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Review

The Bird Strike Challenge

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Abstract: Collisions between birds and aircraft pose a severe threat to aviation and avian safety. To understand and prevent these bird strikes, knowledge about the factors leading to these bird strikes is vital. However, even though it is a global issue, data availability strongly varies and is difficult to put into a global picture. This paper aims to close this gap by providing an in-depth review of studies and statistics to obtain a concise overview of the bird strike problem in commercial aviation on an international level. The paper illustrates the factors contributing to the occurrence and the potential consequences in terms of effect on flight and damage. This is followed by a presentation of the risk-reducing measures currently in place as well as their limitations. The paper closes with an insight into current research investigating novel methods to prevent bird strikes.

Keywords: airport; air traffic management; aviation; bird strike; operations; risk; safety; wildlife management

1. Introduction

Collisions between birds and aircraft are as old as aviation. The first recorded bird strike was experienced by the Wright Flyer III on 7 September 1905 [1]. Bird strikes are regular events. Depending on the country, average bird strike rates between 2.83 and 8.19 per 10,000 aircraft movements were reported in civil aviation for the past years. Examples are provided in Table 1.

Table 1. Average bird strike rates (number of strikes per 10,000 aircraft movements) for different countries.

Country	Bird Strike Rate	Period Considered	Source
Australia	7.76	2008–2017	[2]
Canada	3.51	2008–2018	[3]
France	3.95	2004–2013	[4]
Germany	4.42	2010–2018	[5]
UK	7.76 (all) 4.62 (confirmed)	2012–2016	[6]
USA	2.83	2009–2018	[7]

Nevertheless, while collisions between birds and aircraft usually result in lethal consequences for the bird, aircraft damage is rare. Two to eight percent of all recorded bird strikes result in actual aircraft damage in civil aviation [6–10]. Regarding operational impacts, between six and seven percent of all reports indicate a negative operational effect on the flight [6,7,10]. It is estimated that bird strikes cause annual costs of at least one billion US $ to the worldwide commercial aviation industry [11]. Due to incomplete reporting, these figures have to be interpreted as conservative estimates [12–14].

As accidents have demonstrated, collisions between birds and aircraft also bear the potential for catastrophic outcome for the involved aircraft. As of 11 November 2019, bird strikes were determined to have caused 618 hull losses and 534 fatalities since the beginning of aviation [1].

To understand the factors contributing to the risk of bird strikes and find suitable measures for their prevention, broad data analysis is a prerequisite. This requires consequent reporting by the parties noticing bird strikes [15]. Furthermore, international standards and common definitions are needed. Thereby, the focus lies on civil aviation in general and commercial aviation in particular. The first section of this paper deals with the current state of data availability and consistency. Subsequently, the factors determining the risk of bird strikes are introduced. Thereafter, measures taken on the ground, in the air and by regulatory means as well as their limitations are presented. Finally, current research and its potential to further reduce the risk of bird strikes is discussed.

2. Definitions and Data Availability

Bird strikes are defined as *a collision between a bird and an aircraft which is in flight or on a take off or landing roll* [16]. To include other animals colliding with aircraft, the term can be broadened to *wildlife strike*. In general, statistics are provided for birds and terrestrial animals separately, for example by the aviation authorities of Canada, the United States of America (USA) and the United Kingdom (UK). One exception is Australia, where all flying animals, including flying foxes and bats, are included in the bird strike statistics [2,6,7,10].

This paper focuses on collisions involving birds and the term *bird strike* is used. First, the vast majority of wildlife strikes occur with birds, for example: 98% in Australia, 95% in Canada and 95% in the USA [2,7,10]. Second, terrestrial animals can be prevented from entering airport perimeters, for example by installing fences [17]. In contrast, birds can enter airfields regardless. Furthermore, they do not only pose a risk on the airfield, but also in the approach and departure corridors. The related challenges are addressed in this paper.

International Civil Aviation Organization (ICAO) requests its contracting states to report bird strikes [18]. Data are usually collected by the Civil Aviation Authorities (CAA). Its quality relies on consistent reporting by the parties involved in aircraft and airport operations: The pilots, maintenance crews, air traffic control and wildlife control. In recent years, the importance of complete bird strike reporting has been recognized and has since been encouraged or even enforced by many CAAs across the world. Within this context, the European Union (EU), which previously had no consistent reporting regulations among its member states, put into force mandatory bird strike reporting in 2015 [19]. All parties involved in air traffic operations within the EU have been obliged to report observed bird and wildlife strikes [20]. In Australia, mandatory reporting has already been in place for several years. Furthermore, in many countries, action has been taken to increase the motivation to report. This has resulted in increasing numbers of bird strike reports. For example, in the USA, where a mainly voluntary reporting system is in place, the ratio between all reported bird strikes and all bird strike occurrences increased from 41% to 91% for commercial aircraft in the period from 1990 to 2013 [13]. When including airports, which handle general aviation and commercial traffic, the share amounts to 47%. In the UK, pilots have been required to report all bird strikes since 2004. Before, only damaging bird strikes had to be reported [21]. The number of reports strongly increased since the implementation of this mandate [22]. Both in the USA and UK studies, the reason for the rise is mainly attributed to better reporting, rather than increased bird strike risk. The authors of both studies (Refs. [13,22]) reason with the ratio between number of damaging strikes and all strikes. In case of an increased risk, the rise of reports would be expected to be similar for damaging and non-damaging strikes. However, in both countries, the proportions of damaging strikes fell. This is supported by the latest USA data for the period until 2015, as visualized in Figure 1. In the subsequent years, a slight increase can be observed. Data from the years to follow will have to confirm if this represents the beginning of a trend in the opposite direction and bird strike risk is increasing.

