgesetzt. Dieses Papier stellt die Projektergebnisse sowie eine erste Studie zur Wirksamkeit der Implementierung nach vier Jahren Betrieb vor.

Summary

Abstract: The risk of bird strikes is highest for operations below 3000 ft. Therefore, aircraft performing flight operations at low altitudes are especially vulnerable to collisions with birds. FCS Flight Calibration Services GmbH provides flight inspection and flight validation services. For thie reason, the company´s aircraft mainly fly at low altitudes and therefore in the high-risk-area. Because of an increasing trend in number of strikes occurring to FCS aircraft over the past years, the company initiated a research project to evaluate potential counteracting options. To determine risk-factors, the company´s bird strike reports were analyzed for trends with regard to season, daytime, affected aircraft and location. To find potential counteracting measures, a literature on options to reduce bird strike risk review was performed. Based on the results, operational measures as well as adaptions to the aircraft were implemented. This paper presents the project findings as well as an initial study of the implementation´s efficacy after four years of operations.

Reducing the Risk of Bird Strikes for Low-Level Flight Operations

Isabel C. Metz, German Aerospace Center DLR, Institute of Flight Guidance
Markus Schwendener, FCS Flight Calibration Services GmbH

BIOGRAPHY

Isabel C. Metz received her M.Sc. degree in Mobility and Transportation (cum laude) from the University of Technology in Braunschweig, Germany and her PhD degree from Delft University of Technology in the Netherlands. In her current position at the German Aerospace Center's Institute of Flight Guidance, she investigates the safety aspects of Urban Air Mobility operations with emphasis on bird/drone strike prevention. In 2017, Isabel joined FCS Flight Calibration Services GmbH, Braunschweig, Germany, for a one-year project. There, she evaluated solutions to reduce the risk of bird strikes for the company's aircraft fleet.

Markus Schwendener started his career in 1977 as technician at the civil maintenance unit of the Swiss Air Force and continued later on as avionics certifying staff for a major civil aircraft maintenance company. In 1985 he joined the Swiss Federal Office of Civil Aviation as flight inspector continuing this task until today for different companies. Beside his work as flight inspector, Markus worked as project leader for numerous flight inspection system integrations. Currently he is technical director for FCS Flight Calibration Services GmbH and responsible for the airworthiness of the aircraft and the future developments, certification, maintenance and operation of the flight inspection systems. Markus participated to all IFIS since 1988 and prepared and presented some papers.

ABSTRACT

The risk of bird strikes is highest for operations below 3000 ft. Therefore, aircraft performing flight operations at low altitudes are especially vulnerable to collisions with birds. FCS Flight Calibration Services GmbH provides flight inspection and flight validation services. For this reason, the company's aircraft mainly fly at low altitudes and therefore in the high-risk area. Because of an increasing trend in number of strikes occurring to FCS aircraft over the past years, the company initiated a research project to evaluate potential counteracting options. To determine risk-factors, the company's bird strike reports were analyzed for trends with regard to season, daytime, affected aircraft and location. To find potential counteracting measures, a literature on options to reduce bird strike risk review was performed. Based on the results, operational measures as well as adaptations to the aircraft were implemented. This paper presents the project findings as well as an initial study of the implementation's efficacy after four years of operations.

INTRODUCTION

Collisions between birds and aircraft, so called bird strikes, are a threat to aviation safety and cause economic loss (Thorpe 2014, McKee 2016). A bird strike is commonly defined as

> *a collision between a bird and an aircraft which is in flight or on a take-off or landing roll. The term is often expanded to cover other wildlife strikes - with bats or ground animals. (EUROCONTROL 2017a)*

The risk of bird strike occurrences is largest below an altitude of 3,000 ft ground (McKee 2016). Hence, aircraft flying below this altitude are especially endangered. Military aviation, general aviation as well as Search and Rescue operations belong to this group. Furthermore, aircraft performing flight inspection tasks such as the aircraft of FCS Flight Calibration Services have many flight segments at low altitudes. For FCS, this increased exposure has led to an increasing number of bird strikes over the past years. Several of those resulted in damage for the company's two Beechcraft King Air 300 aircraft. This aircraft is categorized as "Normal Aeroplane" as defined by the European Aviation Safety Agency CS-23 (EASA) and the Federal Acquisition Regulations (FAR) 14 CFR Part 23 by the Federal Aviation Administration (FAA) (EASA 2017, FAA n.d). These regulations set relatively weak requirements regarding impact resistance of aircraft components (cf. EASA 2017), As a result, the vulnerability to damaging bird strikes is increased. In their combination, the increased exposure and thus likelihood and the threat of damaging outcomes leads to a high risk for the FCS fleet.

The goal of the here presented project was to identify and implement mitigation measures with emphasis on reducing the likelihood of strike occurrences. To evaluate the impact of the chosen methods, the period prior to the integration was compared to a four-year post-implementation period. Since bird strikes have been identified not only as a safety but also as an economic issue (e.g. Dolbeer, et al., 2021), an in-depth analysis of costs related to the aftermath of bird strike events as well as the price to implement the selected was performed.

METHOD

To establish potential factors contributing to the increasing bird strike trend observed at FCS, the company's internal bird strike reports were analyzed for the period from 2005 to 2017, when the project took place, and compared to German statistics. These are most suitable since FCS mainly operates in this country. Subsequently literature research was performed to identify mitigation measures for the FCS fleet. Multiple of those were implemented between 2018 and 2019. To gain an initial insight of the measures' efficacy, the total number of strikes, the number of damaging strikes as well as the ration between those figures were compared. The latter has been identified as an important measure to account for reporting bias by previous studies (UK Civil Aviation Authority 2006, Dolbeer, 2015). To evaluate bird-strike related costs, a categorization model was defined. The results were compared to the investments to implement the mitigation measures.

Bird Strike Risk Analysis

To analyze factors contributing to the bird strike risk of FCS, the company's databases containing bird strike events served as source. Data was obtained from the company's occurrence reports and the aircraft's discrepancy reports. The FCS fleet includes two Beechcraft Super King Air and one chartered Learjet aircraft. Out of the 34 recorded bird strikes until the end of 2017, 32 occurred to an aircraft the Beechcraft fleet. The two strikes which occurred to the Learjet are too small for any statistical analysis. Hence, only the strikes occurring to the Beechcraft fleet are considered. Within the FCS data base, records of bird strikes are present from 2005 to date. No conclusion about the completeness of the reports could be drawn. Due to the small number of occurrences (n = 32) and missing information in some of the reports, conclusions from the statistics have to be drawn carefully.

The data was analyzed regarding the trend of bird strike occurrences, the seasonal distribution, the locations and the aircraft involved in bird strikes.

Mitigation Measures

To identify potential risk-reducing measures, the web was searched for studies on bird-strike prevention as well as reactions of birds to approaching vehicles or aircraft. The studies were evaluated regarding their findings, the efficacy of the presented solutions and the suitability of implementation within FCS.

Comparison of Bird Strike Occurrences

To analyze potential positive effects of the selected mitigation measures, the bird strike rate for the Beechcraft aircraft was calculated for the period prior and post implementation of mitigation measures and compared to bird strike statistics from civil aviation in Germany, where FCS mainly operates. The bird strike rate is defined as number of bird strikes per 10,000 flights (ICAO 2012).

The flight profiles of the FCS fleet differ significantly from the profiles of commercial airlines. After take-off, a commercial aircraft usually climbs to a cruise altitude of above 30,000 ft and only initiates a descent for landing at the destination airport (Nolan, 2003). In contrast, the profiles of flights for flight inspection, calibration and validation can include multiple low-level cruise phases in the altitude bands prone to bird strike. Hence, mapping the number of bird strikes to the number of flights of the FCS aircraft is only in parts representative for the risk of the fleet's bird strikes. Therefore, the bird strike rate was additionally determined when counting descents to low-level flight phases below 3,000 ft as landings as well. By adding these theoretical landings to the number of effective landings, a theoretical number of flights was calculated based on the four mission profiles of the Beechcraft as given by the Airworthiness Limitations Manual Supplement (Hawker Beechcraft 2010).

The number of theoretical landings per mission profile was weighted with the relative share of the respective mission profile to the total number of mission profiles. Their contribution to the total number of operations as well as the input values to calculate the average number of theoretical flights are provided by Table 1. The profiles themselves are displayed in Figure 1.

