Air Traffic Control Advisory System for the Prevention of Bird Strikes

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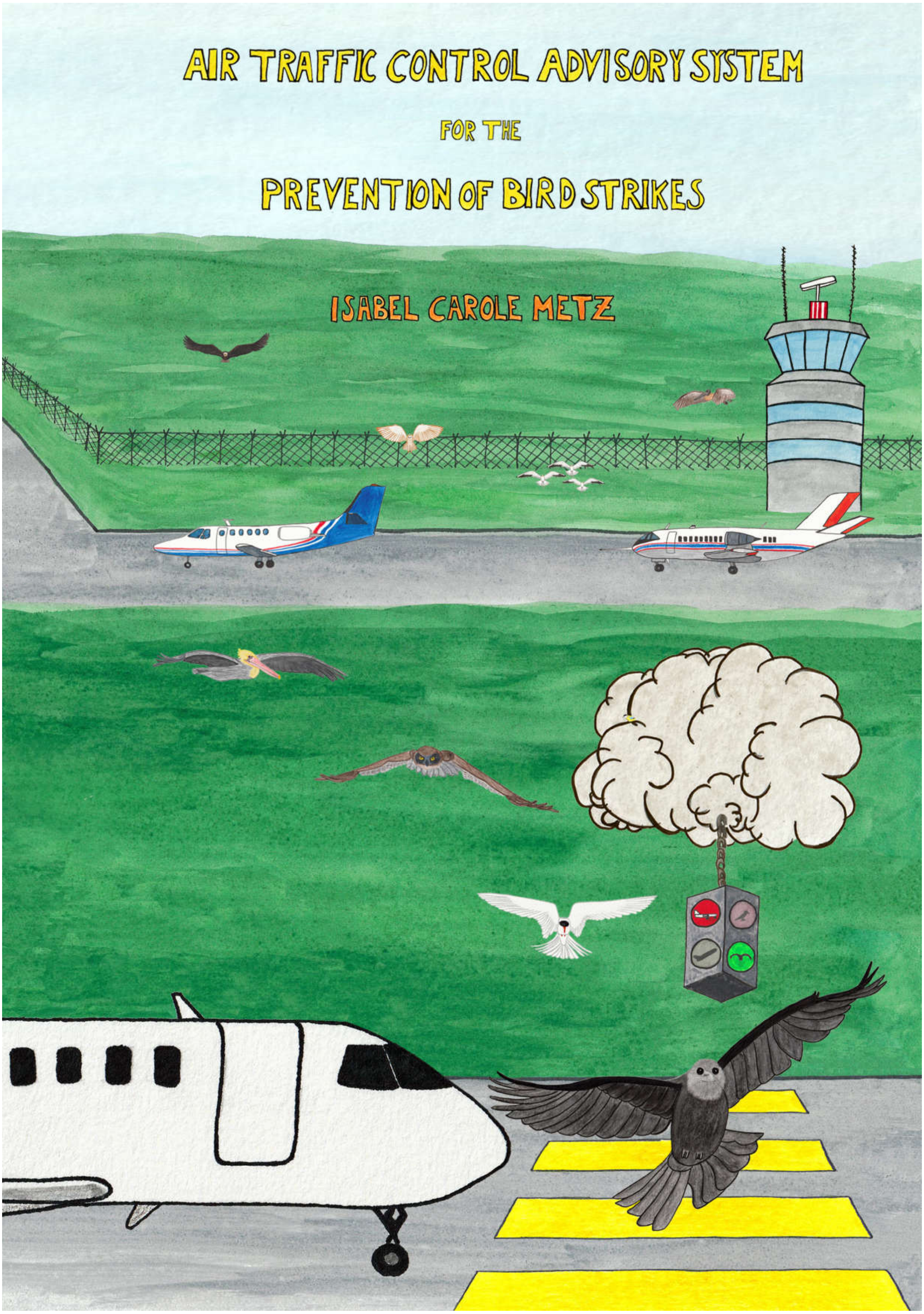
AIR TRAFFIC CONTROL ADVISORY SYSTEM
FOR THE
PREVENTION OF BIRD STRIKES
ISABEL CAROLE METZ

AIR TRAFFIC CONTROL ADVISORY SYSTEM

FOR THE

PREVENTION OF BIRD STRIKES

Air Traffic Control Advisory System for the Prevention of Bird Strikes

Proefschrift

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When life hands you lemons,
you make lemonade.

But when life hands you hurricanes,
you go surfing.

Jon Foreman

Be brave in the wave.

Petra Graber

Contents

SUMMARY

Collisions between birds and aircraft threaten aviation as well as avian safety. This was impressively demonstrated by emergency landings of passenger aircraft into the Hudson river in New York in 2009 and into a cornfield near Moscow in 2019 after encountering flocks of birds. Even without such drastic consequences, bird strikes impact operations and cause significant costs to the aviation industry. Most bird strikes happen up to an altitude of 1,000 m, and thus in the extended airport environment including arrival and departure corridors. At the airports, the actions performed by local wildlife control units have contributed to a strong decrease in the likelihood of bird strikes. However, the risk, especially of damaging bird strikes, remains high beyond the airport fences.

This PhD study aims at investigating the merits of extending the horizon of bird strike prevention to the entire critical area. Therefore, it evaluates an approach that involves controllers and pilots. The key element of the concept proposed here is the installation of a bird strike advisory system for air traffic control. Based on real-time bird movement data, the risk of bird strikes is calculated and provided to the air traffic controller. In case of high risk, the controller can delay departing aircraft until the critical birds have left the area and provide warnings to arriving traffic to enhance situational awareness.

Before actually implementing such a system at an airport, it is essential to demonstrate its feasibility. This is the goal of this PhD study. In particular, the potential to enhance aviation and avian safety is evaluated. In addition, the effects on traffic flows at an airport are analysed. For this purpose, an algorithm underlying a bird strike advisory system has been developed and tested for different conditions. The algorithm focuses on delaying departing aircraft since they are most vulnerable to experience damage. Moreover, birds react in various and hard-to-predict ways to nearing aircraft. Therefore, avoidance maneuvers initialised by pilots could prove counterproductive, namely when they try to divert in the same direction as the birds. For this reason, the algorithm targets the delaying of departing aircraft which can safely be performed. In addition, these are the aircraft most vulnerable to damage and therefore the ones which benefit most from a prevented bird strike. Arriving aircraft are not influenced by the algorithm.

The research performed here focuses on the effect on safety and on traffic flow, including delays and reduction of capacity, of an entire airport. To obtain representative results, Monte Carlo simulations are performed. These incorporate varying air traffic intensities and flight plan patterns as well as bird movements from all seasons. The simulation platform is the BlueSky Open Air Traffic Simulator developed by TU Delft. The simulator is dedicated to represent and simulate air traffic flows in fast-time. Within this work, it is used to study the bird strike risk in general as well as to verify and validate the different implementations of the algorithm underlying a bird strike advisory system. For this purpose, the simulator is enhanced to represent bird movement and to identify collisions between birds and aircraft. A bird movement model is developed based on data from two different radar types. This model also serves as input for the collision avoidance within the algorithm. The resulting simulation environment is the first of its kind, enabling simultaneous fast-time simulations of bird- and air traffic movements.

As revealed by initial simulations of unimpeded air traffic flows alongside bird movement, there is a threefold overestimate of bird strikes in the simulations in comparison to reality. This can mainly be attributed to a high presence of birds on and close to the runway in the bird movement data as well as missing modelling of bird reactions to nearing aircraft in the simulation. Therefore, it is expected that the algorithm which is tested on these data sets, will intervene more often than it would in reality. This is especially relevant when analysing the impact on runway capacity.

The algorithm is developed in multiple stages. First, a collision avoidance algorithm that aims at preventing all bird strikes at a minimum capacity loss is established. For this purpose, perfect predictability of bird movement is assumed. In addition to revealing how strongly safety can be increased in perfect conditions, this allows the verification of the correct implementation of the collision detection logic. In this setting, 99 % of strikes are prevented, the remaining collisions happening with birds which take off after the aircraft. This optimal setting demonstrates the high safety potential of a bird strike advisory system. However, even though the runway throughput can be maintained, some of the imposed delays exceed tolerable limits. Since it is expected that the number of alerts rise when considering the uncertainty in bird predictability, a prioritisation of interventions is recommended. The algorithm should target those birds which cannot be reached by the current measures performed by the wildlife control units. Moreover, it should focus on preventing strikes that are likely to cause damage to aircraft.

In the next stage, the collision avoidance algorithm is extended to a bird strike risk algorithm that calculates bird strike risk for departing aircraft based on the bird movement information available at the intended take-off time. A model based on simple linear regression to predict the continuation of the bird tracks is introduced. Initially, the probability and later the severity of strikes are calculated for all birds. If these values exceed certain thresholds, the algorithm delays departures. Most interventions target birds lingering on or close to the runway, leading to high and often unnecessary delays. This clearly demonstrates the requirement to limit the number of algorithm interventions to keep air traffic flowing. Hence, the final implementation of the bird strike risk algorithm only delays departures if they are predicted to experience a damaging strike with a bird crossing the flight path of that aircraft. With that setting, the number and duration of generated delays remain reasonable for all scenarios. However, linear regression proves insufficient to suitably evaluate the risk of collisions. Even though the algorithm prevents bird strikes, aircraft which inherit delays from previous departures experience more strikes from birds below the risk thresholds or birds taking off after the aircraft. Hence, the algorithm does not significantly change the number of bird strikes. To achieve reliable predictions, in-depth studies of multi-year bird movement data from various sensor types are recommended to develop site- and species-specific bird models. This also allows to improve the threshold-definition to trigger an algorithm intervention based on the current environmental and traffic situation. Additionally, the cumulative risk of all birds rather than individual birds expected to cross flight path of departing aircraft line could be considered. With these measures, the concept of a bird strike advisory system can be further developed to exploit the entire safety potential demonstrated by the initial collision avoidance algorithm.

SAMENVATTING

Aanvaringen tussen vogels en vliegtuigen vormen een gevaar voor zowel de luchtvaart als de vogels zelf. Dat was te zien in een indrukwekkende noodlanding van een passagiersvliegtuig in de Hudson rivier in 2009. In 2019 belandde er een passagiersvliegtuig in een maïsveld dichtbij Moskou na een aanvaring met een zwerm vogels. Ook zonder zulke ingrijpende consequenties hebben vogelaanvaringen een grote impact, en veroorzaken daarbij significante extra kosten voor de luchtvaart industrie. Het merendeel van de vogelaanvaringen gebeurt onder de 1,000 m, wat maakt dat zij plaatsvinden in de buurt van de luchthaven en zijn luchtcorridors van aankomst en vertrek. De maatregelen van lokale vogelwachten hebben sterk bijgedragen aan de vermindering van vogelaanvaringen op het vliegveld. Maar in de lucht blijft het risico op een schadelijke aanvaring aanzienlijk hoog.

Dit proefschrift zal de voordelen van extra maatregelen tegen vogelaanvaringen analyseren, als deze worden uitgebreid naar het gehele kritische gebied. Daarmee wordt een aanpak gekozen die van invloed is op zowel luchtverkeersleiders als piloten. Er wordt voorgesteld een nieuw adviessysteem te installeren bij de luchtverkeersleiding, dat op basis van actuele data het risico op vogelaanvaringen berekent. In het geval van een hoog risico, kan de luchtverkeersleider het vertrek van vliegtuigen vertragen totdat de vogels het risicogebied hebben verlaten. Daarnaast kan de luchtverkeersleider de piloten waarschuwen, en daarmee de piloten bewustmaken van het potentiële aanvaringsgevaar.

Het doel van dit proefschrift is om te onderzoeken of een dergelijk systeem praktisch haalbaar is. In het bijzonder wordt de potentie om de veiligheid van de luchtvaart en van de vogels te verbeteren beoordeeld. Daarnaast worden de effecten op de verkeersafwikkeling van de vliegtuigen beoordeeld. Om dit doel te bereiken wordt een aanvaringverminderingsalgoritme ontwikkeld dat gebruikt zal worden voor een adviessysteem om vogelaanvaringen te voorkomen. Dit algoritme wordt getest onder een breed scala van omstandigheden. Het focust zich op het vertragen van vertrekkende vliegtuigen, aangezien deze categorie extra vatbaar is voor schade. Het algoritme laat aankomende vliegtuigen buiten beschouwing, aangezien vogels verschillend kunnen reageren op een naderend vliegtuig, en het daarmee voor de piloot moeilijk is om een succesvolle ontwijkende manoeuvre uit te voeren.