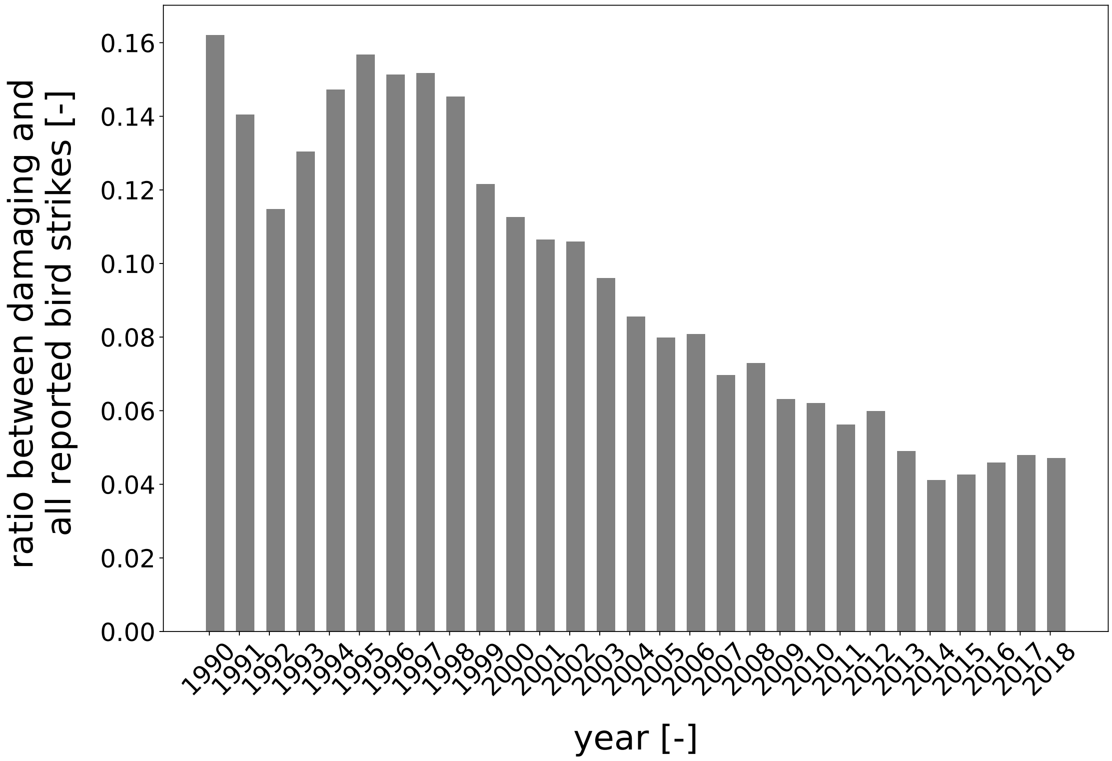

Figure 1. Ratio between damaging strikes and all strikes in the USA between 1990 and 2018. Source: [7].

Over the past few years, bird species hazardous to aviation have expanded and adapted to urban areas [23,24]. As air traffic is rising as well [25], the likelihood of encounters increases due to a higher number of airspace users. However, due to better reporting, the increasing trend in the number of bird strikes does not necessarily—or at least not exclusively—imply a rising risk of bird strikes.

The bird strike data collected and the level of detail published vary among the different countries. For example, some countries provide the altitude distribution via flight phases, others in altitude bands of various intervals. Therefore, comparisons of bird strike rates in particular and statistics in general have to be performed carefully.

The subsequent chapters describe the factors contributing to the bird strike risk. The ICAO defines a safety risk as *the predicted probability and severity of the consequences or outcomes of a hazard* [26]. This definition is applied here.

3. The Probability of Bird Strikes

The probability of bird strikes is determined by many parameters such as altitude, time of day, environmental conditions, geographical location, season and the aircraft itself [27]. This chapter provides an overview of these individual components.

3.1. Altitude

The highest probability of bird-aircraft collisions is at low altitudes [28]. According to Dolbeer et al. [29], 88% of the bird strikes in the USA over the past 27 years have occurred below 2500 ft (71% below 500 ft). A European study concluded that even 95% of all strikes occur below 2500 ft (70% below 200 ft), when considering worldwide traffic [30]. The probability decreases with increasing altitude, as Figure 2 visualizes. This corresponds to the flight phases for which most bird strikes are reported: takeoff, initial climb, landing and approach [31]. However, the share of damaging bird strikes increases with increasing altitude. Contributing factors are a higher kinetic energy due to increasing bird size and rising aircraft velocity. Furthermore, while mitigation measures at airports have been shown to be successful in reducing the number and consequences of bird strikes, outside the airport boundaries, the options for counteracting measures are limited [32].

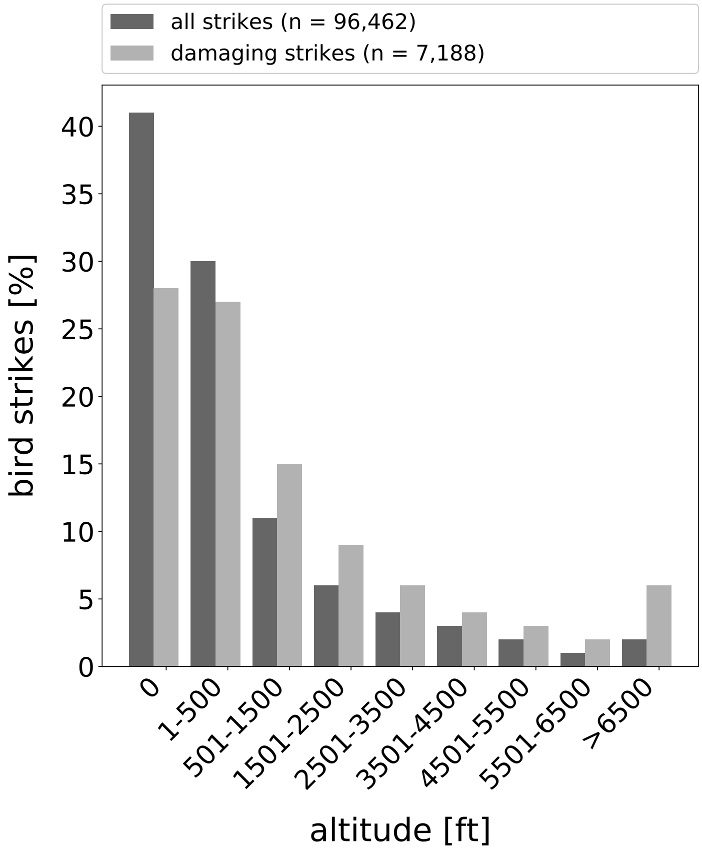

Figure 2. Distribution of bird strikes by altitude band that occurred between 1990 and 2018 in the USA, where the altitude was known (72% for all strikes, 70% for damaging strikes). Source: [7].