Table 1: Overview of flight profiles, their contribution to operations as well as the number of theoretical and effective landings

Profile	*Share (%)*	*Number theoretical landings*	*Number effective landings*	*Total number of flights*
1	50	22	2	24
2	20	0	1	1
3	15	4	1	5
4	15	0	1	1

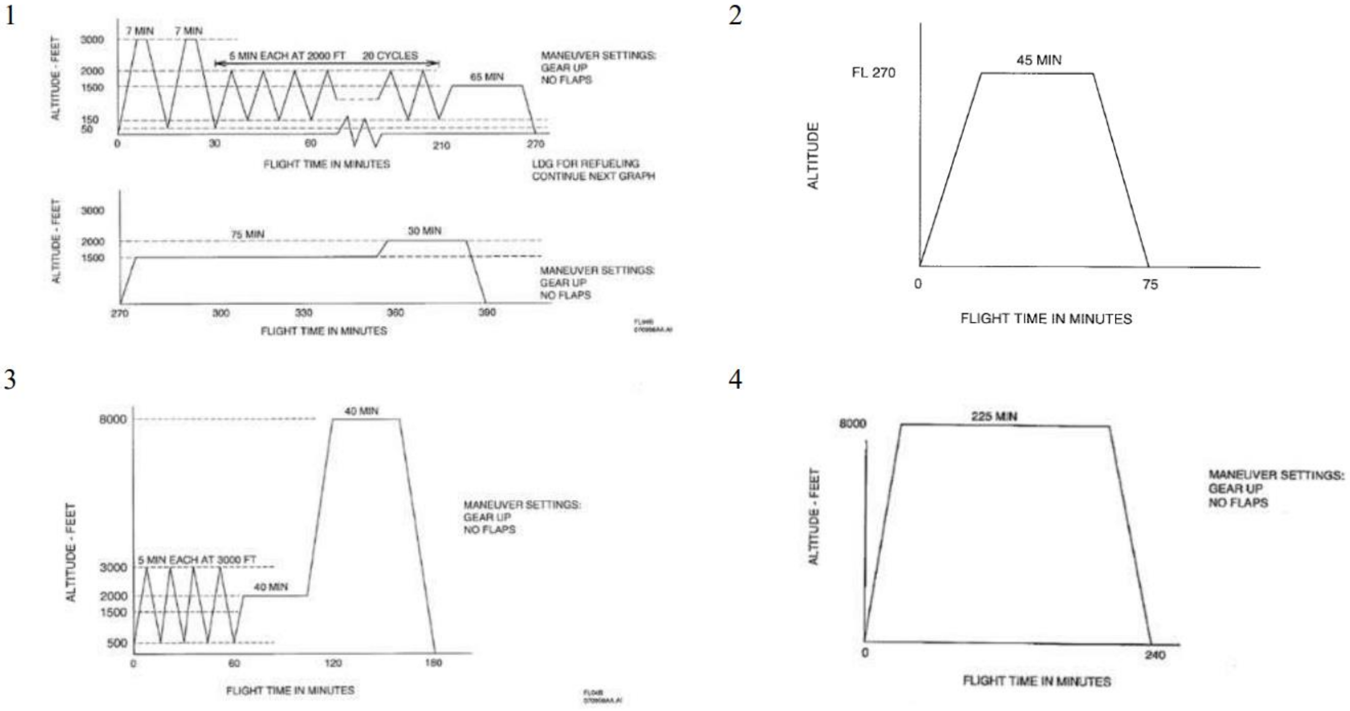


Figure 1: Flight profiles as operated by FCS

In Equation (1), the number of theoretical flights are calculated based on the shares and the total number of flights per profile.

$$\frac{24 \ast 50\%}{2} + 1 \ast 20\% + 5 \ast 15\% + 1 \ast 15 = 7.1 \qquad (1)$$

Studies from different countries determined that damaging bird strikes are usually reported while non-damaging strikes might not be reported due to unconsciousness of the bird strike occurrence or the ignorance of the importance of reporting (UK Civil Aviation Authority 2006, Dolbeer, 2015). With the initialization of the here described project in 2017, FCS introduced a strong emphasis of reporting all observed bird strikes within the internal reporting system. Therefore, higher bird strike rates for the post-phase have to be expected. To assess the magnitude of the reporting bias, the ratio of damaging to all bird strikes was calculated as well.

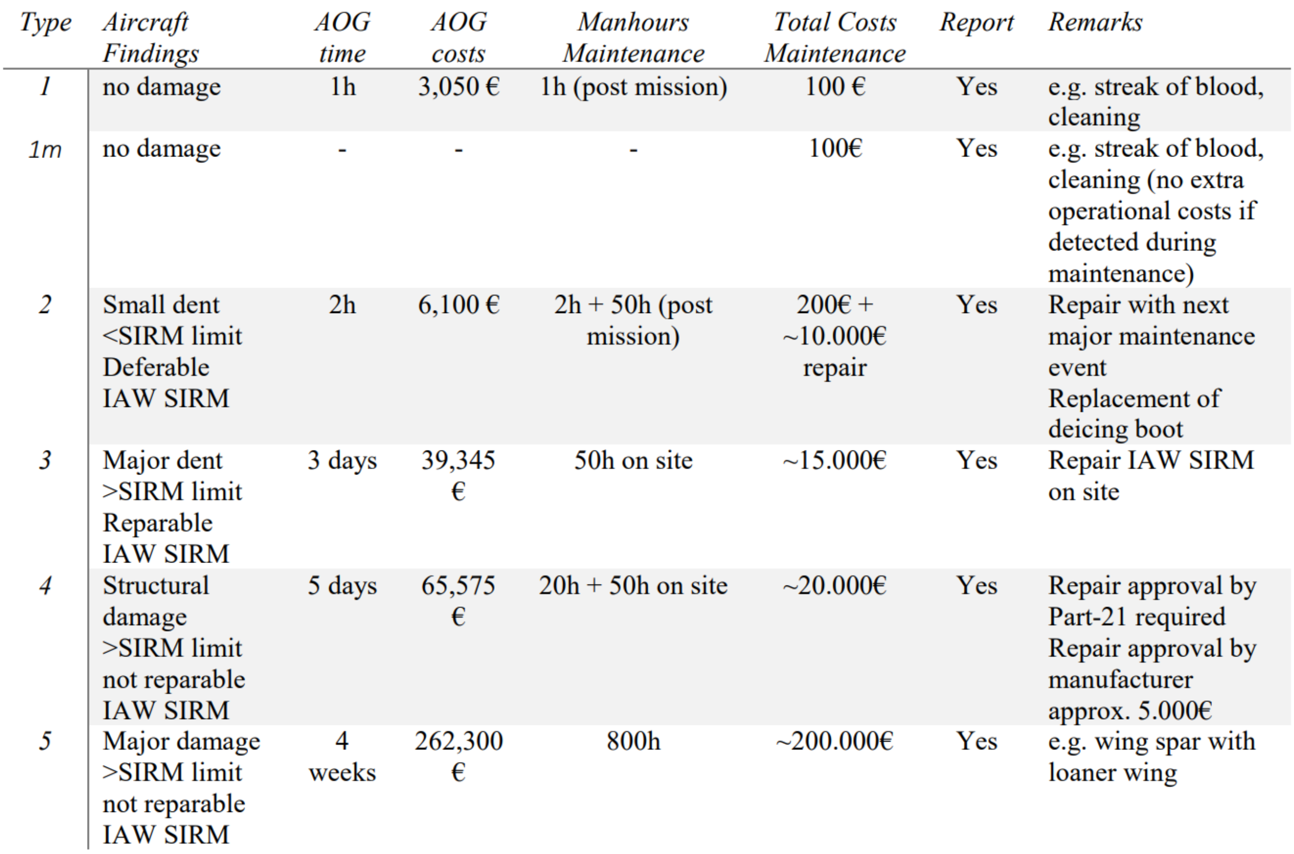
Cost-Benefit Analysis

To calculate an initial cost-benefit analysis of the selected measures, the following steps were performed. First, the costs of bird strikes for FCS were determined. For this purpose, a template to categorize bird strikes depending on the magnitude of operational as well as material costs for repairs was prepared. It can be found in **Table 2**. The difference between the categories *1* and *1m* is the time when the bird strike was detected. Following a bird strike whose occurrence is perceived in-flight, a landing must be performed to inspect the aircraft. This results in Aircraft on Ground (AOG) costs for the time needed for inspection (category *1*). In case that a non-damaging bird strike is only detected after landing, e.g. due to traces of blood or snarge, the cleaning can be performed in time reserved on ground in any case (category *1m*). Hence, no AOG costs occur.