Dit onderzoek focust zich op het effect van zowel de veiligheid als de capaciteit en vertragingen van het gehele vliegveld. Om representatieve resultaten te behalen worden er Monte-Carlosimulaties uitgevoerd onder verschillende omstandigheden, waaronder een variërende verkeersdrukte, en vogeltrek in alle seizoenen. Het platform waar dit onderzoek zich op baseert is de BlueSky Open Air Traffic Simulator, ontwikkeld door de TU Delft, waarin fast-time simulaties mogelijk zijn. Dit platform is speciaal in het representeren van het luchtverkeer. In dit werk wordt het gebruikt voor het bestuderen van aanvaringrisico's alsmede het verifiëren en valideren van de implementaties van het vogelaanvaringsverminderingsalgoritme. Daartoe is de simulator uitgebreid om vliegbewegingen van vogels te kunnen representeren, en om aanvaringen te kunnen identificeren. Daarnaast is een vogelbewegingsmodel ontwikkeld op basis van twee verschillende radar types. Dit model wordt gebruikt als input van het botsingsdetectiealgoritme.

De resulterende simulatie is de eerste in zijn soort, en maakt het mogelijk om gelijktijdig fast-time simulaties uit te voeren van zowel vogel- als vliegtuigbewegingen.

Al in een vroeg stadium werd zichtbaar dat er een drievoudige overschatting van vogelaanvaringen werd gemaakt in het simulatieplatform, zonder dat het algoritme invloed uitoefende op het luchtverkeer. Dit kan worden verklaard door zowel de grote aanwezigheid van vogels dicht bij de start- en landingsbaan, als doordat de reactie van vogels op naderende vliegtuigen niet wordt gemodelleerd. Wanneer het algoritme wordt ingeschakeld, zal dit bij deze datasets vaker ingrijpen dan dat het in de praktijk daadwerkelijk zou doen. Dit fenomeen is in het bijzonder relevant tijdens het beoordelen van de effecten van het algoritme op de capaciteit van het vliegveld.

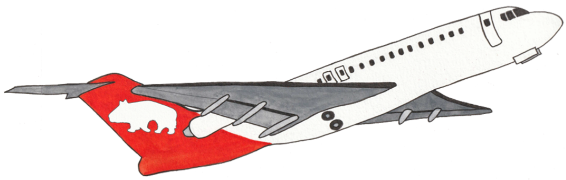
Globaal gezien wordt het algoritme ontwikkeld in de volgende stappen. Allereerst wordt de capaciteit bepaald wanneer een vogelaanvaringsverminderingsalgoritme actief is dat zoveel mogelijk aanvaring voorkomt met een minimaal capaciteitsverlies. Hierbij wordt verondersteld dat de vliegbewegingen van vogels perfect te voorspellen zijn. Deze eerste stap laat ook zien hoeveel extra veiligheid het algoritme kan opleveren. Daarnaast is het ook een verificatie voor de correctheid van de implementatie van het ontwikkelde algoritme. Uit de tests blijkt dat een dergelijk systeem 99 % van alle aanvaringen voorkomt. De overige 1 % van de aanvaringen worden veroorzaakt door vogels die pas later dan het vliegtuig opstijgen. Ook blijkt dat hoewel de capaciteit van het vliegveld onveranderd blijft, er sprake is van onaanvaardbare lange wachttijden. Aangezien het in de lijn der verwachtingen ligt dat het aantal meldingen zal stijgen wanneer de onzekerheid in de vogelbewegingen toeneemt, is het noodzakelijk om prioriteiten te stellen bij het ingrijpen. De focus moet liggen bij vogels die niet kunnen worden beïnvloed door de vogelwachten. Daarbij moet het algoritme zich focussen op aanvaringen die naar waarschijnlijkheid veel schade aan het vliegtuig kunnen aanrichten.

In de volgende stap wordt het vogelaanvaringverminderingsalgoritme uitgebreid naar een vogelaanvaringsrisicoalgoritme dat het risico op aanvaringen bij vertrekkende vliegtuigen kan berekenen op basis van actuele bewegingen van vogels. Er wordt een model geïntroduceerd dat op basis van simpele lineaire regressie de baan van de vogels voorspeld. In eerste instantie wordt de kans, en later ook de ernst, van de aanvaringen voorspeld. Wanneer deze waarden bepaalde drempelwaarden overstijgen, zal het algoritme het vertrek van het vliegtuig vertragen. De meeste vertragingen worden dan veroorzaakt door vogels die dralen over of dichtbij de start- en landingsbaan, waardoor er veel onnodige extra wachttijden ontstaan. Dit laat duidelijk zien dat de aantal keren wanneer het algoritme ingrijpt zal moeten worden beperkt, zodat het vliegverkeer door kan blijven stromen. Daarom moet de uiteindelijke implementatie van het vogelaanvaringrisicoalgoritme alleen een vlucht vertragen wanneer deze naar waarschijnlijkheid veel schade ondervindt door een vogel die het vliegpad van het vertrekkend vliegtuig oversteekt.

Bij het vogelaanvaringsrisicoalgoritme blijft het aantal en de duur van de geïntroduceerde wachttijden binnen de perken. Echter blijkt deze methode met lineaire regressie nog niet genoeg in staat om een goede schatting te maken van het risico op aanvaringen. Hoewel het algoritme aanvaringen voorkomt, zorgt het er ook voor dat vliegtuigen die vertraagd vertrekken als gevolg van eerdere vertragingen, hier nadeel van kunnen hebben. Deze hebben meer kans op vogelaanvaringen van zowel vogels, die onder de drempelwaarden vallen, als van vogels die later dan het vliegtuig opstijgen.

Hierdoor blijft het aantal vogelaanvaringen ongeveer gelijk in de periode voor en nadat het algoritme ingrijpt.

Voor een betrouwbare voorspeling is het bij vervoglstudies nodig vogeldata te hebben van meerdere jaren en van verschillende sensor-types, zodat er modellen ontwikkeld kunnen worden die specifiek zijn voor het type vogel en de omgeving van het vliegveld. Dit zal de drempelwaarde die een ingreep van het algoritme veroor-zaakt laten afhangen van de milieu- en verkeerssituatie. Daarnaast moet het cumulatieve risico van alle vogels, in plaats van individuele vogels, die vliegpaden van vertrek-kende vliegtuigen oversteken verder bestudeerd worden. Hiermee kan het concept van een adviessysteem om vogelaanvaringen te voorkomen verder ontwikkeld worden om dichter bij het niveau van veiligheid te komen van het initiële vogelaanvaringsverminderingsalgoritme.



1

Introduction

1

SUMMARY

Birds have been soaring in the skies for millions of years. While the introduction of manned flight strongly contributed to globalization and human wealth, it also marked the beginning of additional negative impacts on nature. Despite their much larger size, the aircraft are vulnerable to damage resulting from collisions with birds. In the worst case, bird strikes can even lead to the crash of the involved aircraft. One of the very first powered aircraft, the Wright Flyer III, collided with a bird. Since then, thousands of these birds strikes have occurred, causing fatalities on both sides. To reduce the probability of such events, many measures have been implemented. Their majority aims at keeping birds off the airport perimeters, which has contributed to reducing bird strikes there. However, the options to keep aircraft and birds safe in low-level flight phases in the departure- and approach corridors are limited, especially since pilots and controllers are not involved. To contribute to enhancing the scope of bird strike prevention to beyond the airport boundaries, this doctoral thesis studies a new approach. Based on real-time bird movement information, departing aircraft are held back if the risk of a collision with birds is too high. The effects on the safety as well as the ones on air traffic flows of such a bird strike advisory system are analysed and a feasibility study is performed. This chapter introduces the general bird strike problem, leading to the motivation of and the research question to be answered within this thesis. Thereafter, its experimental set-up is described.

1.1. BIRD STRIKES

COLLISIONS BETWEEN BIRDS AND AIRCRAFT

On September 7 in 1905, the Wright Flyer III experienced the first recorded bird strike in aviation. While the aircraft remained free of damage, the involved bird was killed [120]. In 1912, the first bird strike-related human fatality occurred. The collision between a Wright Flyer Model B and a gull caused the aircraft to crash into the sea, killing its pilot [121]. These early occurrences already demonstrated the limitations of a sky shared by aircraft and birds at the very beginning of powered aviation. To prevent such collisions between birds and aircraft, numerous measures are in place at airports which are performed by local wildlife control units [34]. In addition, modifications to aircraft to achieve enhanced perceptibility have been developed [1, 143]. Furthermore, certification specifications by the aviation authorities require impact-resistance of aircraft components and engines to limit the danger of damage in case of a collision [63–65]. Despite these efforts, bird strikes are still regular events with a potentially catastrophic outcome for the involved aircraft. This was shown in three major accidents with commercial aircraft over the past years. In 2009, the crew of an Airbus A320 had to perform an emergency ditching on a river after colliding with multiple Canada Geese during departure [133]. In 2012, a Dornier Do-228 aircraft hit a Black Kite during take-off. The collision resulted in the crash of the aircraft [93]. In 2019, a bird strike involving multiple gulls led to the emergency landing of an Airbus A321 aircraft in a cornfield[17].

These events have in common that the bird strike happened during departure. In two of these accidents, the collisions took place beyond the airport boundaries. These areas are not covered by traditional bird strike prevention which is performed by special wildlife control units. Their target is to keep birds away from the airport perimeter [105].

These measures are geographically limited to within the airport boundaries.

Research has shown that the risk of bird strikes is highest below 1,000 m [121], decreasing with altitude. However, the danger of damage resulting from strikes increases with altitude, due to the presence of larger birds and higher aircraft velocities at higher altitudes [48]. Moreover, the danger of a catastrophic outcome of bird strikes is largest during departure when the engines run on full power and thrust is required to be able to reach the airport of origin or another airport in the vicinity for a safe landing [19, 46]. Consequently, to include critical areas in the extended airport environment in the bird strike prevention process, new approaches for risk reduction have to be found.

Over the past years, it has been requested to include the parties actually controlling the aircraft – namely pilots and air traffic controllers – in the process of bird strike prevention [121]. By providing them with real-time information about the current bird strike risk, pilots and controllers can actively contribute to enhance aviation and avian safety. Enablers for this operational bird strike prevention process are surveillance technology such as avian radars tailored to locate and track birds. Based on the real-time recording of tracks, future bird movement can be predicted and the bird strike risk can be determined. In case of high risk, warnings can be released to controllers and aircrew.

An increasing number of airports have been installing avian radars, of which the majority serve to provide the local bird strike prevention units with information to locate hot spots of bird activity [121]. Air Traffic Control (ATC) usually has no link to the radar's output. A promising exception is the King Shaka International Airport in Durban, South Africa. Based on radar observations, ATC can be advised to hold departing traffic back in case of a high bird strike risk [118]. The situation at this airport is special in the sense that the risk occurs twice a day when millions of wintering swallows cross the extended center line to move between resting and feeding areas. Hence, the timing and duration of these warnings are very predictable, and can therefore be effectively used by ATC.

The introduction of such a concept of operational bird strike prevention at airports with less predictable presence of birds faces multiple challenges. First, methods to predict local bird movement as reliably as possible have to be established. Second, a suitable level of support for the controller has to be developed and evaluated. Potential levels of support range from visualizing the current and predicted bird tracks up to a system advising the controller when it is safe to use the runway.

A crucial element to be considered with regard to acceptance of such a concept is legal responsibility. Due to limitations in the predictability of bird movement, there will always remain an uncertainty in the reliability of the output of the system. It has to be ensured that the controller's decisions based on that output do not result in any personal legal responsibility.

On the airport level, the influence of such a concept on the air traffic flows is a relevant criterion. The number of generated warnings and thus the number and duration of imposed delays as well as the effect on runway capacity depend on the predictability of the bird movement and the defined warning levels. Furthermore, the question to what extent bird strikes can be prevented at all, remains to be analysed.

This thesis addresses the questions of the impact on safety as well as capacity and as such the feasibility when implementing operational bird strike prevention. It is assumed that the controllers receive full support by a bird strike advisory system. In case of high bird strike risk, the system requests the controller to hold departing air traffic back. Arriving traffic remains unimpeded. Aircraft flight paths are known; all uncertainty with regard to trajectories is projected to the bird movement.

1.2. Research Approach and Key Challenges

The key question to be answered in this PhD research project can be summarised as

> **Main Research Question**
>
> How feasible is the implementation of an air traffic control advisory system for the prevention of bird strikes?