3.2. Season

The likelihood of bird strikes depends on seasons. Figure 3 illustrates the distribution of bird strikes over the year for regions in the northern and southern hemispheres. It can be seen that, during the respective winters, the risk of collisions between birds and aircraft is lowest. In contrast, during summertime, when the juveniles of many bird species fledge especially in the countries in the Northern hemisphere [33–35], the highest number of bird strikes is recorded. During spring and autumn, an increased bird activity due to migration between summer and winter residences leads to more strikes [36,37].

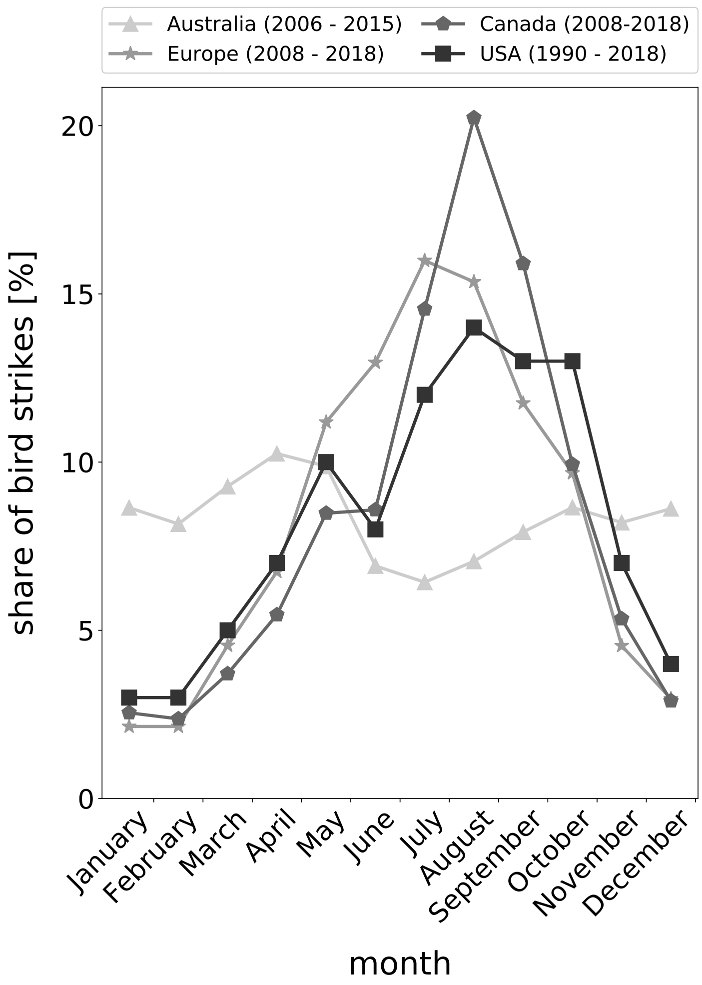

Figure 3. Seasonal distribution of bird strikes for Australia, Europe, Canada and the USA [7–10].

3.3. Location and Environmental Conditions

The probability of bird strikes depends on the geographical location [36]. This is related to the abundance of different bird species with variable behavior, size or tendency for flocking. In the direct airport environment, the landscape characteristics are a determining factor [38]. In regions situated along a migratory flyway, the danger of collision remarkably increases during migration seasons [36,37]. Another factor to be considered is the time of day. When comparing the number of bird strikes to the number of flights, most occurrences take place during the night [39,40]. This is caused by increased bird activity at night, especially for migrating birds [41]. Furthermore, many airports cease dispersing activities at night. However, because much more air traffic takes place during the daytime, the absolute number of strikes is higher in this period [31,42].

In addition to the geographical location, the attractiveness of an airport's environment also strongly influences the risk of bird strikes. The ICAO requests the bird strike hazard to be assessed at every airport [43]. In case of a determined bird strike risk, action should be taken to reduce the number of hazardous birds at and around the airport.

Furthermore, potential attractants such as sources of food and water on the field as well as in the vicinity of the airport should be prevented or eliminated, as they significally influence the risk of bird strike [38,43]. For this purpose, the ICAO's Airport Service Manual [44] requests an airport wildlife management plan which has to include the environment up to a radius of 13 kilometers around the airport, and, if necessary, beyond. Namely, *significant attractants*—sources for food, water and shelter—should be removed and off-airport bird monitoring performed [44].

Not only the presence of birds but also the characteristics of aircraft using a certain airspace have an influence on the likelihood of bird strike. These influences are described subsequently.

3.4. Aircraft Characteristics

Individual aircraft characteristics are another determining factor in the probability of bird strike. Due to their large size and high suction effect, turbofan engines are more likely to ingest birds than other engine types [45]. Moreover, due to their higher speeds during take-off and landing, turbofan aircraft are more difficult to avoid than other aircraft types [46]. Over the last years, turbofan engines increased in diameter [47], which increases the risk of ingestion even further. The number of turbofan aircraft as well as their share in the total number of aircraft increased significantly over the last years: In 2006, 20,444 commercial turbofan aircraft were registered, which corresponds to 79.6% of the commercial aircraft fleet of the time. In 2015, the number of commercial turbofan aircraft amounted to 22,690, which corresponds to 86.5% of all commercial aircraft [48,49]. According to Canadian data from 2008 to 2018, turbofan aircraft experienced 1.7 times more bird strikes than aircraft equipped with propellers [10].