Second, the bird strikes experienced were categorized respectively and average costs prior and post the implementation

calculated. Third, the costs for implementing the selected mitigation measures were summed up and added to the post- implementation costs.

Table 2: Categorization of bird strikes depending on magnitude of impact (AOG: Aircraft on Ground; IAW: In Accordance With; SIRM: Structural Inspection and Repair Manual)



Type	*Aircraft Findings*	*AOG time*	*AOG costs*	*Manhours Maintenance*	*Total Costs Maintenance*	*Report*	*Remarks*
1	no damage	1h	3,050 €	1h (post mission)	100 €	Yes	e.g. streak of blood, cleaning
1m	no damage	-	-	-	100€	Yes	e.g. streak of blood, cleaning (no extra operational costs if detected during maintenance)
2	Small dent <SIRM limit Deferable IAW SIRM	2h	6,100 €	2h + 50h (post mission)	200€ + ~10.000€ repair	Yes	Repair with next major maintenance event Replacement of deicing boot
3	Major dent >SIRM limit Reparable IAW SIRM	3 days	39,345 €	50h on site	~15.000€	Yes	Repair IAW SIRM on site
4	Structural damage >SIRM limit not reparable IAW SIRM	5 days	65,575 €	20h + 50h on site	~20.000€	Yes	Repair approval by Part-21 required Repair approval by manufacturer approx. 5.000€
5	Major damage >SIRM limit not reparable IAW SIRM	4 weeks	262,300 €	800h	~200.000€	Yes	e.g. wing spar with loaner wing

COVID-19

The COVID-19 pandemic influenced both, the schedules of FCS as well as the abundance of birds. Both elements influence the risk and especially the likelihood of bird strikes, however, in a conflicting manner. In 2020 and 2021, FCS reduced the number of airports from which they operated. Hence, the performed flights included more ferry-segments to and from airports which would usually be landed at. The share of these shuttles above 3,000 ft amounted to ca. 5% of the total flight time. In exchange, the time spent in holdings at airports below 3,000 ft was reduced. In addition, approximately 20 % of operations which are usually being flown during night-time were performed during the day in 2020. Higher shares of flights at higher altitudes and during the day would both be expected to reduce the likelihood of strikes (Dolbeer & Cleary, 2005, Dolbeer, 2021).

In contrast, multiple studies and statistics reflect an increase in bird strike rates due to the pandemic. For example, the German bird strike rate experienced an increase of about 20 % in contrast to the previous years (DAVVL 2021, DAVVL 2022). Contributing factors may lie in the reduced activities of wildlife management programs at airports and the missing dispersal effect of aircraft themselves, leading to higher bird activity at and around airports (Malka, 2021, Mountain and Giordano 2020, Parsons, Malouf & Martins, 2022). Since it is difficult to judge the magnitude of these counteracting elements, the conclusions drawn from the comparison with the years of 2020 and 2021 have to be interpreted attentively.

RESULTS

This section first presents the mitigation measures identified within the literature review as well as the ones selected for introduction within FCS. Thereafter, the bird strike numbers prior and after their implementation are compared to each other as well as to German bird strike statistics. Finally, the costs of bird strike as well as the ones for implementing the mitigation measures are evaluated and a cost-benefit ratio is calculated.

Mitigation Measures

The FCS fleet mainly operates at low altitudes and therefore in areas with high bird abundance. In addition, their Beechcraft King Air aircraft have a high vulnerability of damaging strikes. This results from the limited impact resistance requirements which the aviation authorities demand in their airworthiness standards for *Normal Aeroplanes* (CS-23, EASA 2017), to which these aircraft types belong. The relevant paragraphs from EASA's specification requirement for this aircraft category in CS-23 read as follows:

Windshield panes directly in front of the pilot(s) in the normal conduct of their duties, and the supporting structures for these panes must withstand, without penetration, the impact of a 0·91 kg (2 lb) bird when the velocity of the aeroplane relative to the bird along the aeroplane's flight path is equal to the aeroplane's maximum approach flap speed. (EASA 2017 CS 23.775 Windshields and windows).

For commuter category aeroplanes, where duplicate airspeed indicators are required, their respective pitot tubes must be far enough apart to avoid damage to both tubes in a collision with a bird. (EASA 2017, CS 23.1323 Airspeed indicating system).

No structural resistance has to be proven by aircraft certified by CS-23 standards, as it would be for Large Aeroplanes certified by specifications of CS-25 (EASA 2019). The King Air aircraft has the additional disadvantage of a relatively large front wing area due to the thick profile of the leading edge. In addition, the rubber de-ice system limits the chance of birds to slide off the wing which increases the risk of an actual impact.

To reduce the risk of bird strikes for low-flying aircraft, some countries provide Notice to Airmen information (NOTAMS) considering bird activity, so-called BIRDTAMs. These contain forecasts for increased bird densities, especially during the migration season. In Germany, the German Bundeswehr Geoinformation Office provides BIRDTAM information for the entire country, updated every 30 minutes (https://www.notams.faa.gov/common/birdtam.html). Furthermore, airports provide BIRDTAMs about bird activity in their vicinity. These different forms of BIRDTAMs have in common that their resolution in the timely and areal perspective is very low. Hence, they serve as general information about bird activity. In addition, changes in the calibration program due to BIRDTAM predictions on short notice may conflict with scheduled airport calibration slots and navigation aid NOTAMs. Hence, they require a careful assessment.

Some countries such as the US, Israel, the Netherlands and Belgium offer information with higher resolution (Dekker et al. 2008, McKee 2016, Flysafe homepage, n.d.). These initiatives are usually driven by the military forces and available to the public. For example, the Dutch-Belgian Flysafe project offers *near real-time measurements of local bird movements, altitude profiles of bird densities as well as forecasts of bird migration intensity over the Netherlands and Belgium* (Dekker et al. 2008, Flysafe homepage, n.d.). Air forces which use such information for their planning of low-level training flights could reduce the number of damaging bird strikes by 45 % (van Gasteren, et al., 2019). Options to support pilots and controllers with real-time information have been investigated (Metz, et al., 2021) but, with few local exceptions[1], not operational yet.

There are options for the aircraft operator to independently reduce the individual risk of bird strikes however. These involve technical adaptations to the aircraft as well as operational measures. They are described in the subsequent paragraphs.

Research has shown that many bird species[2] try to avoid approaching aircraft. However, they often fail to escape a collision due to slow or delayed reaction. This can be caused by a late perception of the threat, habituation to air traffic or misjudgment of the approaching threat. Hence, it is suggested that increasing the conspicuity of an aircraft reduces its risk of bird strikes (Lima 2005, Bernhardt et al., 2010). For example, Burger (1983) determined that aircraft that generate more noise and therefore can be perceived from a further distance, experience less bird strikes. More recent studies target different sensory channels. Sheridan et al. (2015) focused on the influence of stationary or moving radar on bird reaction to aircraft. The study's results indicate that an active radar increases the alertness of birds to the approaching aircraft which enhances their chance for a successful escape (Bernhardt et al. 2010). Newcamp (2016) presented an aircraft-mounted system to trigger the aural and visual channels of birds to allow them to perceive approaching aircraft earlier. The underlying concept was filed with the US patent office in 2015 and is yet waiting for approval (Newcamp 2016, J. Newcamp, Delft University of Technology, PhD candidate, personal communication 7/11/2017). The remaining research projects of the past years focus on exclusively increasing the visibility of aircraft. Research was performed on the effect of various aircraft lighting, different fuselage colors and striped propellers. Blackwell et al. (2004, 2009, 2012) performed various studies on reaction of birds to aircraft with different lighting. This includes stationary as well as pulsing light in different frequencies. The authors show that different species react differently to different light treatment. Furthermore, the bird's reactions depend on the surrounding light conditions. The authors conclude that pulsing light does have the potential to increase avian visual awareness. However, depending on the species, different pulse frequencies and wavelengths of light might be required as different birds have a different visual perception (Blackwell & Bernhardt 2004). Blackwell et al. (2012) conclude *that vehicle-mounted lighting can influence avian alert behavior depending (among other factors) upon the sensory system of the target species and ambient light conditions.* As a consequence, when choosing the right pulsing frequency and light wavelength, an earlier response to approaching vehicles can be triggered. The difficulty in applying a specific system lies in finding light parameters influencing as many species as possible respectively the critical species. The reason is that the light spectrum perceived by different species might differ as well (Blackwell et al. 2016).