To answer this question, multiple research steps are carried out within this thesis. The key element is the development of a bird strike risk algorithm underlying the bird strike advisory system. A realistic implementation takes into account the bird movement observed at the intended take-off time of an aircraft. Based on the tracks of the birds present and the forecast of their propagation, the collision risk is calculated. If the risk is too high, the aircraft is delayed until the risk falls below the threshold again. The algorithm is a complex system consisting of four main elements. First, bird movement has to be predicted based on the currently known bird tracks. Second, the collision risk has to be calculated. Therefore and third, the definition and detection of collisions is required. Fourth, the aircraft has to be rescheduled to a collision-free departure without interfering with arriving traffic.

To ensure the correct implementation of the individual steps of the bird strike risk algorithm, it is developed in different levels. Its structure is set up in a modular fashion to facilitate later enhancements. First, the modules to detect and avoid collisions is established. The resulting algorithm is referred to as collision avoidance algorithm. It resolves bird strikes based on the assumption of perfectly predictable bird movement. This allows to verify the correct collision detection and rescheduling of aircraft within the algorithm. Moreover, the results based on these idealised conditions demonstrate the maximum potential of a bird strike advisory system. Hence, they will serve as a benchmark for more realistic implementations.

In the second step, the collision avoidance algorithm is enhanced to the full bird strike risk algorithm by implementing modules to predict bird movement and to calculate the probability as well as expected severity of strikes. In the initial settings, the bird strike risk algorithm considers all birds present in the extended airport environment. Thereby, the different effects of the algorithm when considering solely the probability of a strike or when taking into account severity as well are evaluated. In the final and main version, birds present on or close to the runway are excluded for two reasons emerging from the study of the initial settings. First, the birds present on or close to the runway are over represented in the simulation environment. Second, these birds are targeted by prevention activities already in place. Therefore, the final version of the algorithm aims at birds crossing the extended runway center line where the highest potential of safety enhancement for the concept of operational bird strike prevention lies.

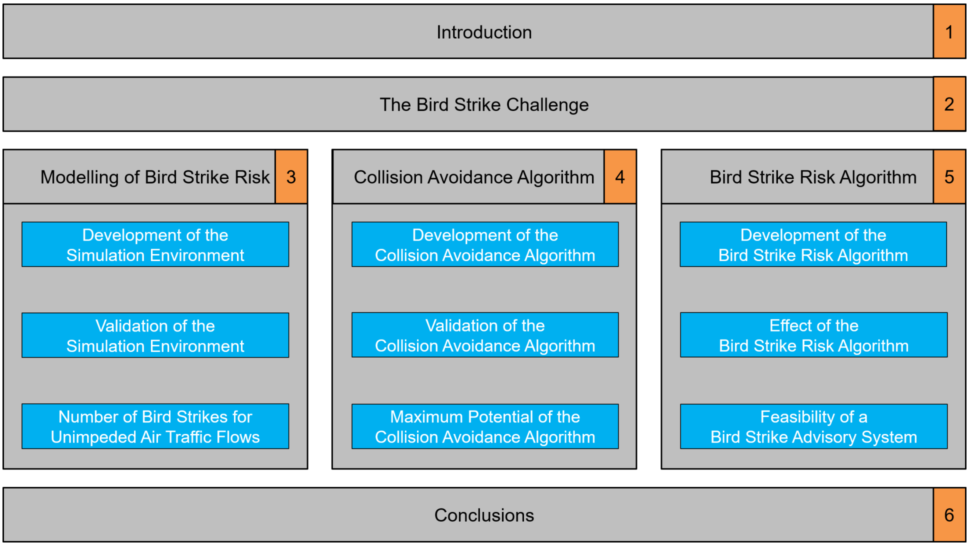


Figure 1.1: Overview of the thesis structure.

The bird strike risk algorithm receives aircraft flight plans and bird movement information as input. The output consists of new flight plans including revised take-off times where a rescheduling due to bird strike risk is necessary. By comparing the initial and revised flight plans, the imposed delays as well as the impact of the algorithm on airport capacity can be analysed and compared throughout the different development stages.

To evaluate the effect on safety, the number of strikes taking place prior and after the intervention of the algorithm are observed. Therefore, fast-time simulations including the original and revised flight plans as well as the bird movement information are performed and the occurring strikes recorded. The BlueSky Open Air Traffic Simulator, which serves as simulation environment for this purpose, is dedicated to simulate air traffic flows. Within this thesis, BlueSky is enhanced to incorporate bird movement as well as to detect collisions and near misses between birds and aircraft. The developed bird model also underlies the collision avoidance algorithm, ensuring full comparability between the results of the two applications.

To obtain representative results of the effects of a bird strike advisory system and consequently its feasibility, Monte Carlo Simulations are performed for the validation of the simulation environment and for all development stages of the bird strike risk algorithm. Air traffic patterns are randomised in intensity as well as shares of departures and arrivals. Bird movement information is included from all seasons to consider the variation in bird abundance.

Figure 1.1 presents the described elements of this PhD research and places them within the thesis structure. The challenges arising from aircraft and birds sharing airspace are presented in chapter 2. Chapter 3 introduces the simulation environment used for this PhD research and describes how it was extended to represent bird movement information and to recognise bird strikes. Next, the results of the validation of the simulation environment and the analysis of the bird strike risk without any operational measures are presented. In chapter 4, the collision avoidance algorithm is outlined. This is followed by the validation of the algorithm and the discussion of the maximum potential of a bird strike advisory system. In chapter 5, the collision avoidance algorithm is enhanced to build the bird strike risk algorithm. With this step, the algorithm moves from deterministic collision avoidance to risk evaluation by predicting bird movement and calculating the probability as well as the severity of potential strikes. Based on the results obtained from the study of the bird strike risk algorithm, the feasibility of a bird strike advisory system is discussed. The thesis closes with the conclusions in chapter 6.

The contents of chapters 2 to 5 were published in scientific journals or within conference proceedings. Hence, these chapters can be read independently. A summary at the beginning of each chapter puts its content into the context of the full thesis. To reduce redundancy in the introduction and method sections, minor adjustments were performed.

In Appendix A, the bird strike risk observed in the simulation environment is analysed considering the impact and thus the damaging potential of bird strikes. In Appendix B, the results of the initial bird strike risk algorithm, considering strikes with all birds present in the airport environment, are presented.

2

The Bird Strike Challenge

This chapter is based on the publication

I.C. Metz, J. Ellerbroek, T. Mühlhausen, D. Kügler and J.M. Hoekstra, *The Bird Strike Challenge*, Aerospace **7**, 3 (2020) [124].

SUMMARY

Collisions between birds and aircraft pose a severe threat to aviation and avian safety. To understand and prevent these bird strikes, knowledge about the contributing factors is vital. However, even though bird strikes are a global issue, data availability strongly varies and is difficult to put into a global picture. This chapter aims at closing this gap by providing an in-depth review of international studies and statistics to obtain a concise overview of the bird strike problem in commercial aviation. The chapter illustrates the factors contributing to the occurrence and the potential consequences in terms of effects on flight and damage. This is followed by a presentation of the risk-reducing measures currently in place as well as their limitations leading to the motivation for this PhD research.

2.1. 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 [18]. Collisions between birds and aircraft are regular events. Depending on the country, average bird strike numbers between 2.83 and 8.19 per 10,000 aircraft movements were reported in civil aviation over the past years. Examples of various countries are provided in Table 2.1.

Table 2.1: 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	[16]
Canada	3.51	2008–2018	[160]
France	3.95	2004–2013	[42]
Germany	4.42	2010–2018	[36]
UK	7.76 (all) 4.62 (confirmed)	2012–2016	[161]
USA	2.83	2009–2018	[52]

Nevertheless, while bird strikes 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 [15, 52, 116, 160, 161]. Regarding operational impacts, between six and seven percent of all reports indicate a negative operational effect on the flight [52, 160, 161]. It is estimated that bird strikes cause annual costs of at least one billion US $ to the worldwide commercial aviation industry [9]. Due to incomplete reporting, these figures have to be interpreted as conservative estimates [50, 54, 162].

As accidents have demonstrated, bird strikes also bear the potential for catastrophic outcome for the involved aircraft. As of 10 February 2021, bird strikes were determined to have caused 618 hull losses and 534 fatalities since the beginning of aviation [18].

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 [140]. Furthermore, international standards and common definitions are needed. In this chapter as well as within the PhD study, the focus lies on civil aviation in general and commercial aviation in particular. The first section of this chapter 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.

2.2. 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* [71]. 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 (US) and the United Kingdom (UK) [52, 160, 161]. One exception is Australia, where all flying animals, including flying foxes and bats, are included in the bird strike statistics [16].

This chapter focuses on collisions involving birds and the term *bird strike* is used. First, the vast majority of wildlife strikes occur with birds. For example, the shares amount to 98 % in Australia, 95 % in Canada and 95 % in the US [16, 52, 160]. Second, terrestrial animals can be prevented from entering airport perimeters, for example by installing fences [40]. 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 chapter.

The International Civil Aviation Organization (ICAO) requests its contracting states to report bird strikes [98]. 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 recognised and has since been encouraged or even enforced by many **CAAs!**s (**CAAs!**s)s 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 [72]. All parties involved in air traffic operations within the EU have been obliged to report observed bird and wildlife strikes [73]. 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 US, 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 [50]. 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 [92]. The number of reports strongly increased since the implementation of this mandate [7]. The reason for the rise is mainly attributed to better reporting, rather than increased bird strike risk. This is explained with the ratio between the number of damaging strikes and all strikes [7, 50]. 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 pro-

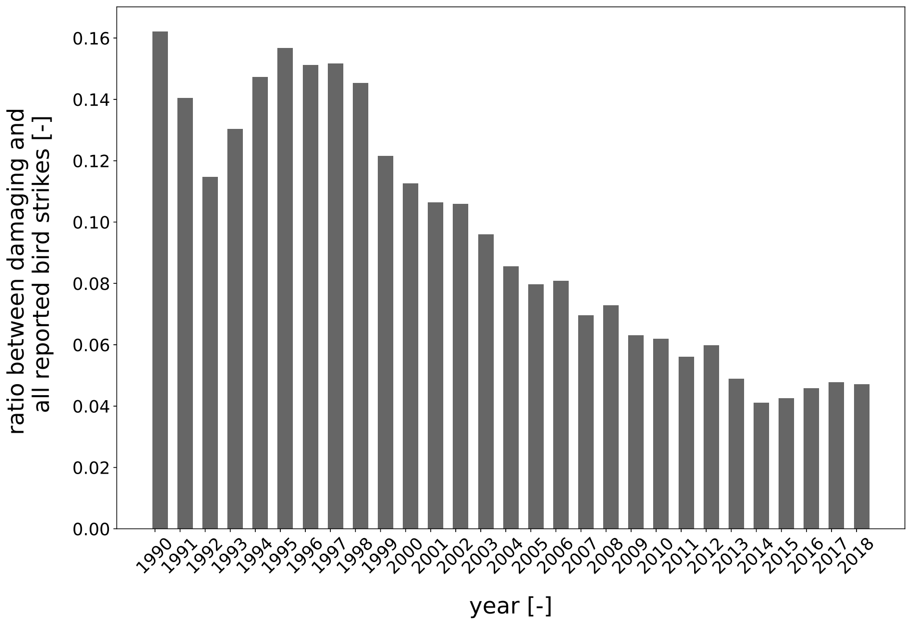


Figure 2.1: Ratio between damaging strikes and all strikes in the US between 1990 and 2018. Source: [52].

portions of damaging strikes fell. This is supported by the latest US data for the period until 2015, as visualised in Figure 2.1. 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.

Over the past few years, bird species hazardous to aviation have expanded and adapted to urban areas [13, 47]. As air traffic is rising as well [102], 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 sections 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* [101]. This definition is applied here.

2.3. 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 [117]. This section provides an overview of these individual components.