Aircraft noise emission has an effect as well: the quieter an aircraft, the higher the risk that birds cannot avoid them, as they hear the aircraft approaching too late to initiate a successful avoidance manoeuvre [50]. Over the past years, airlines have been replacing their older aircraft fleet with more efficient and quieter aircraft which contributes to an increase in bird strike risk [47,51].

4. The Severity of Bird Strikes

The consequences of a bird strike for the aircraft involved are depending on the circumstances of the individual collision. The major criterion is kinetic energy

$$E_{kin} = \frac{1}{2} \cdot m \cdot v^2 \tag{1}$$

where E_{kin} refers to kinetic energy in $Joule$, m to mass in kg and v to velocity in $\frac{m}{s}$.

With regard to mass, the number of birds involved, their biomass as well as parts of the aircraft hit, determine the consequences of a collision for the aircraft [24]. Considering the velocity component, due to the high relative difference, mainly the aircraft's speed is relevant.

Based on data from the Federal Aviation Administration (FAA)'s National Wildlife Strike Database for Civil aviation, Dolbeer performed a study to evaluate the consequences for damages resulting from bird strikes below and above 500 ft in 2011 [32]. Even though the majority of strikes—approximately 75% in the period between 1990 and 2009—happen below 500 ft, only 55% to 65% of the damaging strikes took place in this altitude band. This indicates that a large proportion of strikes above 500 ft cause in damage, which is also reflected in Figure 2. This observation is supported by a study performed for the European Aviation Safety Agency (EASA) in 2009 [24] that takes into account data from civil aircraft from the UK and Canada for the period between 1990 and 2007. For these countries, 57% of all strikes happened during take-off and landing, 39% during climb and approach and approximately 1% during en-route flight for the observed period. The remaining 3% of all strikes happened during taxi and parking. The amount of damage per flight phase increases with increasing height: 3.7% of all strikes during take-off and landing, 7.9% of all strikes during approach and climb, and 34% of the en-route bird strikes caused damage. This can be explained by larger aircraft velocities at higher altitudes as well as by the fact that larger birds such as Canada Geese and Turkey Vultures fly at higher altitudes [24,52,53]. The combination of these two factors lead to a significant increase in the kinetic energy of the impact and thus to a higher probability of damage with increasing height.

4.1. Parts Struck

The majority of bird strikes hit the large front-parts of the aircraft: the nose, the wings' leading edges, and the engines. The shares of strikes to the various parts differ between different sources (e.g., [2,7,31]). Exemplary, Figure 4 presents the proportion of damaging and non-damaging strikes per aircraft component. The magnitude of damage resulting from a bird strike strongly depends on the part(s) struck. Small parts such as the pitot tube and lights are most vulnerable to damage due to their exposed positions and missing requirements on impact-resistance. The danger of hazardous consequences for the aircraft is especially high, when large or multiple birds are ingested into one or more engines because this can lead to partial or total loss of thrust. This is reflected by the accident statistics: Out of the 30 accidents involving hull losses and fatalities that happened since 1960, 23 were a result of one ore more engines struck [1,54,55]. Currently, approximately 94% of the world's aircraft fleet is equipped with two engines only [49]. Due to the resulting smaller redundancy, the danger is larger when birds are ingested [51]. Thereby, substantial engine damage is most likely during departure [56]. Over the past years, two major crashes occurred due to the ingestion of birds in both engines of twin-engine aircraft. In January 2009, an Airbus A320 aircraft lost thrust in both engines during initial climb out of LaGuardia Airport after the ingestion of several Canadian Geese. The crew successfully performed an emergency landing on the Hudson river [57]. In August 2019, a similar accident took place in Moscow when the crew of an Airbus A321 performed a successful emergency landing in a corn field after the engines failed due to ingestion of multiple gulls during departure [58]. In both cases, all passengers and crew survived.