Up to the author's knowledge, one commercially available product, the Pulselite system by PreciseFlight is available on the market applying the concept of pulsing light on aircraft. The system pulses an aircraft's existing landing and recognition lights to enhance its visibility and the conspicuity of the aircraft's flight path. As a result, pilots of other aircraft as well as wildlife can detect and avoid the equipped aircraft better. The aircraft's lights are pulsed with a frequency of approximately 46 times per minutes in a fixed pattern. The pulsing function can be overridden by the pilot, if desired. The system is optionally connected to an aircraft's Traffic Alert and Collision Avoidance System (TCAS). Once the TCAS releases a Traffic Advisory (TA), the system is automatically activated. A positive side-effect of the installation lies in an enhanced lifetime for lamps. Due to the pulsing of the lights between 20 and 80% of the lamp's power, the lamp remains cooler and the lamp's wear sinks. The system is approved by the Federal Aviation Administration (FAA) and accepted by EASA for the majority of fixed and rotary wing aircraft. It is available for general aviation aircraft, commercial aircraft as well as military and transport aircraft. After multi-year trials with Alaska Airlines and Qantas Airlines, the company claims that the system has the potential to reduce the risk of bird strikes by 30 to 66% for commercial aircraft (Precise Flight 2018).

A study by Fernández-Juricic et al. (2011) analyzed the influence on fuselage color on the number of bird strikes. The study's results indicate that aircraft with brighter fuselages (rear or both, front and rear section) experience fewer bird strikes than aircraft with dark fuselages. This results from the higher contrast that these aircraft build in towards the sky. The results were significant for the aircraft types Boeing 737-, DC-9 and Embraer RJ145. Two limiting factors in the study's method should be considered. First, the study based on reported bird strikes which might be biased towards damaging bird strikes. Second, factors that could have influenced the concluded relationship between fuselage color and risk of bird strike rate such as ambient light conditions were not considered. Still, the authors conclude that it is likely that *"enhancing aircraft visually through a bright color scheme might facilitate a bird's ability to detect and distinguish aircraft shape in time to perform avoidance behavior."* (Fernández- Juricic, et al. 2011).

For propeller-driven aircraft, an additional option to increase the contrast is to apply paint to the propellers. A

---

[1] To the authors knowledge, there are three airports where Air Traffic Control is supported with specific information on bird movements in the critical areas: Durban, South Africa, Riga International Airport, Latvia and Warsaw-Modlin Mazovia International Airport, Poland (Atkins 2013)

[2] some birds of prey see aircraft as intruders in their territory and therefore attack instead of avoid them (Carrier & Melquist 1976; Pennycuick 1972)

study performed by the FAA (Welsh, et al., 1978) had analyzed three different layouts of propeller paintings for their increase in conspicuity (in general, not for bird strikes). Within the study, 30 FAA employees were asked to judge the increase in visibility of the three layouts from three different viewing angles. According to the study's results, a black- and white painting has the highest effect.

From 2012 to 2017, Widerøe Airlines and the Natural History Museum of the University of Oslo tested, if such a black- and white layout could help to reduce the risk of bird strikes. The layout as defined by the FAA as well as applied on the aircraft of Widerøe are shown in Figure 2.

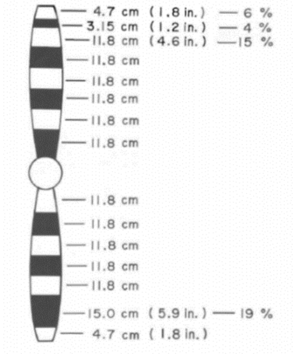


Figure 2: Pied propeller layout as defined by the FAA (Welsh, et al., 1978)

Table 3 summarizes the fleet of Widerøe Airlines and the number of aircraft participating in the study. The study compared the bird strike rates of the respective fleets for two years without painted propellers against two years including painted propellers. For the Dash 8-Q400 fleet, where no paintings were performed, the rates were compared as well. **Table 4** visualizes the results.

In general, statistical results can be interpreted as significant (i.e. reproducible), if their p-value is smaller than 0.005. In this study, only the results for the Dash 8-100/200 fleet are significant. This could be related to the different sample sizes of the fleets. The Dash 8-100/200 fleet experienced a decrease in bird strike rate while the rate increases for the Dash 8-300 fleet. When interpreting these mixed results, it has to be considered that overall sample size is limited and the period with painted propellers only amounted to one year. In addition, the report gives no indications, whether the changes in bird strike rates result exclusively from the change in aircraft appearance due to the painted propellers or whether there are other influences as well such as an increase in reporting or flights during more/less critical seasons or times of day.

Nevertheless, based on the results of the Dash 8-100/200 fleet on the bird strike rate as well as the increased visibility of the aircraft for ground personnel, Winderøe Airlines has decided to keep the design with the painted propellers. (Aas and Johansen 2018, C.Aas, Researcher, Natural History Museum of Oslo, personal communication 06/03/2018).

Table 3: Fleet Widerøe Airlines

aircraft type	*number*	*number included in study*	*number painted for study*
Dash 8-100/200	23	20	20
Dash 8-300	7	7	7
Dash 8-Q400	11	7	0

Table 4: Bird strike rates of Widerøe Airlines with and without painted propellers

aircraft type	*bird strike rate without painted propellers (2010-2011)*	*bird strike rate with painted propellers (2016-2017)*	*p-value (significance)*
Dash 8-100/200	0.42	0.16	0.003
Dash 8-300	0.52	0.92	0.06
Dash 8-Q400	1.02	1.29 (not painted)	0.11

A factor that counteracts the efficacy of increased aircraft visibility adaptations is velocity. Studies found that birds initiate an escape at a given, probably species-specific, distance from an approaching aircraft or vehicle. Aircraft-mounted devices to increase its perceptibility can increase this distance. However, the time gained by the earlier perception reduces with increasing speed as the aircraft needs less time to travel the distance the bird starts its escaping behavior at. (Blackwell et al. 2016). Hence, the authors suggest that the chances for successful escapes rise mainly when aircraft are taxiing but not during take-off, landing and flight, when the vehicle's velocity is significantly higher. This is supported by DeVault et al. (2014 and 2015) who found in experiments with turkey vultures and brown-headed cowbirds that the animals had difficulties to perform a timely escape once an oncoming vehicle was travelling faster than 90km/h (49 kts; turkey vulture) respective 120km/h (65 kts; brown-headed cowbird). Doppler et al. (2015) even found that birds (brown-headed cowbirds) react with an increasing delay when the vehicle approaches with higher speeds. This increases the risk for a strike, as the bird has even less time to escape. According to the authors, this negative speed effect can, to some extent, be reduced by increased aircraft lighting. Nevertheless, reducing flight speed as much as possible during low-level operations is advisable both to provide birds with enhanced chances for avoidance as well as to reduce the impact in case of a strike.

With regard to operational measures, the pilots can inform themselves on the current bird strike risk by consulting BIRDTAMs, NOTAMs and the bird migration reports regularly published by the German Bird Strike Committee (DAVVL 2018). Additionally, by contacting wildlife control at frequent airports, current local information can be obtained. During operations, the pilots should always be alert to a potential bird strike. While taxiing, they should scan their surroundings for wildlife activity. If in doubt, rather than taking off, they should alert air traffic control and delay their departure. Additionally, the sky should be regularly scanned during low-level operations and approach. In case that birds are spotted in the distance and there is a realistic chance of avoiding them successfully, a corresponding maneuver should be performed (AOPA 2012). In case that the aircraft experiences a collision with a bird, the optimum reaction depends on the flight phase. During departure, a take-off should only be aborted, if the aircraft is still below V0. If the aircraft has already passed this velocity, the take-off has to be performed and a return to the airport considered. Subsequently to in-flight bird strikes, it is crucial to immediately check the controllability of the aircraft and to consider a safety-landing at the closest airfield. If the windshield was damaged, the aircraft should be flown at minimum speed to reduce the risk of further damage. During approach, a go-around should only be performed, if the birds are sighted from a distance large enough to pass them in a safe distance. If an avoidance maneuver is unlikely to be successful or if birds have been hit, the approach should be continued because

The full extent of any damage, to the engines and/or the control surfaces and landing gear, may not be apparent until applying power, configuring, or maneuvering the aircraft. It might therefore be the case that, if a go-around is initiated, the pilots rapidly finds themselves in a situation where the runway is disappearing beneath them but the aircraft cannot safely fly a missed approach. (EUROCONTROL 2017b).