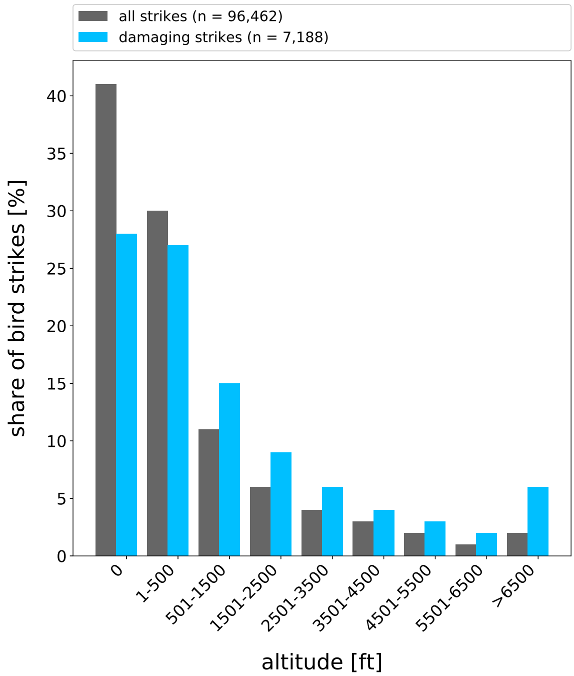


Figure 2.2: Distribution of bird strikes by altitude band that occurred between 1990 and 2018 in the US, where the altitude was known (72 % of all strikes, 70 % of damaging strikes). Source: [52].

2.3.1. ALTITUDE

The highest probability of bird-aircraft collisions is at low altitudes [121]. 88 % of the bird strikes in the US over the past 27 years have occurred below 2500 ft (71 % below 500 ft) [55]. When considering worldwide traffic, 95 % of all strikes occur below 2500 ft (70 % below 200 ft) [57]. This corresponds to the flight phases most prone to bird strikes: takeoff, initial climb, landing and approach [103]. Figure 2.2 shows the decreasing probability with increasing altitude. 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. Moreover, while mitigation measures at airports have been successful in reducing the number and consequences of bird strikes, outside the airport boundaries, the options for counteracting measures are limited [48].

2.3.2. SEASON

The likelihood of bird strikes depends on seasons. Figure 2.3 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 [60, 164, 166], 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 [35, 167].

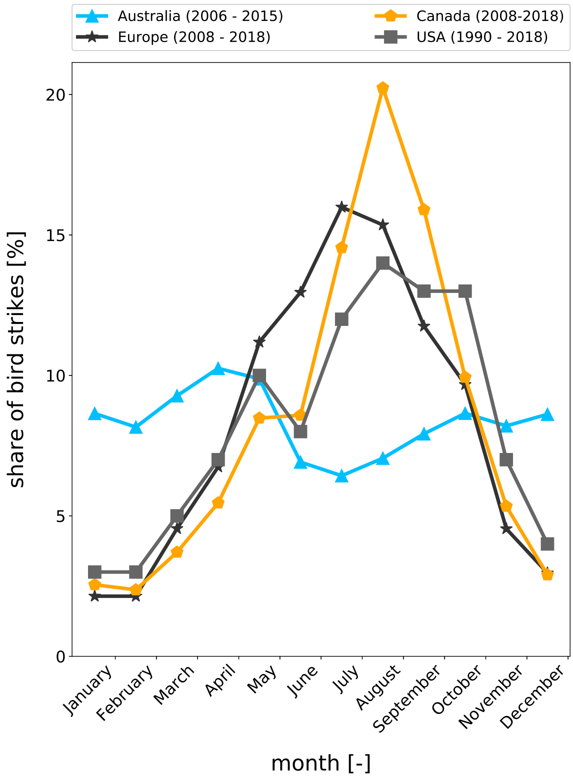


Figure 2.3: Seasonal distribution of bird strikes reported from Australia, Europe, Canada and the US. Sources: [15, 52, 116, 160].

2

2.3.3. Location and Environmental Conditions

The probability of bird strikes depends on the geographical location [35]. This is related to the abundance of different bird species with variable behavior, size or tendency to flock. In the direct airport environment, the landscape characteristics are a determining factor [139]. In regions situated along a migratory flyway, the danger of collision remarkably increases during migration seasons [35, 167]. 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 at night [31, 45]. This is caused by increased bird activity, especially in case of migrating birds [6]. Furthermore, many airports cease dispersing activities at night. However, since much more air traffic takes place during daytime, the absolute number of strikes is higher in this period [51, 103].

In addition to the geographical location, the attractiveness of an airport's environment also strongly influences the risk of bird strikes. ICAO requests all airports to assess the individual bird strike hazard [104]. 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 strongly influence the risk of bird strikes [104, 139]. For this purpose, ICAO's Airport Service Manual [105] 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 should be performed [105].

Next to the birds, also the characteristics of aircraft have an influence on the likelihood of bird strike. These influences are described below.

2.3.4. Aircraft Characteristics

Aircraft characteristics influence the probability of bird strikes. Due to their large size and high suction effect, turbofan engines are more likely to ingest birds than other engine types [14]. Moreover, due to the higher speeds during take-off and landing of turbofan aircraft, birds have more difficulties to avoid these than other aircraft types [39]. Over the last years, turbofan engines increased in diameter [89], 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 that time. In 2015, the number of commercial turbofan aircraft amounted to 22,690, which corresponds to 86.5 % of all commercial aircraft [131, 132]. According to Canadian data from 2008 to 2018, turbofan aircraft experienced 1.7 times more bird strikes than aircraft equipped with propellers [160].

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 [155]. 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 [34, 89].

2.4. SEVERITY OF BIRD STRIKES

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

$$E_{kin} = \frac{1}{2} \cdot m \cdot v^2 \tag{2.1}$$

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 [13]. 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, a study to evaluate the consequences for damages resulting from bird strikes below and above 500 ft in 2011 was performed [48]. 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 damage, which is also reflected in Figure 2.2. This observation is supported by a study performed for the European Aviation Safety Agency (EASA) in 2009 that takes into account data from civil aircraft from the UK and Canada for the period between 1990 and 2007 [13]. 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 especially larger birds such as Canada Geese and Turkey Vultures fly at higher altitudes [13, 41, 112]. The combination of these two factors leads to a significant increase in the kinetic energy of the impact and thus to a higher probability of damage with increasing height.

2.4.1. 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., [16, 52, 103]). Exemplarily, Figure 2.4 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 [18, 157, 158]. Currently, approximately 94 % of the world's aircraft fleet is equipped with two engines only [131]. Due to the resulting smaller redundancy, the danger is larger when birds are ingested [34].

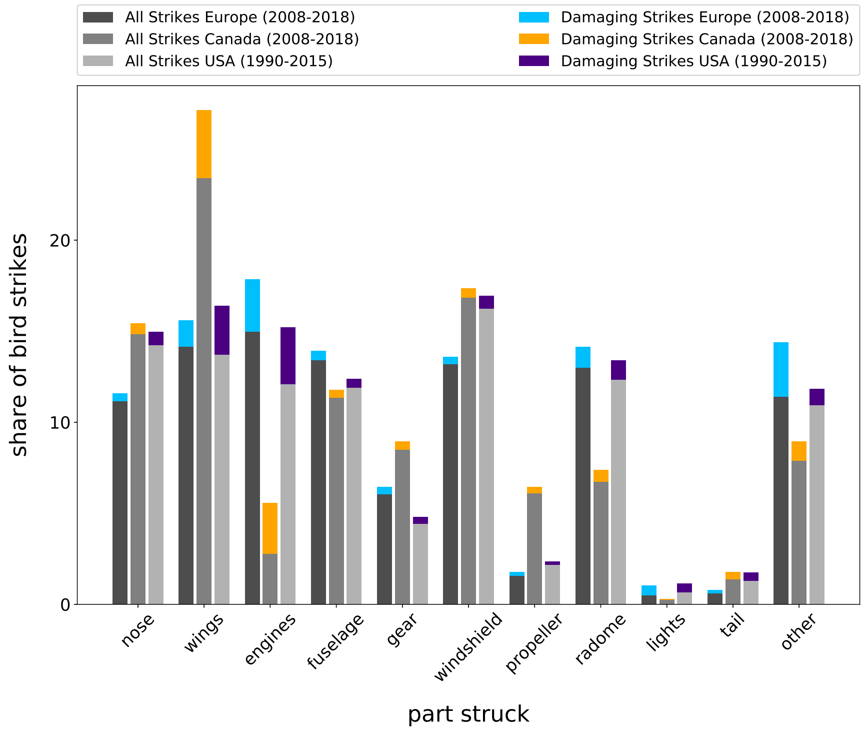


Figure 2.4: Total number of bird strikes per part indicating number of damaging strikes for Europe, Canada and the US. Sources: [52, 116, 160].

Substantial engine damage is most likely during departure [46]. 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 Canada Geese. The crew successfully performed an emergency landing on the Hudson river [133]. 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 [17]. In both cases, all passengers and crew survived.

2.4.2. Risk of Accidents

The number of serious bird strike-related accidents are comparable to serious accidents due to other environmental causes, as Figure 2.5 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 [20]. The effect of these measures, especially on turbulence-related accidents, is visible in Figure 2.5.

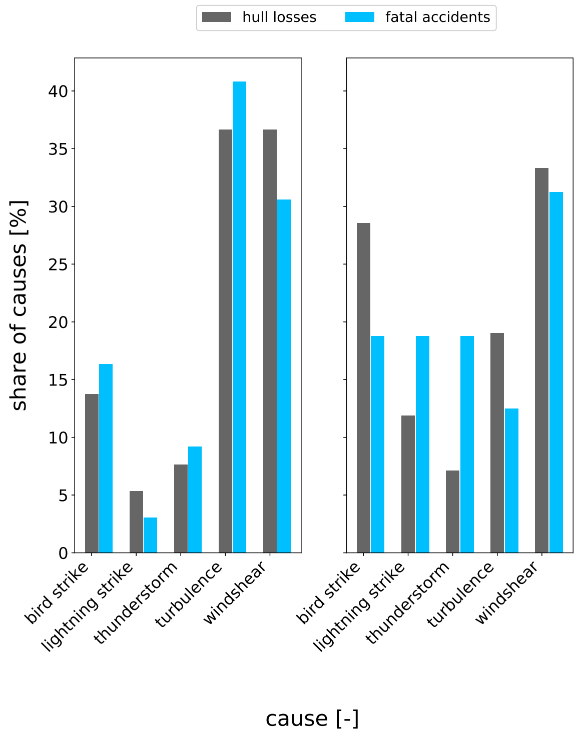


Figure 2.5: Comparison of different accident causes for the periods 1960–1999 (left) and 2000–2015 (right). Sources: [144, 158].

On the other hand, the shares of serious accidents due to bird strike, lightning strike and thunderstorm increased.

2.4.3. 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 2.2 provides an overview of operational impacts for various countries and continents. Furthermore, the worldwide reports collected by ICAO [103] are presented. While the share between *none* and *unknown* varies among the sources, the effect-categories have a similar influence.

Independent of the impact, an examination to ensure the airworthiness of the aircraft involved has to be performed before the next departure [76]. Hence, all recognised bird strikes affect operations and consequently result in costs. Moreover, airport operations might be impaired, e.g. due to temporary runway closure to remove bird remains.

Table 2.2: Reported operational effects in Europe, Canada, the US as well as world-wide in percentages. Sources: [54, 103, 116, 160].

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 assigns *none* and *unknown* to a shared category.

2.4.4. 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 [135]. 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 $ [155]. In 2003, the total annual costs for the world aviation fleet was estimated to be approximately one billion US $ [8]. 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. In total, the average costs for a damaging strike amount to US $ 225,329. More recent data is available from the FAA [52], which is summarised in Table 2.3. 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, only a small proportion of reports included this information as Table 2.3 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. Hence, projected costs are based on the averages obtained from the reports which include cost information.

Aircraft downtime represents another cost measure. Based on the 5 % of reports including information about aircraft downtime, an average of 101 hours per wildlife strike results [52]. When including missing reports, an average of 4,521 days of aircraft downtime per year due to wildlife strikes is projected.

Table 2.3: Repair and indirect costs resulting from wildlife strikes in the US from 1990 to 2018. Source: [52].

Cost type	Total / average	Reported cost [US $]	Projected cost [US $]	Number of reports	Share of reports
repair costs	total	4.6 M	4,465 M	4,534	2.2 %
	average	158,573	154 M	156	
indirect costs	total	726,044	962 M	3,683	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 information about repair as well as indirect cost. Hence, a total number of reports cannot be obtained.

2.5. 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 [45, 105]. In this context, the ICAO requests airports to maintain a wildlife strike program [104, 105]. In addition to the measures to prevent bird strikes, regulations to minimise the risk of damage are in force. These are described at the end of this section.

2.5.1. MITIGATION MEASURES ON THE GROUND

Successful bird strike prevention at airports requires the identification of hazardous species as well as the understanding of the types and reasons of their movements [23, 38]. 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 [7, 11, 34, 39]).