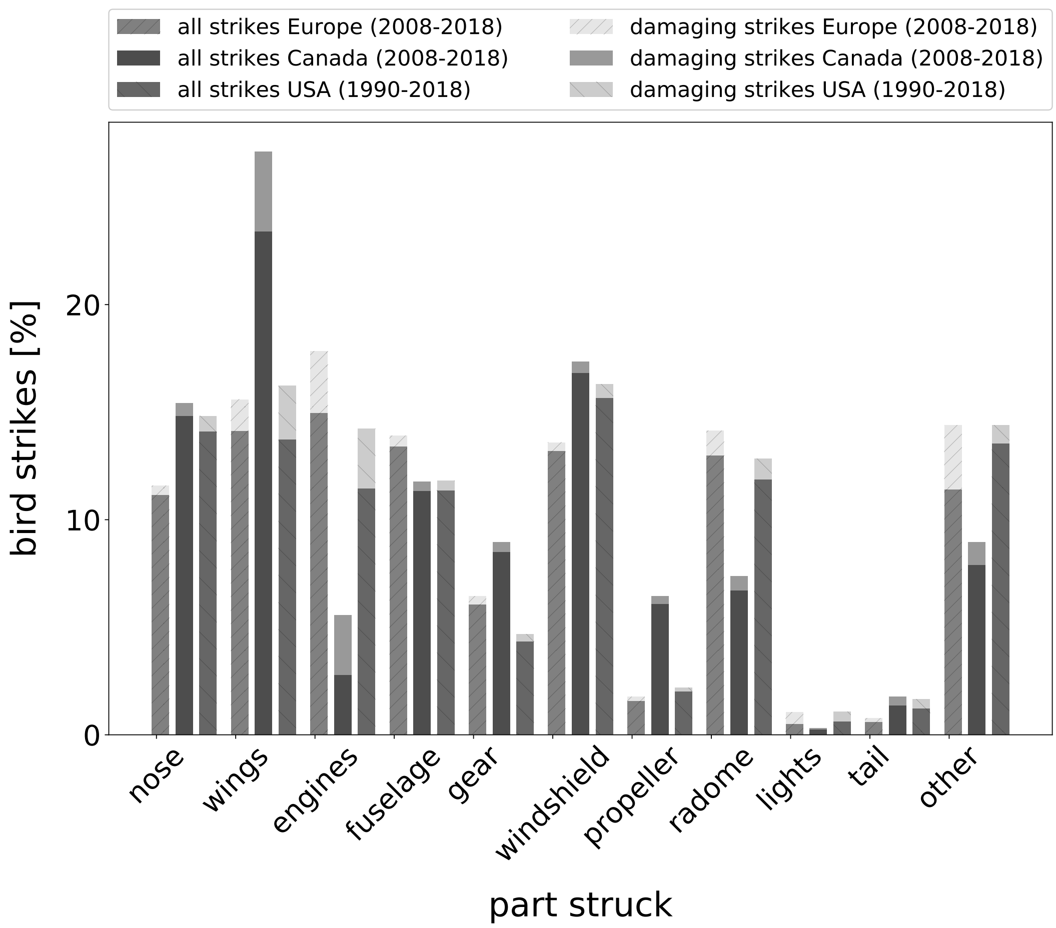

Figure 4. Total number of bird strikes per part indicating number of damaging strikes for Europe, Canada and the USA [7,8,10].

4.2. Risk of Accidents

The number of serious bird strike-related accidents are comparable to serious accidents due to other environmental causes, as Figure 5 shows. This figure compares the share of fatal and hull loss accidents resulting from environmental hazards for the periods 1960–1999 and 2000–2015. To compensate for the different length of the compared periods, the shares and not absolute numbers of accidents are provided. Over the last few decades, technological improvements and additional safety equipment have been introduced to reduce the number of windshear and turbulence related accidents [59]. The effect of these measures, especially on turbulence-related accidents, is visible in Figure 5. On the other hand, the shares of serious accidents due to bird strike, lightning strike and thunderstorm increased.

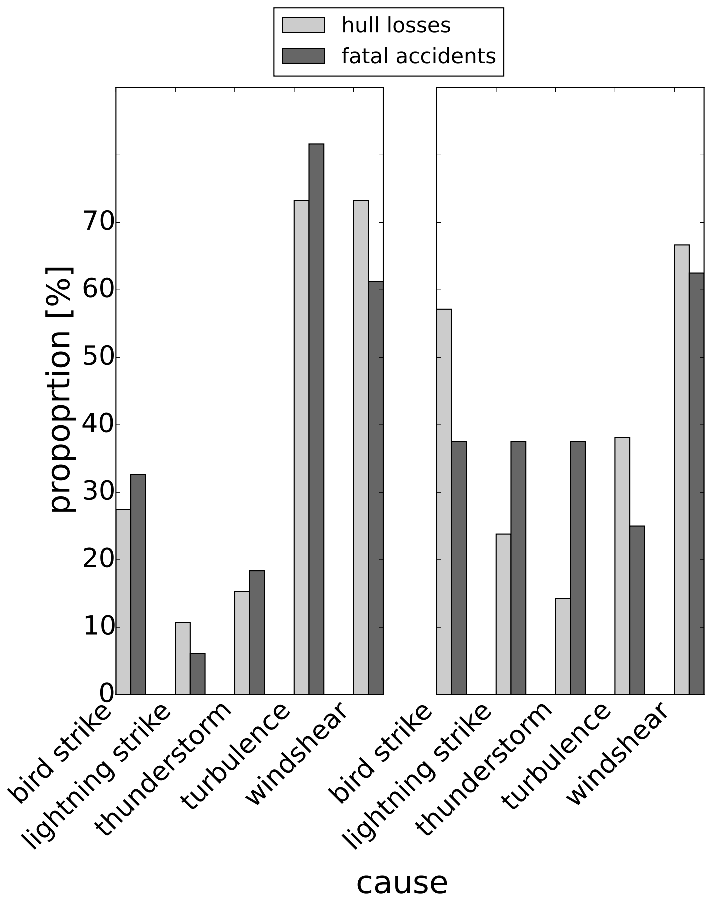

Figure 5. Comparison of different accident causes for the periods 1960–1999 (**left**) and 2000–2015 (**right**) (sources: [55,60]).

4.3. Effect on Flight

Depending on the magnitude of the damage, there is a direct operational effect on the flight. In addition to the aircraft involved, airport operations and other airspace users may also be impaired. Table 2 provides an overview of operational impacts for various countries and continents. In addition, the worldwide reports collected by ICAO [31] are presented. While the share between *none* and *unknown* varies among the sources, the effect-categories have a similar influence.

Independent of their impact on a flight, an examination to ensure the airworthiness of the aircraft involved has to be performed before the next departure [61]. Therefore, not only damaging but all recognized bird strikes affect operations and consequently result in costs. Furthermore, airport operations might be impaired—for example due to temporary runway closure to remove bird remains.

Table 2. Reported operational effects in Europe, Canada, the USA as well as world-wide in percentages [8,10,14,31].

Operational Impact	Europe (2008–2018)	Canada (2008–2018)	USA (1990–2018)	Worldwide (2008–2015)
none	95 [a]	69	56	83
unknown		21	46	12
precautionary landing	1	5	3	1
aborted take-off	1	2	1	1
engine shut-down	<1	<1	<1	<1
other	3	3	1	3

[a] Europe groups *none* and *unknown* into one category.

4.4. Costs of Bird Strikes

Little information is available about the costs resulting from bird strikes. This is related to the reluctance of airlines to report damage costs due to competitive reasons [62]. Global estimates are from the early 2000s. For example, depending on the damage caused, Sodhi approximated in 2002 that the costs for engine repairs range from US $ 250,000 to one million US $ [50]. Allan et al. approximated in 2003 the total annual costs for the world aviation fleet to be approximately one billion US$ [63]. Based on data obtained from United Airlines (UAL) for the years between 1999 and 2002, costs of a non-damaging strike sum up to approximately US $22,417 per strike. This includes, for example, an aircraft check following a bird strike. They conclude that the average costs for a damaging strike amount to US$225,329. More recent data are available from the FAA [7], which is summarized in Table 3. Some of the reported strikes between 1990 and 2015 include information about repair and indirect costs. Indirect costs result from lost revenues, passenger rebooking, aircraft rescheduling and flight cancellations. On average, the repair costs amounted to US $ 164,595, the average indirect costs to US $ 27,599 , resulting in total average costs of US $ 192,194 per damaging strike. However, this information was included only in a small proportion of all reports, as Table 3 indicates. Hence, these numbers might not be representative. Furthermore, due to incomplete reporting of strikes in general, the authors of the study presume a strong underestimate. Therefore, projected costs are based on the averages obtained from the reports that include cost information. These are also presented in Table 3.