Selected Measures

Based on the results from the literature review, it was decided to implement pulsing lights and to paint the propellers with the pattern as suggested by the FAA (Welsh, 1978). The propellers were painted with Photoluminescent Safety Paint to benefit from the phosphorescence during night calibration. Furthermore, pilot’s awareness for the risk of bird strikes was increasingly trained during the regular safety-training and the importance of reporting emphasized. Finally, the aircraft were equipped with forms to report and materials to sample and post bird remains directly from all potential countries of destinations in order to send them for DNA analysis.

The installation of the pulsing lights and the paintings of the propellers took place on the dates indicated in Table 5. Since the painting of propellers took place in alignment with maintenance activities, there are different dates for the left and right propeller of each aircraft. The aircraft D-CFMD ended its service in February 2020. Its successor, D-CFMF started operating in July 2019.

Table 5: Dates of instalment for pulsing lights and propeller paintings

Aircraft	*Pulselight*	*Propeller Painting*	
		#1 (left)	*#2 (right)*
D-CFMD	July 2018	November 2018	December 2018
D-CFME	July 2018	October 2018	December 2019
D-CFMF	August 2019	December 2019	December 2019

Bird Strike Risk Analysis

The risk analysis was performed at the beginning of the project and includes FCS flights up to the end of 2017. Since the beginning of recording at FCS in 2005, the number of bird strikes occurring to FCS aircraft were generally increasing until the start of the project, as **Figure 3** shows. All figures refer to data from the Beechcraft aircraft. Within the FCS database, some strikes were marked as having occurred to the Beechcraft fleet, but not to which of the two aircraft. These occurrences are only reflected in the bar *all flights*.

The seasonal distribution (cf. Figure 4, left) of strikes shows an increased risk in early spring, mid-summer and autumn. This reflects the general dependency of bird strike risk on time of the year as found in literature: During spring and autumn, broad front bird migration leads to increased bird activity. In late spring, birds are breeding and thus airborne less frequently. This leads to a reduction of bird strike events. In June and July, juvenile birds fledge and learn to fly. Due to their lack of experience, they cause significantly more bird strikes than adult birds. (van Gasteren, et al., 2014, Ebert and Pfleging, 2016).

However, when comparing the bird strike occurrences of FCS to statistics from Germany (Figure 4, right) in in detail, two differences become apparent. The FCS aircraft experienced more strikes in the month of October and less in summer. The connection most likely lies in the time spent airborne. Civil aviation has most flights between May and October (Figure 4, right) with a peak in June and July. In contrast, the number of flights at FCS peak in October while having a local minimum in June and July (Figure 2, left).

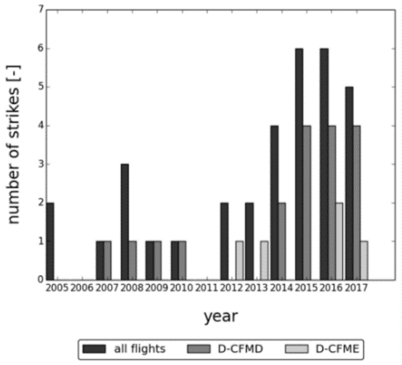


Figure 3: Number of FCS bird strikes between 2005 and 2017.

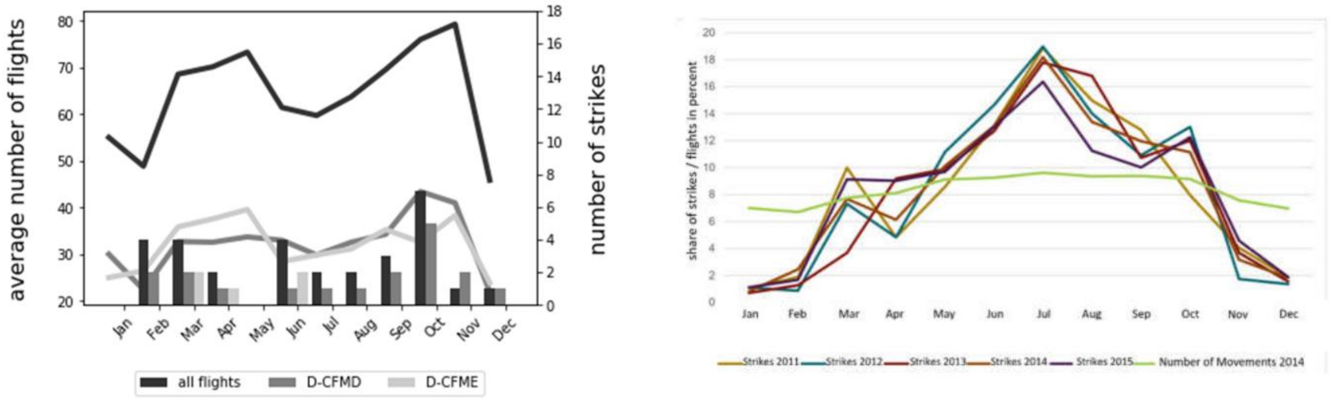
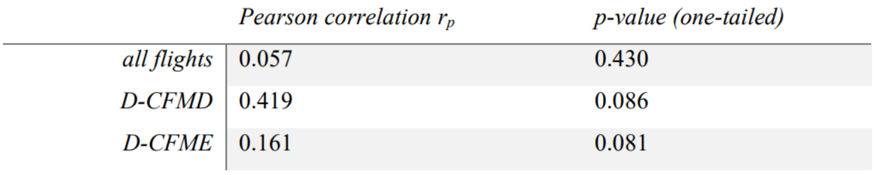


Figure 4: Seasonal distribution of flights (lines) and bird strikes (bars) with FCS aircraft from 2005 to 2017 (left) and seasonal distribution of bird strikes in Germany from 2011 to 2015 (right; source: Ebert and Pfleging, 2016, axes translated from German)

Within the FCS data, except for the month of October, there is barely any correlation between number of strikes and number of flights per month as **Table 6** shows. Furthermore, the results are all insignificant and the sample size is very small. Still, there is an indication that the season influences the bird strike risk more than the time of exposure. Another influencing factor could be the daytime of flight. The risk of bird strike is highest around sunrise and sunset, as well as during the night (Cleary, et al, 2003).

Table 6: Correlation between number of flights and number of bird strikes per month



	Pearson correlation r_p	*p-value (one-tailed)*
all flights	0.057	0.430
D-CFMD	0.419	0.086
D-CFME	0.161	0.081

The FCS statistics were analysed regarding the location where bird strikes occurred. Of the 22 cases, where the place of the bird strike occurrence is given in the data, 8 (36%) happened in the vicinity of Frankfurt airport (EDDF) while the remaining 14 strikes took place all over Germany, Switzerland and Austria.

Among the airports served by FCS, EDDF is the airport with most landing systems to be calibrated[3]. Hence, the required flight time and thus the time of exposure to the risk of bird strike is much higher than for other airports. Furthermore, the flights at EDDF usually take place during the night. The following paragraph elaborates on the enhanced risk situation at EDDF.

In general, when normalizing number of bird strikes to number of flights, more occurrences take place during the night than during daytime (cf. Cleary, et al, 2003 and Dolbeer 2006). This is caused by increased bird activity, especially the one of migrating birds (Alerstam 2009). Furthermore, due to the reduced visibility, it is more difficult for birds to see aircraft and for pilots to see birds, which exacerbates the chance for collision avoidance. Two risk factors present specifically at EDDF might also have an influence. First, flight restrictions are effective between 23:00 and 05:00. This is the period when FCS is flying at the airport. Consequently, all EDDF strikes occurred in the night. Due to the missing of other traffic, birds might be less vigilant which increases their reaction time and limits the chances for successful escapes. Second, in this period, Wildlife Control at EDDF is not on duty and thus no harassment of birds takes place.