The measures range from habitat management to exclusion, harassment, capture, and shooting of wildlife [34]. Within *habitat modification*, the airport grounds are made as unattractive to birds as possible, by removing sources of water, food and shelter or by making them inaccessible [148]. 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 [34]. 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 [22].

The category *capture and relocation* includes trapping of birds on the airfield and reassigning them to new habitats away from the airport. Among others, a minimum distance between the airport and translocation area should be kept to limit returns to the airport [142]. The *lethal* category covers shooting of birds. It pursues two goals. First, the population density of critical bird species should be limited to lower 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. Moreover, lethal methods are forbidden or restricted in many countries [53, 145].

The described efforts at airports are vital for reducing the risk of bird strikes and many control programs have shown positive effects [47, 52]. 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 3,000 ft [121, 139]. Considering that there is an increasing trend of damaging strikes outside the airport boundaries [48], expanding the horizon of bird strike hazard mitigation beyond the airport fences is essential [121]. Therefore, aircraft-related risk-reducing measures have been researched over the past few years, as described in the following section.

2.5.2. 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., [24, 27, 28, 80, 84, 153]). 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 true for experienced birds as well. 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 [37]. By increasing an aircraft's perceivability, birds can detect its approach earlier and the chances for a successful avoidance manoeuvre rise. [24, 114]. 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 [80]. 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 [1, 168].

Research on increasing aircraft lighting found that pulsing light has the potential to enhance avian visual awareness [25, 27, 28]. However, as visual perception depends on the bird species, different pulsing frequencies and wavelengths might be required [26]. 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 [84].

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

Table 2.4: Magnitudes of damage resulting from bird strikes in Europe and the US. Sources: [54, 116].

Magnitude of 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 airworthiness [66]; [b] When experiencing substantial damage, an aircraft's structural strength, performance or flight characteristics are adversely affected and a major repair is required [66].

in the US for a duration of three years. Compared to the three years previous to installation, the number of bird strikes had decreased by 33.5 % [141]. In another trial, ten aircraft of Qantas Airways were equipped with the system. The installation remained in service between 12 and 24 months. In comparison to the fleet's non-equipped aircraft, a reduction in bird strikes between 54 % and 66 % resulted. [143]. Hence, pulsing lights seem a promising addition, especially to prevent bird strikes at low velocities.

2.5.3. REGULATORY MITIGATION MEASURES

Table 2.4 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., [14]). 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 CAA, 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 [117].

CERTIFICATION REQUIREMENTS

Aircraft have to meet certification requirements to prove their airworthiness [99]. In this section, the European regulations as defined by EASA and the US regulations by the FAA are considered. Aircraft are grouped into size 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 2.5. 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 [131]. In Europe, the majority of commercial aircraft is certified by the standard *CS 25-Large Aeroplanes* [65]. The US-American counterpart consists of the Federal Aviation Regulations (FAR) *14 CFR Part 25-Transport Category Airplanes* [77].

2

Table 2.5: 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 19,000 lb or less [64]	*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 lb or less [77]
CS-25 Large Aeroplanes turbine-powered aeroplanes of more than 12,500 lb maximum certified take-off weight, excluding commuter airplanes which are covered by the category Normal Aeroplanes [62, 65]	*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 lb [79]

These regulations contain the following requirements regarding damage-tolerance of aircraft parts.

- Windshield: Withstand without penetration an impact of a 4 lb bird such as a great black-backed gull at cruise speed.
- Structure: Successfully completing a flight after an impact with a 4 lb bird when the aircraft velocity relative to the bird along the aircraft flight path equals cruise speed at sea level or 0.85·cruise speed at 8,000 ft, whichever is more critical.
- Empennage: Successfully completing a flight after an impact with a 8 lb bird such as a greylag goose at cruise speed (FAA only).
- Pitot tubes: sufficient separation to prevent an impact damaging all of them.

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* [64, 77]. 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 demand tests considering the ingestion of single large birds and large flocking birds [63]. The FAA add tests for small and medium single and flocking birds [74]. Depending on the engine's diameter, different criteria regarding bird mass and thrust settings are required.

The certification criteria are fulfilled if none of the test scenarios results in a *Hazardous Engine Effects*. EASA defines the following events as *Hazardous Engine Effects* [63]:

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.*

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 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 [45, 55]. Many countries such as Canada, Mexico, the US and Germany have applied such a regulation [61, 159].

2.6. NEXT STEPS

Over the past years, the awareness has risen that it is vital to include the parties actually handling air traffic, ATC and pilots, to further reduce the risk of bird strikes in civil aviation [121]. Currently, the controllers can provide general warnings on bird activity in the airport area based on visual observations or reports by pilots [69, 117]. 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 Notices to Airmen (NOTAM) which provides information on current bird strike risk [70]) and bird migration reports, where available [12, 70, 117]. Furthermore, they expected to stay alert throughout the flight and report observations on enhanced bird activity as well as experienced bird strikes [117]. In general aviation, route planning should consider the avoidance of areas abundant of birds. By flying at high altitudes, the probability, and by flying at low speeds, the impact of a potential bird strike can be reduced [12, 117].

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 [33, 113, 165]. In the beginning, this mainly included flight restrictions during peaks of bird migration [167]. 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 has become possible [121]. The military efforts have mainly focused on en-route intervention of flight operations for low-level training flights [165, 167]. 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 [121]. In contrast to military aviation, which has a certain flexibility in flight planning, civil aviation is bound to schedules [138]. 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 pilots could be raised. Second, aircraft taking off could be advised to adjust their rate of climb to pass critical height layers more quickly. And 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* [100]. However, to enable 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 [21]. 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 units 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 [118, 121]. 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 [121]. The general introduction of comparable procedures at other airports are currently 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 [43, 83, 119]. Therefore, not all birds are observed by the radar and no warning can be presented with respect to potentially critical strikes. 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, the risk of bird strikes is distributed throughout the day. This could lead to increased workload for the controllers and to an unjustifiable reduction in runway capacity at high-density airports.

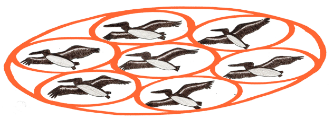
An FAA study addressed the question of workload increase for controllers when involving them in the bird strike hazard reduction process [88]. In human-in-the-loop simulations, controllers were presented with four test conditions in which they had to control air traffic at an airport. In the baseline scenario, bird activity information was provided as observations by pilots transmitted via radio, representing current procedures. In the three remaining scenarios, 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.

This PhD research focuses on the potential effects on the safety and capacity of an airport when implementing procedural risk-reduction methods.

Alternatively to ground-based warning systems, there are ideas to integrate radar-based alerting systems into the aircraft [163]. Independent of the chosen approach, a close collaboration between research and operational personnel is crucial to successfully implement new measures [87].

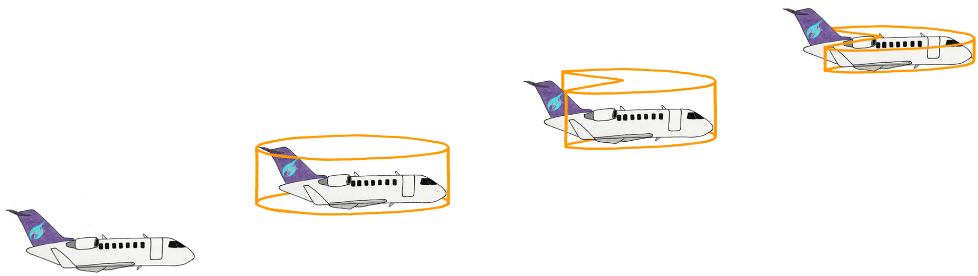
2.7. CONCLUSIONS

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.



3

Modelling of Bird Strike Risk



This chapter is based on the publications

I. Metz, J. Ellerbroek, T. Mühlhausen, D. Kügler, and J. M. Hoekstra, *Simulating the Risk of Bird Strikes,* Proceedings of the 7th SESAR Innovation Days, Belgrade, Serbia, 2017 [123].

I.C. Metz, T. Mühlhausen, J. Ellerbroek, D. Kügler, H. van Gasteren, J. Kraemer and J.M. Hoekstra, *Simulation Model to Calculate Bird-Aircraft Collisions and Near Misses in the Airport Vicinity,* Aerospace **5**(4), 112 (2018) [130].

SUMMARY

This chapter presents the fast-time simulation environment to validate the collision avoidance algorithm developed within this PhD research. An existing air traffic simulator was enhanced to simulate air and bird traffic simultaneously and to recognise collisions as well as near misses between them. Hence, bird movement information from different radar sources was integrated. After a verification with an initial data set, Monte Carlo simulations were performed to validate the simulation environment. It was found that approximately three times as many bird strikes occur in the simulation as in reality. When considering bird reaction to aircraft, which is not covered in the simulation, as well as unreported strikes, this implies an adequate result. The number of bird strikes and near misses is reproducible within the expected variance. Its predictability increases with increasing numbers of birds and aircraft. By including bird movement information from all seasons and a sufficient air traffic volume, the described set-up leads to stable results.

3.1. INTRODUCTION

The introduction of operational bird strike prevention in general and a bird strike advisory system for air traffic control in particular has the potential to prevent bird strikes that nowadays would be inevitable. However, delaying of traffic reduces runway capacity which could turn out especially critical for airports with high traffic demand. So far, the consequences on the safety and capacity of an airport when implementing a bird strike advisory system have not been analysed. As a framework for a corresponding study, a fast-time simulation environment has been developed. The applicability of the simulation environment as a research tool for assessing the risk of collisions between aircraft and birds was verified with an initial data set of real bird movements as well as different air traffic intensities. Bird strikes are relatively rare events. Hence, they are, in parts, subject to chance. Therefore, there is a risk that the outcomes of the simulations are sensitive to the specific input data and thus not representative. To confirm whether the results are reproducible and to establish a convincing conclusion about the developed simulation environment, Monte Carlo simulations were performed. To further increase the number of events, near misses - situations where birds and aircraft come dangerously close - were considered additionally to actual collisions. As near misses occur much more often than bird strikes, this measure extends the data set available for statistical analysis considerably. It was hypothesised that due to the random nature of bird strike occurrences, variations in bird strike numbers would occur within the individual replications of the Monte Carlo simulations.

3.2. METHOD

This section provides an overview of the simulation environment's components as well as their specifications.

3.2.1. SIMULATION PLATFORM

To develop a simulation environment for the analysis of bird strikes, an underlying simulation platform is required. This study relies on the BlueSky Open Air Traffic Simulator developed by Delft University of Technology. This simulator facilitates the analysis and visualization of air traffic flows as well as Air Traffic Management (ATM) concepts. Air traffic can be simulated in real- and fast-time, including validated aircraft performance characteristics [95, 127]. Hence, the representation of air traffic required for this study is already provided by the simulation platform. [1]

Within this work, BlueSky was extended to represent bird movements and to record collisions as well as near misses between birds and aircraft. Similar to the existing aircraft representation, birds are modelled as point-masses within the simulation. No bird behaviour or reaction to aircraft is modelled. Data from different studies suggest that in reality, some bird species show avoidance reactions to approaching aircraft and sometimes manage timely escapes [25, 81, 107]. Therefore, it is expected that the number of bird strikes is overestimated in the simulation. This corresponds to a conservative estimate of the bird strike risk.

BlueSky is organised in a modular fashion and is exclusively based on open sources as well as open data. Therefore, it can freely be downloaded and modified. This simplified the integration of modules for bird traffic and collision detection between birds and aircraft. The resulting simulator set-up facilitates the simultaneous simulation of bird movements and air traffic as well as the recognition of bird strike and near miss events. Figure 3.1 shows the simulator modules. The BlueSky-version resulting from this study can be downloaded from [122].

To perform simulations in this set-up, input data for bird movements and air traffic is required. The following paragraphs describe how these were obtained and processed for the simulation. Thereafter, the developed conflict-detection algorithm to identify bird strikes and near miss events within the simulation is presented. Finally, the adaptations implemented for the Monte Carlo simulations are presented and the final simulation set-up is summarised.

3.2.2. BIRD MOVEMENT

The module to simulate bird movements within BlueSky was developed with data sets acquired from specific locations. However, any movement information in the format of the Bird Movement Plans (BMPs) resulting from the here described method can be used as input for the simulation.

To represent bird movements within the simulation, data from two different sources is used to cover the extended airport area up to a height of 1,000 m. This is the area where the risk of bird strike is the highest [45, 121]. From ground level to a height of

[1] This work bases on the BlueSky version a8675a3635d3be7bf8b3e398a25eba6f9302c813, programmed in Python 2. The latest BlueSky-version, programmed in Python 3, can be downloaded from [94].