Table 3. Repair and indirect costs resulting from wildlife strikes in the US from 1990 to 2018 [7].

Cost Type	Total/Average	Reported Cost (US $)	Projected Cost (US $)	Number Reports	
repair costs	total	4.6 M	4465 M	4534	2.2%
	average	158,573	154 M	156	
indirect costs	total	726,044	962 M	3683	1.7%
	average	25,036	33 M	127	
total costs	total	5.3 M	5427 M		a
	average	183,609	187 M		

[a] Some reports might contain both information about repair and indirect cost. Hence, a total number of reports cannot be obtained.

Another type of cost can be expressed in aircraft downtime. Based on the 5% of reports including information about aircraft downtime in [7], an average of 101 hours per strike result. When including missing reports, the authors project an average of 4521 days of aircraft downtime per year due to wildlife strikes.

5. The Counteracting Measures

To reduce the risk of bird strikes, many measures have been implemented. They can either be ground- or aircraft-related. On the ground, the focus of bird strike hazard reduction in civil aviation explicitly lies on the airports and their direct surroundings. This is related to the altitude distribution of bird strikes with the highest risk at low altitudes [40,44]. In this context, the ICAO requests airports to maintain a wildlife strike program [43,44].

In addition to the measures to prevent bird strikes, regulations to minimize the risk of damage are in force. These are described in the end of this section.

5.1. Mitigation Measures on the Ground

Successful bird strike prevention at airports requires the identification of hazardous species as well as the the understanding of the types and reasons of their movements [64,65] Multiple risk assessment procedures have been developed to support the bird strike units in prioritizing and performing their measures. Depending on the model, the input parameters include species, their abundance and potential to cause damaging strikes as well as cost-estimates (for example [22,46,51,66]).

These range from habitat management to exclusion, harassment, capture, and shooting of wildlife [51]. Within *habitat modification*, the airport grounds are made as unattractive to birds as possible, by removing sources for water, food and shelter or by making them inaccessible [67]. Habitat management is considered as the foundation of successful and long-term wildlife management. *Exclusion* can partly be achieved by wires, netting or covers. Furthermore, chemical repellents such as anthraquinone or methyl anthranilate are used [51]. The category *harassment* includes all techniques which aim at chasing away birds which have already entered the airfield. The main groups of harassing tools are auditory deterrents such as gas exploders, alarm and distress calls as well as pyrotechnics, visual repellents such as effigies, predator models, lasers, reflecting materials, lights, mirrors as well as drones, trained dogs and falconry [68]. The category *capture and relocation* includes trapping of birds on the airfield and reassigning them to new habitats further away from the airport. Among others, a minimum distance between the airport and translocation area should be kept to limit returns to the airport [69]. The *lethal* category covers shooting of birds and pursues two goals. First, the population density of critical bird species should be limited to reduce the risk of strikes. Second, by shooting target individuals of a group, habituation to other techniques by the remaining birds should be limited. The efficacy of shooting birds is not entirely clear. Furthermore, lethal methods are forbidden or restricted in many countries [70,71].

The described efforts at airports are vital for reducing the risk of bird strikes and many control programs have shown positive effects (see, e.g., [7,23]). However, airport-bound wildlife management is limited in its efficacy. Firstly, birds can grow accustomed to harassing methods, which reduces their effectiveness over time. Secondly, the range of the dispersing measures lies within the airport boundaries rather than in the entire area with increased risk, i.e., below 3000 ft [28,38]. Considering that there is an increasing trend of damaging strikes outside the airport boundaries [32], expanding the horizon of bird strike hazard mitigation beyond the airport fences is essential [28].

Therefore, aircraft-related risk-reducing measures have been researched over the past few years, as described in the following section.

5.2. Aircraft-Related Mitigation Measures

Various studies on bird reactions to approaching aircraft have been performed to study the options of reducing strikes by enhancing the perceivability of the aircraft (e.g., [72–77]). They commonly concluded that many bird species try to avoid collisions with aircraft. However, due to their reaction time and the aircraft's high speed, especially during flight, the birds' attempts to escape are often unsuccessful. This is even true for experienced birds. Even though they were found to initiate their escape earlier than inexperienced birds, the remaining time to collision is usually insufficient to prevent a collision [78]. By increasing an aircraft's perceivability, birds can detect its approach earlier and the chances for a successful avoidance manoeuvre rise [72,79]. The majority of research in this area has focused on increased visibility. A rather general study analysed the correlation between fuselage color and bird strike risk [75]. The authors concluded 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.'*. For turboprop aircraft, such an effect can be gained by applying colored patterns to the propeller to enhance the aircraft's contrast against the sky [80,81].

Research on increasing aircraft lighting found that pulsing light has the potential to enhance avian visual awareness [73,74,82]. However, as visual perception depends on the bird species, different pulsing frequencies and wavelengths might be required [83]. An experiment identified that certain wavelengths do trigger strong avoidance reactions of birds, while other wavelengths did not cause any behavioral response. This implies that the choice of lights to be installed can support successful collision avoidance [77].

Long-term tests with two airlines demonstrated the safety potential of implementing a pulsing light system to aircraft. The system tested pulses for the existing landing and logo lights to enhance aircraft visibility and the predictability of the aircraft's flight path at night. The system was installed on aircraft from Alaska Airlines, a regional airline in the USA for a duration of three years. Compared to the three years previous to installation, the number of bird strikes had decreased by 33.5% [84]. In another trial, ten aircraft of Qantas Airways were equipped with the system. The installation remained between 12 and 24 months. Compared to the fleet's non-equipped aircraft, a reduction in bird strikes between 54% and 66% resulted [85]. Therefore, pulsing lights seem to be a promising addition to wildlife management at airports, especially to prevent bird strikes at low velocities.