According to Petri (2003), compared to the other runways, there is an increased risk of bird strike on the North-East runway at EDDF due to two reasons. First, the runway is located adjacent to the Mönchwald lake, which is an important resting area for water fowl during winter. Second, the approach corridor of 07L / the departure path of 25R crosses the river Main at relatively low heights. During migratory season, the Main river bundles migratory birds. Because of the ICE bridge and the bridge of the highway close to the airport, birds are forced to fly in an altitude of at least 60 m at this point. Aircraft approaching runway 07L cross the river in approximately 120 m height (Petri 2003). The remaining, major part of the airfield is less critical, as it is mainly surrounded by forests which most birds avoid.

In the pre-phase, 32 of the 34 FCS bird strikes occurred to one of the Beechcraft Super King Air aircraft, the remaining two to the Learjet. Of the 22 bird strikes, where the registration of the affected Beechcraft aircraft is known, 17 happened to the aircraft with the registration "D-CFMD". Out of those, seven of the strikes, where the location is known, took place at EDDF during nighttime. As the two Beechcraft aircraft are identical in construction and appearance, the aircraft's schedule and thus risk exposure might be responsible for this unequal distribution among them.

Of the strikes with known daylight conditions, 67% took place during night (n = 8) and 33% during daytime (n = 4).

Bird Strike Occurrences in the Post-Phase

In total, 33 strikes were experienced by the FCS fleet between 2018 and 2021, of those 10 by the D-CFMD (30%), 14 by the D- CFME (42%) and 9 by the D-CFMF (27%). This corresponds better with the time in service than in the pre-implementation phase – and with duration of periods in which the airframe measures were completed (cf. **Table 5**). The D-CFMD flew for 26 months (of which 14 months with completed installation), the D-CFME for the entire 36 months (of which 31 months with completed installation), and the D-CFME for 29 months (of which all months with completed installation), in that period. Five strikes happened in EDDF, four of which during night time and four strikes took place in LSZH, of which three during the night.

The distribution of strikes per daytime and year can be found in **Table 7**. The higher number of daytime strikes in 2020 corresponds to the reporting of more daytime flights in that year.

---

[3] 8x ILS in EDDF, 4x in LSZH and LOWW

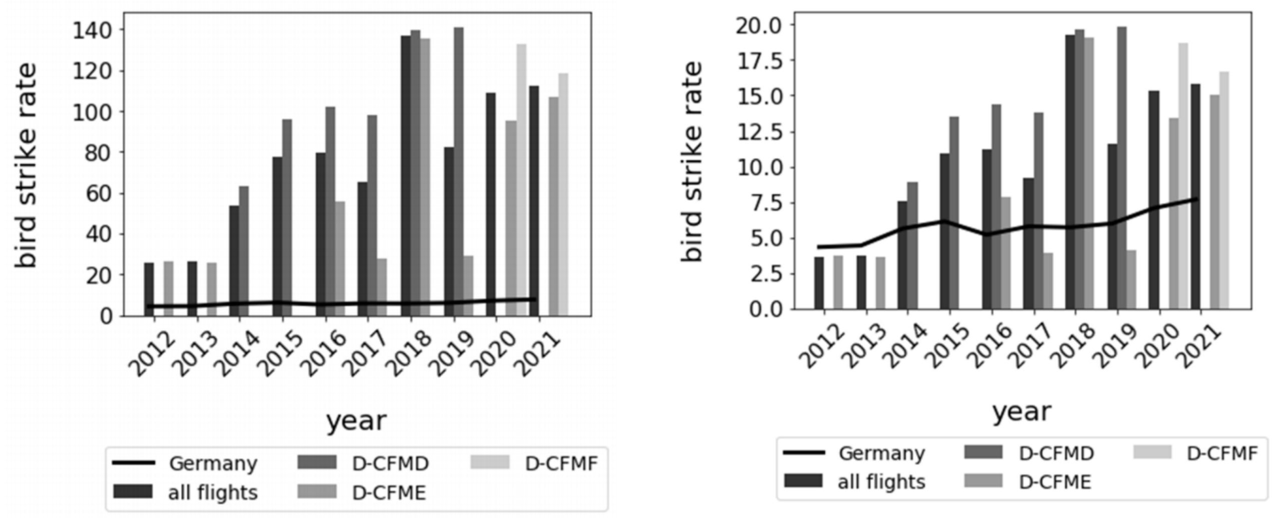
Table 7: Distribution of strikes in the post-phase by daylight conditions

Year	Day	Night	Total
2018	3	7	10
2019	1	5	6
2020	6	3	9
2021	4	4	8

Comparison of Bird Strike Occurrences

For the evaluation of potential changes in bird strike occurrences, the bird strike rates, expressed in number of strikes per 10,000 landings, were calculated for the period of 2012, from which flight data was available, to 2021. The period of 2012 to 2017 represents the pre-implementation period, the years from 2018 to 2021 the post-implementation periods. The time in which the propellers were only partially painted (between 2018 and 2019, cf. Table 5) are included there to avoid further scattering of the data.

Figure 5 shows the bird strike rates for the FCS fleet as well as for Germany for the entire period. Figure 5a considers all effective landings of the FCS fleet. Figure 5b incorporates the factor to calculate the number of theoretical landings to account for the FCS-specific flight profiles, descending to below 3,000 ft multiple times per flight. It can be seen that when only counting the effective flights, the bird strike rates are much higher for the FCS aircraft than for the German average. When considering the theoretical number of flights to account for the low-flight phases, the strike rates lie closer together. Still, the rate for the FCS flights is higher what conforms to the hypothesis of an increased risk of bird strike for the company's flights. Since the *all flight* bar represents the average rate of all aircraft, the rates of individual aircraft can be higher. The bird strike rates of *all flights* rise in 2018 before lowering again in 2019. In 2020 and 2021 the rates increase again somewhat as they do for the German average.



a) number effective landings

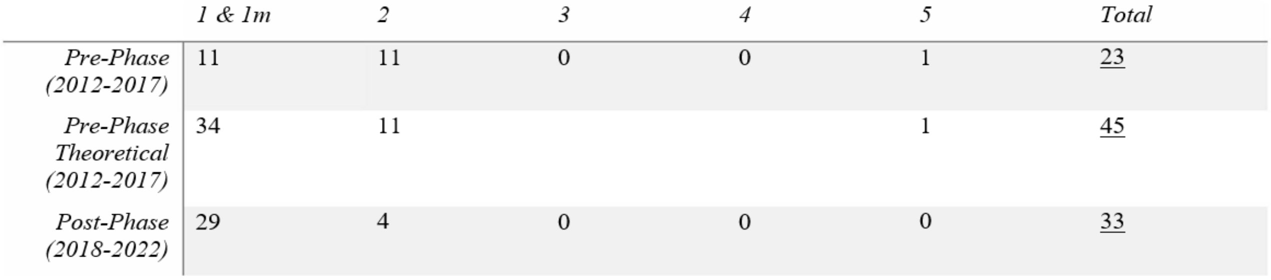
b) number theoretical landings (factor 7.1)

Figure 5: Bird strike rates of the FCS fleet and for Germany (Source: DAVVL 2020, 2021)

To evaluate the potential influence of reporting bias, the distribution between non-damaging and damaging strike rates was considered. In the pre-period, 11 strikes were reported as non-damaging (categories *1* and *1m*). Of the 12 damaging strikes, 11 were assigned to category *2* and one to category *5.* The ratio of all damaging to all non-damaging strikes amounts to 0.85. In addition, the number and rate of strike types per year was compared for the two phases.

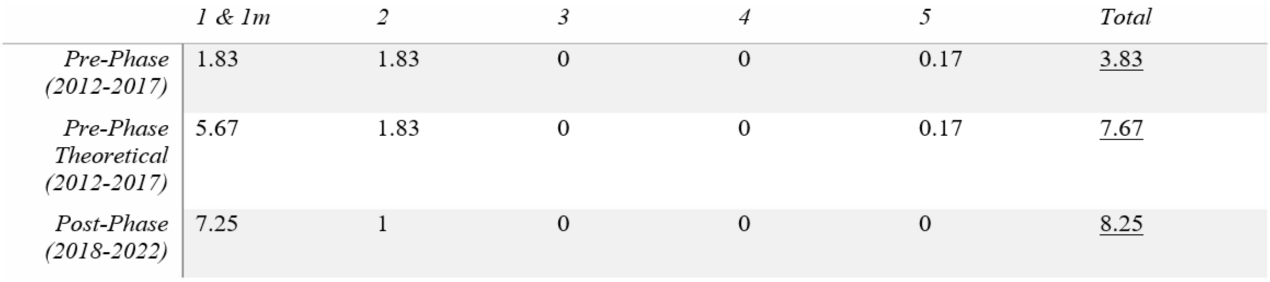
Table 8 presents the numbers of strikes, while **Table 9** provides the calculated number of strikes per year and phase. An internal estimate concluded that in the pre-phase, approximately 50% of strikes were not reported. Since it can be expected that strikes with damaging outcome are always reported, these additional collisions would fall in the categories *1* or *1m*. Therefore, the rows *Pre-Phase Theoretical* includes the anticipated missing strikes for category *1* and *1m*. It can be seen that, while the original total rate of the pre-phase is much lower than the one of the post-phase, the theoretical rates of the pre- and post-phase lie much closer together. In the post-period, 29 strikes were reported for the non-damaging categories *1* and *1m* and four to the damaging category *2*. The damaging to non-damaging ratio amounts to 0.14 which is significantly lower than the ratio of the pre-period.