200 m, an avian radar located at an airport serves as input. Avian radar is specifically designed to track birds up to distances of 11 km and heights of 1.5 km [21]. However, due to radar shadowing and limitations in tracking single birds, especially close to the ground and with increasing distance from the radar [43, 83], not all birds present are actually represented in the avian radar data. The reduced number of individual birds close to the ground is not addressed in this study. Therefore, the actual number of birds and the related collision risk is expected to be slightly underestimated on the airport grounds. To receive more representative data for birds at larger distances, i.e. outside the airport boundaries, the avian radar data was complemented with information from weather radar. Weather radar has been used for the quantification of bird movements for several decades [58, 82] and for studies on large-scale bird migration [137, 150]. The weather radar data is used to represent bird movement from 200 m to 1,000 m.

This study uses data from two Dutch radars, namely the avian radar at Eindhoven airport and the weather radar located in De Bilt. The output from the avian radar provides two-dimensional tracks of individual birds and flocks. The weather radar delivers bird reflectivity which can be transformed to bird density. Both radars have limitations with regard to information about flocking birds. The subsequent paragraphs describe the processing of the radar data to receive three-dimensional bird tracks for the simulation and to include flock information for both sources.

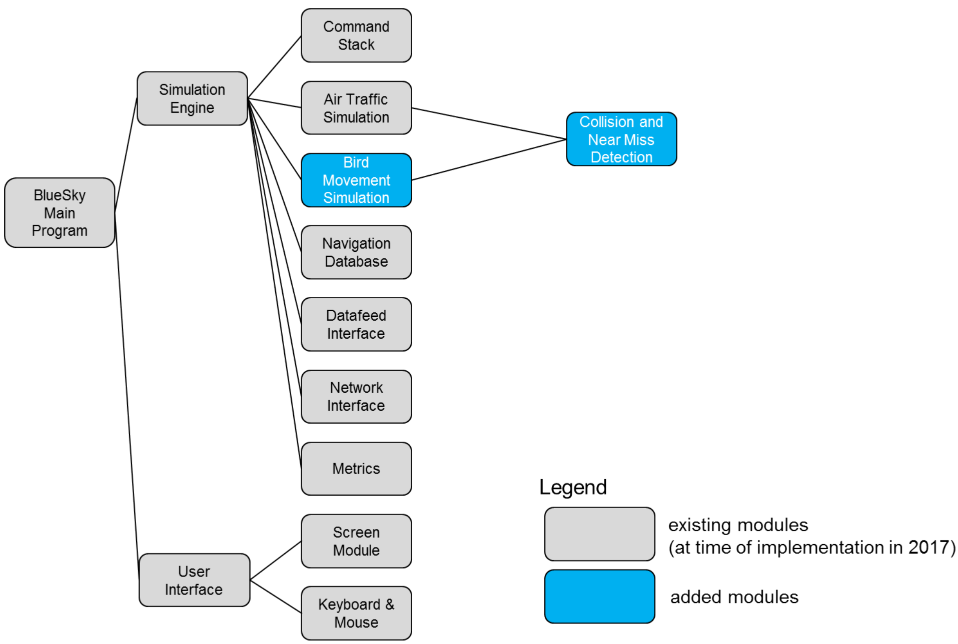


Figure 3.1: Overview of BlueSky after enhancement with modules for bird movements and collision/near-miss detection (own figure, adapted from [95]).

Processing of Avian Radar Data

The input data obtained from avian radar contains time-stamped two-dimensional positions of moving objects that are connected to tracks by a Kalman-Filter. Every track is assigned to an id as well as an object type. To utilise the data as simulation input, it was processed by performing the following steps.

Filtering of tracks The bird tracks used for the simulation were filtered by object type and length of track. The avian radar data distinguishes between the object types *small bird, medium bird, large bird, flock, vehicle, aircraft, insect, small target* and *unknown*. For this study, the data was filtered for the object types *small bird, medium bird, large bird* and *flock*. To gain representative tracks, only birds with at least 20 recorded data points were selected. With a radar turning frequency of 0.75 Hz, this corresponds to a minimum track duration of about 27 seconds. This filtering reduces the number of tracks and is thus expected to slightly decrease the number of bird strikes in the simulation.

Assignment of altitude The avian radar at Eindhoven is a horizontal X-band radar. The beam-width of the antenna in this configuration is narrow in the azimuth pane and wide in the elevation beam-width. Consequently, range and azimuth can be provided with a high accuracy while the resolution of elevation and height information is low. Hence, only latitude and longitude of bird positions can be obtained from that radar [146]. Therefore, birds were assigned to an altitude by using uniform distribution between 0 and 200 m. As the beam size of the radar increases with distance, the range of potential vertical positions rises as well. At a lateral distance of about one kilometre from the avian radar, the beam exceeds an altitude of 200 m. As weather radar data is used from 200 m upwards, an overlap of the two sources occurs as Figure 3.2 illustrates. Area 3 is considered by both radars. To avoid double counts, the number of birds tracked by the avian radar was set as follows: Assuming that birds fly at constant height once airborne, all birds flying within the range of area 1 for at least one time step were selected. For the outer range (areas 2 and 3), birds were filtered corresponding to altitude distributions determined by Shamoun-Baranes, van Gasteren and Ross-Smith, 2017 [152]. They conclude that 48 % of all birds fly below 200 m during daytime. At night, 35 % fly below 200 m. Consequently, two out of three birds were removed from areas 2 and 3 to gain a conservative estimate of the number of birds. Area 5 is not covered by neither of the radars.

Storing of tracks The resulting three-dimensional tracks were stored as input-data for the simulation.

Processing of Weather Radar Data

This section describes, how bird tracks were obtained from the weather radar data. For this purpose, the following steps were performed. The data of the chosen C-band weather radar in De Bilt contains information about bird reflectivity ($\frac{cm^2}{km^3}$). Furthermore, Northern and Eastern speed components are given. The data is provided in altitude bins of 200 m. For this study, the altitude bands from 200 m to 1,000 m were considered. To receive bird tracks, these parameters were processed by applying the following steps.

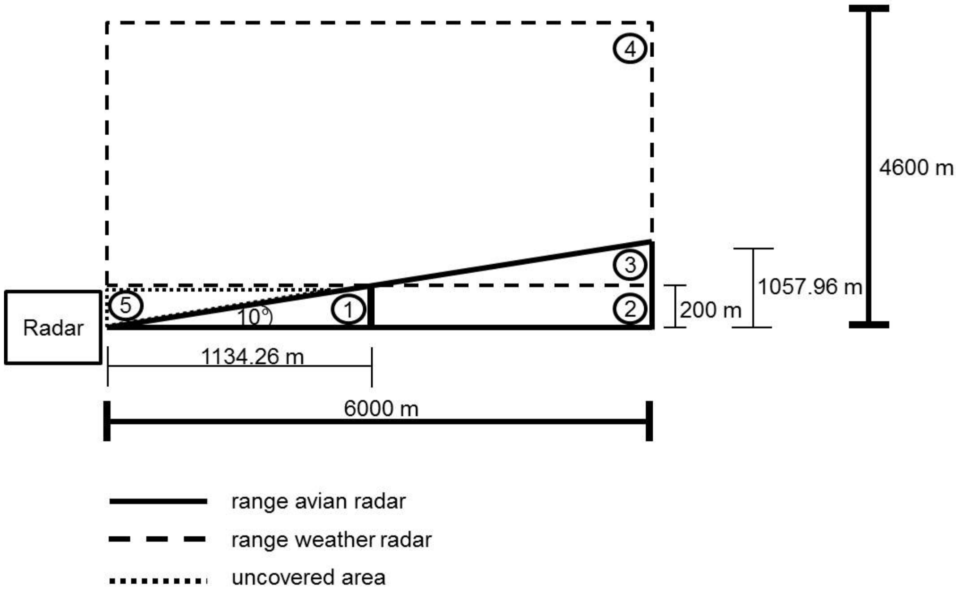


Figure 3.2: Areas covered by the avian and weather radar (not to scale). Area 1 and 2: avian radar. Area 3 and 4: weather radar. Area 5: no coverage.

Conversion from reflectivity to number of birds First, reflectivity was converted to density in $\frac{birds}{km^3}$ to obtain the number of birds present in the airspace. Therefore, the methodology described by Dokter, et al. [44] was followed. Second, the bird density was multiplied with the surface of the simulated area to determine the number of birds present.

Obtainment of bird velocity and direction The velocities and directions of birds were obtained from the Northern and Eastern speed components given in the weather radar data by applying the Pythagorean theorem. The resulting velocity obtained from weather radar is a mix of bird and wind speed. The quality of the approximation of bird speed increases with rising bird density. Over all, bird speed is negatively biased by 3.44 $\frac{m}{s}$ [166]. Consequently, the bird speed obtained from weather radar was increased by 3.44 $\frac{m}{s}$ for this study as suggested by van Gasteren, et al., 2008 [166]. To consider the standard deviations, individual birds were assigned a velocity in a range of 12 $\frac{m}{s}$ around the average velocity. The applied standard deviation for bird direction amounts to 45° [166], (Hans van Gasteren, Royal Netherlands Air Force (RNLAF), personal communication, 11 October 2016). As for the avian radar data, altitude information was assigned based on the uniform distribution within the respective altitude band.

Generation of bird tracks Based on the number of birds, their average velocity and direction, tracks were generated. For the initial set-up, it was assumed that birds covered by the weather radar fly straight through the designated area since these are mainly migrating birds. Hence, only their position, speed and heading at the designated initialization time had to be stored. Within the simulation, the effective track was generated by updating the bird's position. Furthermore, the time, when the bird left the area was stored. Birds were deleted within the simulation as soon as their time of leaving was reached. To obtain a realistic distribution of bird movements over the area considered within the simulation, the following preprocessing steps were conducted.

Definition of the local distribution of birds In the first time-step covered by the weather radar, as many birds as represented in the input data's reflectivity were created at random positions in the focused area. In every update step, bird positions were extrapolated based on speed and direction and compared to the boundaries of the area. Birds that left the area were marked to be deleted. They were replaced by new birds in order to keep the flow constant. These new birds were initialised on the boundary opposite of the one where the predecessors left to account for the straight flight path of the birds. The number of these fly-ins was corrected for potential changes in reflectivity between time steps. Furthermore, the number of birds remaining in the area was adapted to represent the current bird reflectivity. If it increased, additional birds were randomly generated over the entire area. In case of a decrease, birds were randomly deleted. Each initialization and each removal calculated in the preprocessing was stored.

Creation of Bird Movement Plans

After preprocessing the avian and weather radar data individually, the resulting tracks from both sources were merged in BMPs per day. BMPs serve as input for the actual simulation. A BMP consists of a list of bird positions as well as additional information. Every line of the list represents one position of one bird. The required information per position consists of time, bird id, latitude, longitude, altitude, weight category, flock or individual bird, number of birds, heading, speed as well as a second bird id. A difference in the two id's indicates the end of the track.

During the simulation, the bird's position was interpolated (avian radar) respectively extrapolated (weather radar) based on the data in the BMP. Every bird in the plan can represent one or multiple birds, i.e. flocks. The next section describes how flock size compositions were calculated and how they are represented within the simulation.

Composition of Flocks

Many bird species move in flocks, especially during daytime [111, 136]. Flock information is partially provided by the avian radar. Weather radar does not offer any flock information. As the size of birds and flocks is strongly relevant to determine potential damage resulting from bird strikes [49], a flock model was developed. It is based on a study on bird migration over the Netherlands between 1981 and 1983 [112]. The study is the most complete source offering information on flock compositions of birds in the Netherlands. Moreover, it considers bird movements below and above 200 m separately which makes it directly applicable to the boundaries between avian and weather radar selected here. Although the distribution between individual species might have changed, the study is still a valuable source for this research. Table 3.1 provides an overview of the species represented in the range of the avian and the weather radar.

Table 3.1: Bird species chosen for modelling flock compositions. Note that shares relate to the species chosen for the study. Source: [112].