5.3. Regulatory Mitigation Measures

Table 4 indicates that the majority of reported bird strikes do not result in any severe consequences for the involved aircraft. This has three main causes. Firstly, many bird strikes involve small birds (cf. e.g., [45]). Because of their lower mass, they have low kinetic energy and are therefore much less likely to cause damage. The second reason is the impact-resistance of aircraft. To meet the certification requirements by the Civil Aviation Authoritys (CAAs), aircraft have to be able to withstand a certain impact caused by birds, as described subsequently. Thirdly, requirements for reduced aircraft speeds below 10,000 ft have proven effective [27].

Table 4. Magnitudes of damage resulting from bird strikes in Europe and the US in percentages [8,14].

Damage	Europe (2008–2018)	USA (1990–2015)
none	63	51
unknown/uncertain	30	46
minor [a]	4	2
substantial [b]	2	<1
destroyed	<1	<1

[a] After experiencing minor damage, simple repairs or a replacement without extensive inspection suffices to render the aircraft airworthy [86]; [b] When experiencing substantial damage, an aircraft's structural strength, performance or flight characteristics are adversely affected and a major repair is required [86].

5.3.1. Certification Requirements

Aircraft have to meet certification requirements to prove their airworthiness [87]. In this chapter, the European regulations as defined by EASA and the US regulations by the FAA are considered. Depending on their size, aircraft are grouped into categories. Airplanes used for commercial aviation are either in the category Normal (EASA)/Normal Category Airplanes (FAA) or Large Aeroplanes (EASA)/Transport Category Aircraft (FAA). The categories and their descriptions, which are mostly corresponding, can be found in Table 5. By 2014, approximately 97% of aircraft in the worldwide commercial fleet were certified as Large Aeroplanes/Transport Category Aircraft; the remaining 3% were certified as Normal/Normal Category Airplanes [49]. In Europe, the majority of commercial aircraft is certified by the standard *CS 25—Large Aeroplanes* [88]. The US-American counterpart consists of the Federal Aviation Regulations (FAR) *14 CFR Part 25—Transport Category Airplanes* [89]. These regulations contain the following requirements regarding damage-tolerance of aircraft parts.

Table 5. Certification categories relevant for commercial aviation aircraft in Europe and the US (CS: Certification Specifications; CFR: Code of Federal Regulations).

Europe—EASA	**US—FAA**
CS-23 Normal Aeroplanes aeroplanes with a passenger-seating configuration of 19 or less and a maximum certified take-off mass of 8618 kg (19,000 lbs) or less [90]	*14 CFR Part 23 Normal Category Airplanes* airplanes with a passenger-seating configuration of 19 or less and a maximum certificated take-off weight of 19,000 lbs or less [89]
CS-25 Large Aeroplanes turbine-powered aeroplanes of more than 5700 kg (12,500 lbs) maximum certified take-off weight, excluding commuter airplanes which are covered by the category Normal Aeroplanes [88,91]	*14 CFR Part 25 Transport Category Aircraft* multi-engine airplanes with more than 19 seats or a maximum take-off weight greater than 19,000 lbs [92]

- Windshield: withstand without penetration an impact of a 2 lb bird at cruise speed.
- Structure: Successfully completing a flight after an impact with a 4 lb bird when the aircraft's velocity relative to the bird along the aircraft's flight path equals cruise speed at sea level or 0.85 cruise speed at 8000 ft, whichever is more critical.
- Empennage: Successfully completing a flight after an impact with an 8 lb bird at cruise speed (FAA only).
- Pitot tubes: sufficient separation to prevent damage to all of them in case of a bird strike.

Aircraft in the category *CS 23–Normal Aeroplanes* respective *14 CFR Part 23—Transport Category Airplanes* only have to prove an impact-resistance of the windshields. Both the European and the US regulations demand that *each windshield and its supporting structure directly in front of the pilot must withstand, without penetration, the impact equivalent to a two-pound bird when the velocity of the aeroplane is equal to the aeroplane's maximum approach flap speed.* [89,90]. Consequently, category 23 aircraft are more vulnerable to damage due to collisions with birds.

Regarding the impact-resistance of engines, which have to be certified independently of the aircraft, separate EASA and FAA regulations are in force. To prove that an engine responds in a safe manner to bird ingestion, it must undergo an engine ingestion test. The European regulations (CS-E 800 [93]) demand tests considering the ingestion of single large birds and large flocking birds. The FAR add tests for small and medium single and flocking birds [94]. Depending on the engine's diameter, different criteria regarding bird mass and thrust settings are required. In all tests, the ingestion of the bird must not lead to a hazardous engine effect. EASA defines the following events as *Hazardous Engine Effects* [93]:

i. *non-containment of high-energy debris,*
ii. *concentration of toxic products in the engine bleed air for the cabin sufficient to incapacitate crew or passengers,*
iii. *significant thrust in the opposite direction to that commanded by the pilot,*
iv. *uncontrolled fire,*
v. *failure of the engine mount system leading to inadvertent engine separation,*
vi. *release of the propeller by the Engine, if applicable,*
vii. *complete inability to shut the engine down.*

5.3.2. Speed Limitations

A further reason why only a small number of all bird strikes lead to aircraft damage results from regulations for maximum aircraft speeds of 250 kts (Knots-Indicated Airspeed (KIAS)) below 10,000 ft as a matter of Air Traffic Control (ATC) airspace organization. Among others, the limitation of speed should reduce the kinetic impact of bird strikes in the areas where bird strikes mostly occur [29,40]. Many countries such as Canada, Mexico, the USA and Germany have applied such a regulation [95,96].