Table 8: Number of strikes per observation phase and category. The row *Pre-Phase Theoretical* includes anticipated missing reports in category *1* and *1m*



	1 & 1m	*2*	*3*	*4*	*5*	*Total*
Pre-Phase (2012-2017)	11	11	0	0	1	23
Pre-Phase Theoretical (2012-2017)	34	11			1	45
Post-Phase (2018-2022)	29	4	0	0	0	33

Table 9: Strike rates per observation phase and strike category. The column *Pre-Phase Theoretical* includes anticipated missing reports in category *1* and *1m*



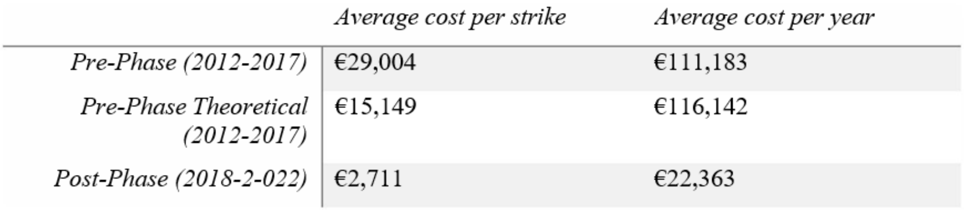
	1 & 1m	*2*	*3*	*4*	*5*	*Total*
Pre-Phase (2012-2017)	1.83	1.83	0	0	0.17	3.83
Pre-Phase Theoretical (2012-2017)	5.67	1.83	0	0	0.17	7.67
Post-Phase (2018-2022)	7.25	1	0	0	0	8.25

COST-BENEFIT ANALYSIS

The painting of the propellers cost €12,160 per aircraft, the installation costs for the Pulselite system amounted to €4,850 per aircraft. As such, the total costs for performing the adjustments to all three aircraft amounted to €51,030.

The strike costs for the pre- and post-phase were calculated as well for the effective as well as the theoretical number of strikes, incorporating non-reports, as provided in **Table 8**. The costs per category are the sum of AOG and maintenance costs as previously calculated in **Table 2**. To calculate costs for the theoretical number of strikes in categories 1 and 1m, the average costs of these two categories were used. Including theoretical strikes strongly lowers the average strike cost for the pre-year. This can be attributed to the category 5 strike (costs of €462,300) which strongly influences the average. By adding 23 strikes with a cost of €1625, the average reduces significantly. Still, the average costs per year in the pre-phase slightly increases due to the additional strikes. The average post-phase costs lie well below the pre-phase costs, both per strike and per year. This, again, can be mainly attributed to the single category 5 strike of the pre-phase. The resulting costs are presented in **Table 10**.

Table 10: Average bird strike costs per strike and year for the pre- and post-phase



	Average cost per strike	*Average cost per year*
Pre-Phase (2012-2017)	€29,004	€111,183
Pre-Phase Theoretical (2012-2017)	€15,149	€116,142
Post-Phase (2018-2-022)	€2,711	€22,363

DISCUSSION AND CONCLUSIONS

The here presented project aimed at achieving a better understanding of the causes for an increased number of bird strikes to the FCS fleet, to identify potential mitigation measures and to evaluate their efficacy.

The FCS fleet operates at altitudes where bird abundance is highest. In addition, many flights take place during night in which there is an increased bird activity. This is reflected by the bird strike numbers – in the years with regular night-time operations and except for 2021, the majority of strikes took place during the night even though the majority of flight hours are performed during the day When including theoretical landings by counting every entering airspace below 3,000 ft as a landing, the bird strike rates of the FCS fleet and Germany became comparable and demonstrated the increased risk for the FCS fleet. General trends between the two figures correspond in the two COVID-years of 2020 and 2021, where an increase took place in both.

Based on a thorough literature study, multiple measures to mitigate the bird strike risk. Since the possibilities of flight planning are reduced due to the dependencies of the airports' traffic schedules, they focused on increasing the conspicuity of the aircraft. Pulsing lights were installed and the propellers painted with a black-white pattern. In addition, an increased emphasis on situational awareness and the importance of bird strike reporting was introduced to the safety trainings.

The bird strike rates in the years after the project completion increased which seems counterintuitive. An analysis of the types of reported strikes in the prior and post-implementation phase revealed a strong offset in the ratio between damaging and non- damaging strikes. In the pre-phase, it amounted to 0.84, in the post-phase to 0.14. This suggests a strong reporting bias towards damaging strikes in the pre-phase. A further indicator is the strongly increased information reported by strike. In the pre-phase, information on the affected aircraft, daylight condition and location of occurrence could only partially be extracted. In the post- phase, it was available for all reports. By accounting for the assumed reporting bias by approximating underreporting of strikes in the pre-phase by 50%, similar ratios of bird strikes per year (pre-phase: 7.67; post-phase: 8.25). Due to mixed influences of the COVID-19 pandemic, the partial installment of pulsing lights and propeller paintings in the first part of the post-period and an overall low sample size, a final conclusion on the efficacy of the implemented measures cannot be drawn. For this purpose, further observation over multiple years, for which the strongly increased data quality builds a strong foundation, would be advisable.

From an economic perspective, the average cost per strike and year was significantly lower in the post-phase. This can mainly be attributed to one strike of the costly category *5* in the pre-phase. With the cost for the installments corresponding to one strike of category *3* if considering the price for all three aircraft, FCS regards the investment as reasonable. Even though the number of strikes which did not happen due to the installment cannot be determined, the prevention potential as well as the better visibility for all airspace users as well as ground personnel are appreciated.

In addition of the installments, also operational measures can be considered to reduce bird strike risk. Flight planning can, as far as feasible, be performed based on bird abundance obtained from BIRDTAMs or the bi-weekly newsletters from the German Bird Strike Committee. In addition, flights during daytime should be preferred. To reduce impact during flight, speeds should be minimized and the pilots maintain situational awareness for the possibility of strikes.

REFERENCES

Aas, C. K. and Johansen, B. (2018). The propeller-painting project of Widerøe - status by February 2018.

AOPA Germay e.V. (2012) AOPA Safety Letter No 22, 2 June 2012.

Atkins Ltd (2013). Hub for London. Wildlife Hazards Good Practice. Inner Thames Estuary Feasibility Study.

Bernhardt, G. E., Blackwell, B. F., DeVault, T. L., & Kutschbach-Brohl, L. (2010). Fatal injuries to birds from collisions with aircraft reveal anti-predator behaviours. *Ibis*, *152*(4), 830-834.

Blackwell, B.F., Bernhardt, G. (2004). Efficacy of aircraft landing lights in stimulating avoidance behavior in birds. In Journal of Wildlife Management 68(3), 725-732.

Blackwell, B., Fernández-Juricic, E., Seamans, T., Dolan, T. (2009). Avian Visual System Configuration and Behavioural Responses to Object Approach. *Animal Behaviour, Vol 77,* 673-684.

Blackwell, B. F., DeVault, T. L., Seamans, T. W., Lima, S. L., Baumhardt, P., Fernández-Juricic, E. (2012). Exploiting avian vision with aircraft lighting to reduce bird strikes. *Journal of Applied Ecology,* 49(4), 758-766.

Blackwell, B.F., DeVault, T.L., Fernández-Juricic, E., Gese, E.M., Gilbert-Norton, L., Breck, Stewart W. (2016). No single solution: application of behavioural principles in mitigating human-wildlife conflict. *Animal Behaviour 120*, 245-254.