Range avian radar (0 m–200 m)				Range weather radar (200 m–400 m)			
Species	**Share [%]** [a]	**Cumulated sum of shares [%]**	**Bird size**	**Species**	**Share [%]** [b]	**Cumulated sum of shares [%]**	**Bird size**
common chaffinch	27.85	27.85	small	*redwing*	25.40	25.40	small
common starling	12.26	40.11	small	*lapwing*	23.58	48.98	medium
redwing	9.34	49.44	small	*black-headed gull*	16.41	65.39	medium
meadow pipit	8.97	58.41	small	*rook*	12.67	78.06	medium
lapwing	5.48	63.90	medium	*eurasian skylark*	4.02	82.08	small
black-headed gull	5.39	69.29	medium	*western jack-daw*	3.31	85.39	medium
barn swallow	5.00	74.28	small	*common wood pigeon*	3.18	88.57	medium
common wood pigeon	4.52	83.72	medium	*common swift*	2.68	94.30	small
eurasian skylark	4.47	88.19	small	*fieldfare*	1.78	96.08	medium
red crossbill	2.99	91.18	medium	*european herring gull*	1.19	97.27	large
fieldfare	2.73	93.92	medium	*buzzard*	0.93	98.20	large
common linnet	2.68	96.60	small	*eurasian spar-rowhawk*	0.91	99.12	medium
common swift	1.97	98.58	small	*common house martin*	0.88	100.00	small
eurasian siskin	1.42	100.00	small				

[a] share of birds flying in flocks and below 200 m; [b] share of birds flying in flocks and above 200 m.

Table 3.2: Bird size categories, the selected weight for simulation as well as example species. Sources: [56, 74**?**]

Size category	Weight range [kg]	Weight selected for simulations [kg]	Example species
small	< 0.085	0.0425	house sparrow
medium	0.085 - 1.15	0.6175	rook
large	> 1.15 - 3.65	2.4	mallard

Avian radar To retrieve flock information for the birds flying in the range of the avian radar, the top 15 species observed to fly below 200 m were selected, representing 89 % of all birds in this category [112].

The data obtained from the avian radar distinguishes between individual birds and flocks of birds. The individual birds are categorised in *small*, *medium* and *large birds* (see section 3.2.2). The size category of birds within the flock is not resolvable. Furthermore, the number of birds per flock is unknown. By applying the steps described below, each flock was assigned to the number of birds contained as well as their size category.

Size of birds per flock The birds within flocks tracked by the avian radar were assigned to a weight category. Thereby, it was assumed that each flock consists of birds of one species. For consistency with individual birds, the categories *small*, *medium* and *large* were applied. For each species, the average weight of individual birds was obtained from Dunning [56]. The species were then grouped by applying the size classes as defined by the aviation authorities [74] and shown in Table 3.2. In contrast to other aviation authorities, the Australian Transport Safety Bureau (ATSB) includes a category *very large*, starting at 3.65 kg. Hence, this value was selected as upper limit for the category *large* as used within this thesis.

Number of birds per flock To determine the number of birds within a flock in the range of the avian radar, the species considered in [112] were sorted by average flock size and manually categorised into three groups with similar flock sizes. This ensured that the entire range of observed flock sizes was represented in the final implementation. Thereafter, the average flock size within each of these groups was calculated. Therefore, the flock size of each species within a group was weighted by the share of species within its group. Subsequently, the distribution between small, medium and large birds per flock size group was determined. For this purpose, the shares of species within each size category was summed up. The result corresponds to the share of the respective size category within the flock size group.

These described distributions for flock and bird sizes are valid for daytime. During the night, only few birds fly in flocks. Most birds travel alone or with large distances between individual birds [111, 136, 169]. The study of Lensink and Kwak [112] focuses on diurnal migration. Hence, to represent nocturnal bird distribution, information was obtained from Hüppop, et al., 2006 [97]. This paper describes a distribution between birds flying individually and in flocks during the night. Furthermore, for the birds that do fly in flocks during the night, three ranges of expected flock sizes for nocturnal migration are presented. These were used to calculate mean flock sizes (cf. Table 3.4). Bird sizes per flock type during the night were calculated based on the number of all birds considered in this study. During the generation of the bird movement information prior to the simulation, the distributions for diurnal and nocturnal flock sizes were applied depending on civil twilight [134]. Tables 3.3 and 3.4 present the flock size distributions for the avian radar. The processing steps to retrieve the size and the number of birds per flock for the avian radar can be found in Figure 3.3a.

Integration into the Bird Movement Plans Within the generation of the BMPs, the number of birds and the size category was assigned to every bird object identified as flock by the avian radar. This was performed as described based on an example for daytime distribution from Table 3.3. First, a group identifier was selected randomly, taking into account the probabilities of occurrence. For example, every flock had a 48 % probability to be assigned to group I, 25 % to be assigned to group II and 27 % to be assigned to group III. Second, the size category was applied randomly, again, by considering the respective probabilities of occurrence. For example, a group I flock had a 10 % chance of consisting of small birds and a 90 % chance of consisting of medium birds. Third, the number of individuals for that flock was determined by applying a Poisson distribution [112], using the average flock size as expected value (3.61 for a group I flock).

Weather radar The weather radar data contains information about the total number of birds present in the airspace. Neither the local distribution, the grouping of flocks nor the weight categories are resolvable. The distributions of the size and the number of birds per flock include the 14 out of 16 species observed to fly above 200 m , for which detailed information is available [112]. For these 14 species, corresponding to 97 % of all individual birds, flock size information was available.

Size of birds per flock As for the species in the range of the avian radar, the weights of individuals from each species were obtained from Dunning [56] and grouped based on the size classes presented in Table 3.2.

Number of birds per flock In contrast to the avian radar, the share between birds flying individually and in flocks is unknown. Hence, in a first step, this share was determined. To establish the relative share of individually flying birds, the percentages of birds per species which fly alone were summed up with respect to the proportion of each species in the entire population. The birds remaining were considered to fly in flocks. To obtain the number of birds per flock for day and night, the same procedure as for the avian radar was applied. Tables 3.5 and 3.6 show the resulting flock size distributions for the weather radar. Figure 3.3b illustrates the processing steps to obtain the size and the number of birds per flock for the weather radar.

3

Table 3.3: Determined flock size groups within the range of the avian radar (0–200 m) during daytime.

Group Identifier	Represented birds [%]	Average flock size [-]	Small birds [%]	Medium birds [%]	Large birds [%]
I	48	3.61	10	90	0
II	25	6.55	57	43	0
III	27	10.86	83	17	0

Table 3.4: Determined flock size groups within the range of the avian radar (0–200 m) during night time.

Group Identifier	Represented birds [a] [%]	Average flock size [-][b]	Small birds [%] [c]	Medium birds [%][c]	Large birds [%] [c]
I	51	15.00	80	20	0
II	26	7.50	80	20	0
III	23	3.50	80	20	0

[a] number of birds flying in respective groups. Source: [97]; source: [b] [97]; [c] source: [112] .

Table 3.5: Determined flock size groups within the range of the weather radar (200 m–1000 m) during daytime. Group IV represents individually flying birds.

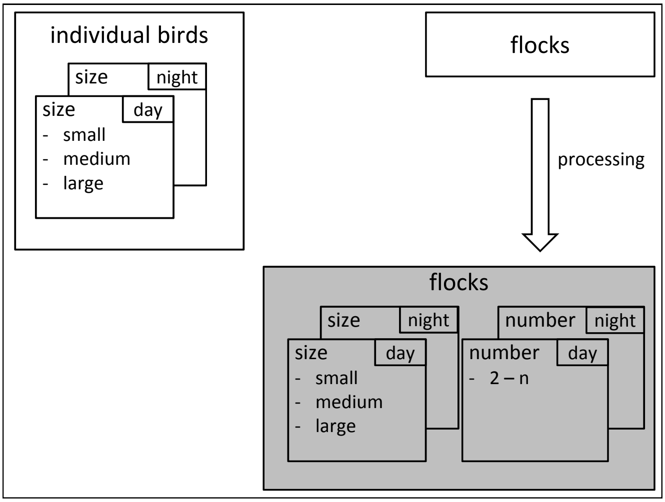
Group Identifier	Represented birds [%]	Average flock size [-]	Individual flyers [%]	Small birds [%]	Medium birds [%]	Large birds [%]
I	84	1.87	55	24	34	44
II	13	6.49	5	48	52	0
III	3	13.51	1	34	66	0
IV [a]	-	1	100	36	62	2

[a] extracted from and summarized over the three groups.

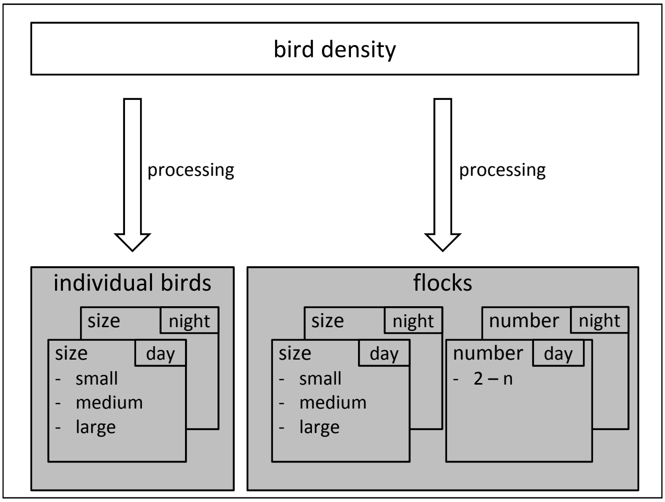
Table 3.6: Determined flock size groups within the range of the weather radar (200 m–1000 m) during night time. Group IV represents birds flying individually.

Group Identifier	Represented birds [a] (%)	Average flock size [-][b]	Small birds [%] [c]	Medium birds [%][c]	Large birds [%] [c]
I	10	3.50	27	37	36
II	5	7.50	27	37	36
III	5	15.00	27	37	36
IV	80	1.00	27	37	36

[a] number of birds flying in respective groups. Source: [97]; [b] source: [97]; [c] source: [112] .



(a) Avian radar. Input contains distribution between individual birds and flocks. For individual birds, size information for day and night is contained. Numbers of birds per flock as well as body size distribution within flocks were modelled.



(b) Weather radar. Input contains bird density. Distributions between birds flying individually and in flocks were modelled for day and night as well as represented bird sizes and number of birds within flocks.

Figure 3.3: Steps for retrieving flock size distributions (white: input information. grey: processed information).

Integration into the Bird Movement Plans To generate bird objects grouped in individuals and flocks from the calculated number of birds present, the following steps were performed. First, the total number of birds was split into birds to fly individually and birds which would be grouped into flocks. The individual birds (groups IV in Tables 3.5 and 3.6) were assigned to a randomly selected bird size, considering their probabilities. For example, a bird observed during daytime had a 36 % chance of being a small bird, a 62 % chance of being a medium bird and a 2 % chance of being a large bird. Considering flocking birds, the required number of flock objects had to be determined. Therefore, the total number of flocking birds was split into the groups I - III by taking into account the share of each of the groups. Per group, the number of flocks was calculated by dividing the number of birds by the average flock size. Then, the number of birds per flock and group was determined by applying a Poisson distribution, using the average flock size as expected value and assuming a minimum of two birds per flock. Due to rounding, the total number of birds expected to fly in flocks and the sum of birds resulting from summing up all flock members could differ. In case of deviations, flocks were added or removed until the two figures matched. Finally, the size of birds represented by each bird was assigned, considering the probability of each size per group.

3.2.3. AIRPORT ENVIRONMENT

To study the effects of bird strikes in the extended airport environment, an airport setup with one operational runway was selected. This excluded the risk of dependencies of operations between different runways. The avian radar data originates from a single-runway airport, namely Eindhoven airport in The Netherlands (cf. section 3.2.2). Therefore, this airport was chosen as a reference airport. It lies beyond the range of the weather radar in De Bilt, which serves as source for the weather radar birds. However, the broad front bird migration patterns over both locations are strongly comparable (Hans van Gasteren, personal communication, 4 December 2016). Hence, the bird densities recorded by the weather radar were projected to the area of Eindhoven airport. Figure 3.4 shows the aeronautical chart of this airport.

In all simulations, the runway was operated in the Northern direction of 30 degrees, which corresponds to the runway label 03. The simulated area which is marked by the rectangle in Figure 3.4 includes the approach corridors of runway 03, beginning at the Initial Approach Fixes (IAF). For departing aircraft, the Standard Instrument Departure (SID) routes are included. Approaching air traffic is simulated from their Initial Approach Fix (IAF) until landing. Departing traffic is simulated from take-off until reaching an altitude of 1,000 m height. Birds from the weather radar are initialised and simulated over the entire area and removed as soon as they reach one of the area's boundaries. The initialization and simulation of avian radar birds is determined by the input data. Collisions and near misses which take place within the area are counted for the evaluation.