6. The Next Step

Over the past few years, the awareness has risen that increasingly includes the parties actually handling air traffic—ATC and the pilots—is vital to further reduce the risk of bird strikes in civil aviation [28]. Currently, the controllers can provide general warnings on bird activity in the airport area based on visual observations or reports by pilots [27,97]. Pilots in commercial aviation can mainly enhance their situational awareness by studying current bird strike risk information in the form of BIRDTAMs (a special form of Notice to Airmen (NOTAM) which provides information on current bird strike risk [98]) and bird migration reports, where available [27,98,99]. Furthermore, they should stay alert throughout the flight and report observations on enhanced bird activity as well as experienced bird strikes [27]. In general aviation, route planning should consider the avoidance of areas abundant of birds in addition. By flying at high altitudes, the probability, and by flying at low speeds, the impact of a potential bird strike can be reduced [27,99].

To introduce operational bird strike prevention further involving ATC and pilots, experiences from military aviation can serve as an example. As military operations are often performed at low altitude, military aircraft spend much more time in areas with high bird densities than civil aircraft. Hence, military operations are more vulnerable to bird strikes than their civil counterparts. For this reason, several air forces across the world have started to implement procedures to adjust flight planning based on current bird strike risk since the 1970s (e.g., [100–102]). In the beginning, this mainly included flight restrictions during peaks of bird migration [37]. With developments in technology and increasing data-sets to model and predict bird movement, a more dynamic and short-term planning to avoid high-risk air spaces at a given time has become possible [28]. The military efforts have mainly focused on en-route intervention of flight operations for low-level training flights [37,102]. For civil aviation, an application of these procedural approaches at and around the airports would be useful and is seen as an important next step in bird strike prevention [28]. In contrast to military aviation which has a certain flexibility in flight planning, civil aviation is bound to schedules [103]. Therefore, regular flight restrictions in cases of high risk are unfeasible. On the other hand, dedicated real-time warnings of high-risk situations resulting in short-term delays could be applicable. Different levels of advice could be possible. First, the general situational awareness of the pilots could be raised. Second, aircraft taking off could be advised to adjust their rate of climb to quicker pass critical zones. In addition, third, in case of high collision risk, air traffic could temporarily be held back.

According to Annex 15 of ICAO, ATC shall provide current information on the *presence of birds constituting a potential hazard to aircraft operations* [104]. However, in order to be able to give precise warnings rather than general information on bird movement, additional surveillance technology is required.

An increasing number of airports have installed radars dedicated to tracking birds, so-called avian radars, over the past few years. They are designed to track individual birds as well as flocks of birds up to distances of 11 km and heights of 1.5 km [105]. While initial installations covered two-dimensional positions only, systems providing three-dimensional positions are increasingly becoming available. Moreover, radar ranges are increasing and the data quality is improving. Thus far, these radars are mainly used by local wildlife control to detect hotspots of bird movements at the airfield. However, avian radars, possibly in combination with other surveillance technology such as thermal or video imaging, have the potential to serve as input for procedural, real-time bird strike prevention. A unique implementation of a radar-based bird strike advisory system for civil aviation is located at the Durban King Shaka International Airport, South Africa [28,106]. During summer, around three million swallows visit a roosting site which is located on the extended runway center line, 2.6 km from the airport. At dawn and dusk, the birds move in large flocks to and from this site. The radar is used to detect these movements. Based on the observed risk level, ATC is advised to temporarily hold back air traffic. Contributing factors to the successful implementation of the procedures are the detectability of huge swarms of birds by avian radars, the short and distinctive periods of threat and the relatively low number of aircraft movements at the airport [28]. The general introduction of comparable procedures at other airports could be limited by the following factors. In contrast to King Shaka airport, bird strike risk is more random at other airports with respect to number of birds and time of day. The ability of avian radars to detect individual birds, even large ones, close to the ground as well as with increasing distance from the radar, is limited [107–109]. Therefore, not all birds are observed by the radar and no warning for potentially critical strikes can be presented due to the missing information. Moreover, tracks of individual birds are more difficult to predict than those of swarms. This reduces the potential positive effect on safety and to superfluous warnings in case of falsely predicted bird movement. Furthermore, bird strike risk is distributed throughout the day. This could lead to increased workload for the controllers and to to unjustifiable reduction in runway capacity at high-density airports.

An ongoing FAA study has addressed the question of workload increase for controllers when involving them in the bird strike hazard reduction process [110]. In human-in-the-loop simulations, controllers were presented with four test conditions in which they had to control air traffic at an airport. In the baseline scenario, bird activity information was provided as observations by pilots transmitted via radio, representing current procedures. In the three remaining conditions, information was provided in different ways via the controller's Human–Machine Interface (HMI). Initial results indicate that the controllers appreciate the increased situational awareness. Moreover, the controllers reported a reduction in workload when receiving dedicated bird strike risk information via their HMI in contrast to information reported by pilots. A European study focuses on the potential effects on an airport's safety and runway capacity when implementing procedural risk-reduction methods [111, 112]. Fast-time simulations involving deterministic bird and aircraft movement revealed a potential for increasing safety and reducing cost with only a small impact on runway capacity [112]. Ongoing research is evaluating the effect when the limited predictability of birds is taken into account.

Alternatively to ground-based warning systems, there are ideas to integrate radar-based alerting systems into the aircraft [113]. Independent of the chosen approach, a close collaboration between research and operational personnel is crucial for a successful implementation of new measures [114].

The presented initiatives to apply operational bird strike prevention based on the positive results from military aviation are preliminary. Nevertheless, they demonstrate the potential to further reduce the risk of bird strike by applying procedural measures.

7. Conclusions

Collisions between birds and aircraft pose a serious risk to aviation. They mostly influence airport and aircraft operations and the efficiency of the air traffic management system. Furthermore, with their potential for severe damage and accidents, they pose a threat to aviation safety and a significant cost to the airline industry. The measures applied at airports, aircraft-mounted systems as well as regulations have reduced the risk and potential of accidents. Initial research on operational bird strike prevention by including air traffic controllers and pilots shows further potential to enhance avian and aviation safety.

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