Burger, J. (1983). Jet Aircraft Noise and Bird Strikes: Why More Birds are Being Hit. *Environmental Pollution (Series A) 30,* 143-152.

Carrier, W. D., Melquist, W. E. (1976). The use of a rotor-winged aircraft in conducting nesting surveys of ospreys in northern Idaho. *Journal of Raptor Research, 10(3),* 77-83.

Cleary, E.C., Dolbeer, R.A., Wright, S.E. (2003). Wildlife strikes to civil aircraft in the United States 1990 – 2002. Federal Aviation
Administration National Wildlife Strike Database.

Dekker, A. et al. (2008). *The European Space Agency's FlySafe project, looking at the bird strike problem from another perspective.* In proceedings of the 28th IBSC conference, Brasilia, Brasil.

DeVault, T. L., Blackwell, B. F., Seamans, T. W., Lima, S. L., & Fernández-Juricic, E. (2014). Effects of vehicle speed on flight initiation by turkey vultures: implications for bird-vehicle collisions. *PloS one, 9(2),* e87944.

DeVault, T. L., Blackwell, B. F., Seamans, T. W., Lima, S. L., & Fernández-Juricic, E. (2015, February). Speed kills: ineffective avian escape responses to oncoming vehicles. In *Proc. R. Soc. B* (Vol. 282, No. 1801, p. 20142188). The Royal Society.

Dolbeer, R. A. (2006). Height Distribution of Birds Recorded by Collisions with Civil Aircraft. *Journal of Wildlife Management. 70(5),*1345-1350.

Dolbeer, R.A. (2011). Increasing trend of damaging bird strike with aircraft outside the airport boundary: implication for mitigation measures. *Human-Wildlife Interactions 5(2),* 235-248.

Dolbeer, R.A.(2015) Trends in reporting of wildlife strikes with civil aircraft and in identification of species struck under a primarily voluntary reporting system , 1993-2013

Dolbeer, R.A., Begier, M. J., Miller, P. R., Weller, J. R. & Anderson, A. L. (2021). Wildlife strikes to civil aircraft in the United States 1990 - 2020. FAA, U.S. Department of Agriculture, Washington, D.C., USA, 2021.

Doppler, M. S., Blackwell, B. F., DeVault, T. L. & Fernández-Juricic, E. (2015). Cowbird responses to aircraft with lights tuned to their eyes: Implications for bird–aircraft collisions. *The Condor, 117(2),* 165-177.

EASA (2017). Certification Specifications for Normal, Utility, Aerobatic and Commuter Category Aeroplanes. CS-23. Amendment 3.

Ebert J. and Pfleging, S. (2016). Bird strikes in the German civil aviation 2011 to 2015. Vogel und Luftverkehr online.

Ebert, J., Haver, T. (2017). Wildlife Control Report 2016. Fraport AG.

EUROCONTROL Skybrary (2017a). Bird Strike. Online. Retrieved on 18 January 2018 from https://www.skybrary.aero/index.php/Bird_Strike.

EUROCONTROL Skybrary (2017b). Bird Strikes on Final Approach: Guidance for Pilots. 2017. Online. Retrieved on 18 November 2017 from https://www.skybrary.aero/index.php/Bird_Strike_on_Final_Approach:_Guidance_for_Flight_Crews.

EUROCONTROL Skybrary (2017c). BIRDTAM. Online. Retrieved on 18 January 2018 from https://www.skybrary.aero/index.php/BIRDTAM

FAA (n.d.) 14 CFR Part 12 – Airworthiness Standards: Normal Category Airplanes

Fernández-Juricic, Estaban, Gaffney, Jimmy, Blackwell, Bradley F. and Pamhardt, Patrice (2011). Bird strikes and aircraft fuselage color: a correlation study. *Human-Wildlife Interctions 5(2),* 224-234.

van Gasteren, H., Both, I., Shamoun-Baranes, J., Laloe, J.-O., Bouten, W. (2014). GPS-logger onderzoek aan Buizerds helpt vogelaanvaringen op militaire vliegvelden te voorkomen. *Limosa 87,* 107-116.

van Gasteren, H., Krijgsveld, K.L., Klauke, N., Leshem, Y., Metz, I.C., Skakuj, M., Sorbi, S., Schekler, I. and Shamoun-Baranes, J., (2019). Aeroecology meets aviation safety: early warning systems in Europe and the Middle East prevent collisions between birds and aircraft. Ecography, 42(5), pp.899-911.

German Bird Strike Committee DAVVL (2022). Jahresbericht 2021 (Annual Report)

German Bird Strike Committee DAVVL (2021). Jahresbericht 2020 (Annual Report)

Hawker Beechcraft (2010). Airworthiness Limitations Manual Supplement Model B300/B300C. Wichita, Kansas, USA.

International Civil Aviation Organization (2004). Aerodromes, Vol. I 3rd ed.. Annex 14 to the Convention on International Civil Aviation. Montreal, Canada.

International Civil Aviation Organization (2012). Airports Service Manual. Doc 9137. Part 3, Wildlife Control and Reduction. Montreal,Canada.

Lima, Steven L., Blackwell, Bradley F., DeVault, Travis L. and Fernández-Juricic, Esteban (2015). Animal reactions to oncoming vehicles: a conceptual review. *Biological Reviews, Vol.90,* 60-75. doi: 10.1111/brv.12093.

Malka, I. (2021). Évaluation et analyse des risques de l'Aviation civile pendant la période de faible activité 2020. Direction de la sécurité de l'Aviation civile, Mission Évaluation et Amélioration de la sécurité, Paris, France

Metz, I.C., Ellerbroek, J., Mühlhausen, T., Kügler, D. and Hoekstra, J.M., (2021). Analysis of risk-based operational bird strike prevention. Aerospace, 8(2), p.32.

Mountain, P. & M. Giordano (2020). Wildlife Hazard Management Guide. EASA, Cologne, Germany

McKee, J., Shaw, P., Dekker, A., & Patrick, K. (2016). Approaches to wildlife management in aviation. In *Problematic Wildlife* (pp. 465- 488). Springer International Publishing.

B. MacKinnon, B. (2004). Sharing the Skies. An Aviation Industry Guide to the Management of Wildlife Hazards. Transport Canada.

Newcamp, Jeffrey M. (2016). *Integration of SE Design Principles in a Capstone Design Course: Airborne Birdstrike Countermeasure.* 26th Annual INCOSE International Symposium. Edinburgh, Scotland, UK.

Nolan, Michael S. (2003). Fundamentals of Air Traffic Control. 4. Edition. Brooks Cole, Belmont, CA, USA

Parsons, D., M. Malouf, and W. Martin. (2022). The impact of COVID-19 on wildlife strike rates in the United States. Accepted for publication in Human-Wildlife Interactions 16.

Pennycuick, C. J. (1972). Soaring behaviour and performance of some East African birds, observed from a motor-glider. *Ibis, 114(2),* 178-218.

Petri, B.(2003). Zwischenstandsbericht zum laufenden Gutachten “Vogelflug am Main und im Bereich der geplanten Landebahn Nordwest”. Zukunft Rhein-Main

Precise Flight. The Bird Strike Story. Online: https://www.preciseflight.com/aviation-bird-strikes-solutions/ Retrieved on 28 December 2017.

Qantas Airlines (n.d.), Precise Flight. Pulselite System B737 Operational Evaluation. Evaluating the Operational Use of the Pulselite Landing Light System in the Australasian Airline Environment.

Sheridan, E., Randolet, J., DeVault, T.L., Seamans, T.W. and Blackwell, B.F. (2015). The effects of radar on avian behavior: Implications for wildlife managements at airports. *Applied Animal Behaviour Science 171*: 241-252.

Thorpe, J. (2014). Update to ‘100 Years of Fatalities and Destroyed Civil Aircraft Due To Bird Strikes’. *Proceedings of the IBSC Conference.* Mexico City, Mexico.

Welsh, K.W., Vaughan, J.A., Rasmussen, P.G. (1978). Conspicuity Assessment of Selected Propeller and Tail Rotor Paint Schemes. Civil Aeromedical Institute Federal Aviation Administration. Oklahoma City, Oklahoma, USA.

The FlySafe Bird Strike Avoidance Model (n.d.). Online: http://www.flysafe-birdtam.eu/ Retrieved on 28 November 2017.