3.2.4. AIR TRAFFIC

To get realistic flight plans for air traffic, scenarios based on real traffic were generated. The availability of bird movement information set the simulation area to Eindhoven airport in the Netherlands. This airport has a very low traffic volume. Between 2015 and 2016 when the bird data was collected, between 80 and 120 civil and military movements

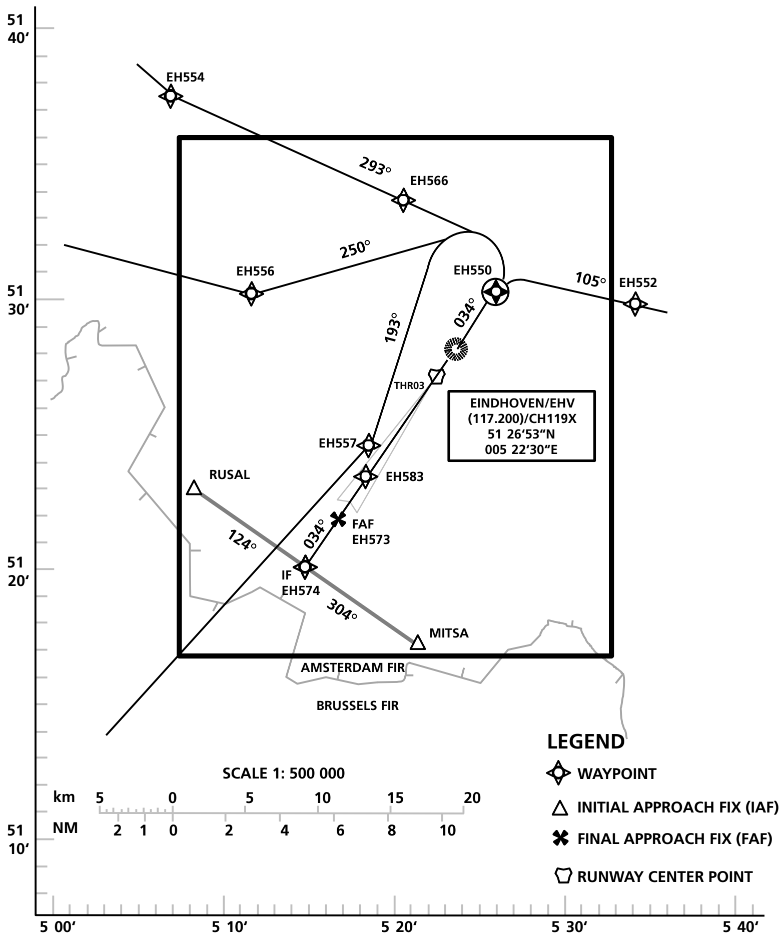


Figure 3.4: Aeronautical chart of Eindhoven airport including arrival and departure routes for runway 03. The airspace within the rectangle is considered for this study (own figure, adapted from [2]).

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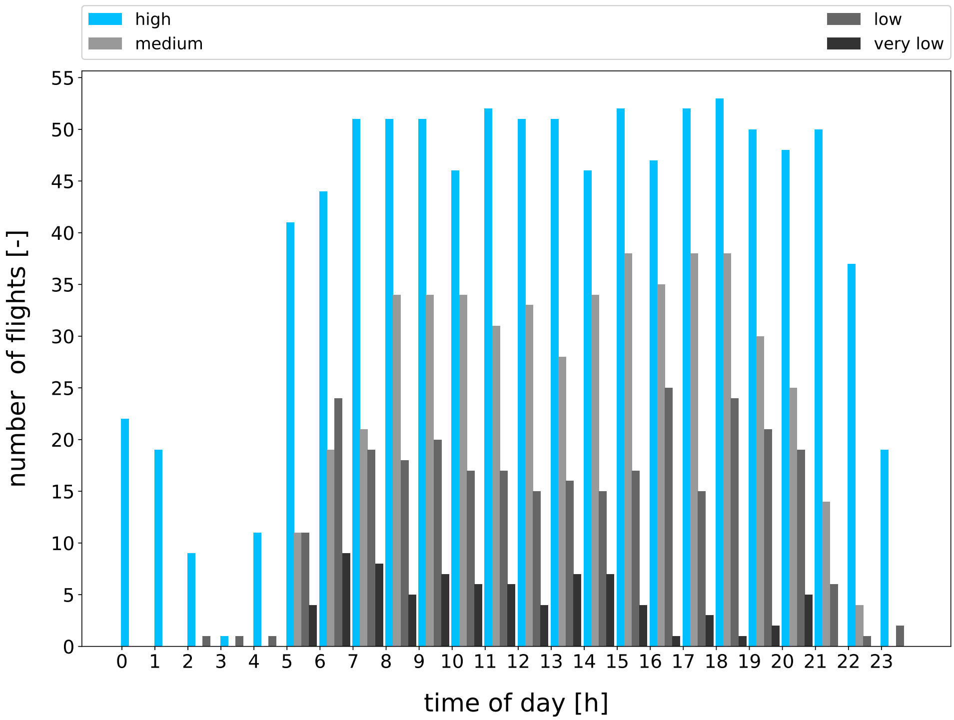

Figure 3.5: Flights per hour for the selected air traffic volumes.

took place per day (RNLAF Bird Strike Database. Hans van Gasteren, RNLAF, personal communication, 20 October 2020). To evaluate the impact of various traffic intensities on the risk of bird strikes, flight plans from additional airports were generated and transferred to the airport of Eindhoven to cover high, medium and low traffic volumes as well. For comparability and to facilitate the integration into the simulated airport area – Eindhoven has one runway – traffic from airports with one operational runway was selected. With regard to their ranking considering the number of flights in the 2015 Airports Council International (ACI) traffic report [5], London Gatwick (UK) for high, Geneva (CH) for medium and Birmingham (UK) for low intensity were chosen. In addition, a scenario covering Eindhoven traffic was created. The flight plans were generated based on data from one representative day per airport in 2016 (source: European Organization for the Safety of Air Navigation (EUROCONTROL) database, accessed via Bruno Nicolas, Statistics Specialist, EUROCONTROL, personal communication, 5 April 2017 & 4 August 2017). Figure 3.5 displays the selected traffic volumes.

Within the initial simulations, the individual airport opening hours were considered. As this reduced the comparability of effects, especially during dawn and dusk, identical opening hours - the ones from the airport with the shortest opening hours - from 0500 to 2200 hrs Coordinated Universal Time (UTC) were applied within the Monte Carlo simulations. The resulting traffic volumes can be found in Table 3.7.

Table 3.7: Traffic volumes for the individual and the Monte Carlo simulations.

Traffic intensity	Individual simulations			Monte Carlo simulations		
	Number of opening hours	Number of flights	Av. flights per hour	Number of opening hours	Number of flights	Av. flights per hour
high	24	954	39.8	17	873	51.4
medium	17.8	501	28.2	17	501	29.5
low	20.6	305	14.8	17	300	17.6
very low	15.7	79	5.0	17	79	4.6

The dataset obtained from EUROCONTROL contains trajectories per aircraft. Each trajectory consists of time-stamped three-dimensional positions which allows an aircraft's flight path to be reproduced. For landing aircraft, the time stamp of their last recorded position within the trajectory was used as initialization time in the flight plan. Departing traffic was initialised at the time of their first recorded position. Due to variances in the input-data, air traffic generated based on these time stamps could overlap and thus collide in the simulation. To exclude the risk of aircraft collisions, a minimum separation at the runway was applied. To keep the scenarios simple, the minimum was consistent between all aircraft. The chosen minimum separation of 66 seconds enables 55 movements per hour and runway, as achieved at Europe's most frequented airport with single runway operations of London Gatwick [10]. Depending on the traffic sequence within the simulation, aircraft could still lose their separation in the simulation. However, the main goal to avoid collisions while changing the input data as little as possible was fulfilled with this measure.

3.2.5. COLLISION AND NEAR MISS DETECTION

To detect collisions between birds and aircraft, protected volumes around each aircraft and each bird are defined. Whenever an aircraft and a bird penetrate each other's protected volume, a bird strike is recorded and the respective bird removed from the simulation, as it is assumed that the collision is lethal for the bird. Within the Monte Carlo simulations, so called near misses are counted. A near miss, as defined by the RNLAF and used within this study, occurs when the separation between an aircraft and a bird gets smaller than 50 m. Near misses happen more often than collisions. Hence, a larger data set is available for the analysis. However, due to the absence of reports about near misses, no comparison between simulated and real data could be performed. The definition of the protected volumes of birds and aircraft is described below.

PROTECTED VOLUMES OF BIRDS

The protected volume of birds depends on the bird's size and the number of birds represented by one bird object. The protected volume around individual and flocks of birds was modelled as a disc to minimise the impairment of the collision detection algorithm on the simulation's runtime performance. The shape of flocks, which varies amongst different species [91], was thus simplified. Due to the small height of birds, especially in

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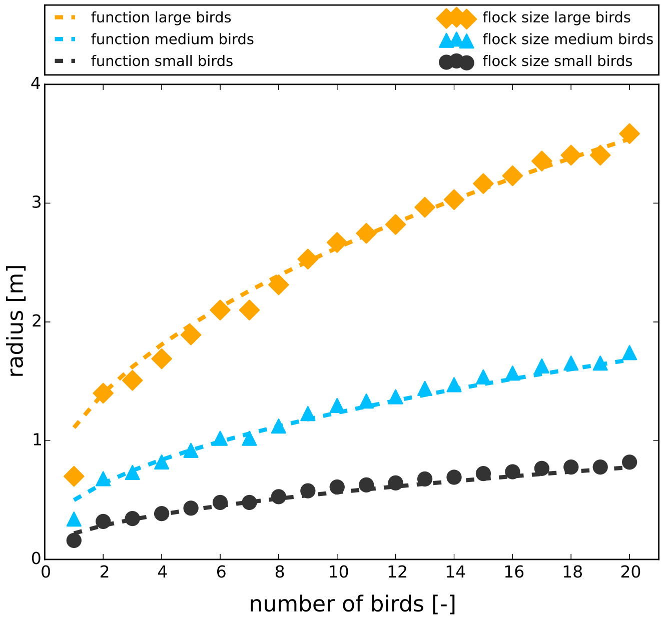

Figure 3.6: Increase in flock size radius with rising number of flock members.

Figure 3.7: Top view of protected volumes of individual birds as well as a flock with three members.

Table 3.8: Radii for different flock sizes.

Bird Category	Wingspan [m]	Flock radius [m]	Standard deviation from flock size [m] in [86]
small	0.32	$\sqrt{n_{birds}} \cdot \frac{0.32}{2} + 0.06$	0.03
medium	0.68	$\sqrt{n_{birds}} \cdot \frac{0.68}{2} + 0.16$	0.04
large	1.40	$\sqrt{n_{birds}} \cdot \frac{1.40}{2} + 0.41$	0.05

comparison to the height of aircraft, the resulting protected volume is flat, i.e. without height and therefore, strictly speaking, a plane. However, for consistency in naming, it is further referred to as protected volume. The diameter of the protected volume of individual birds directly refers to the wingspan of the category it belongs to. For each of the bird categories *small*, *medium* and *large*, a weighted average for the wing span was calculated based on the species considered from [112] and their distribution.

To model the protected volume for flocks, the theory of dense packings of congruent circles in a circle [86] was used as a base. This theory describes how the radius of a circle increases with rising number of circles within that circle. The comprising circles correspond to the protected planes of flocks. They contain up to 20 circles, representing individual birds within the flock. For each bird category, functions for the radii of the resulting protected planes were developed. The neighbouring distance between the individual birds was not considered, because they have only been analysed for few species so far (e.g. [169]). Moreover, for migrating birds, which are mostly relevant in the context of this study, it is most efficient to fly adjacent or even with slightly overlapping wing tips [115]. Hence, the neighbouring distance was set to zero. Table 3.8 summarises the developed functions while Figure 3.6 illustrates them. In Figure 3.7, the protected volumes of an individual bird and, exemplary, of a flock including three birds, are illustrated.

PROTECTED VOLUMES OF AIRCRAFT

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

The diameter of a protected volume corresponds to the aircraft's wing span. Because of their small front surface, an aircraft's rudder and elevator experience almost no bird strikes [15], [54]. Thus, the tail section is cut from the protected area. Its arc length depends on the wing's sweep.

An aircraft's height strongly varies along its wingspan. Hence, if setting the height of a protected volume to the aircraft's largest vertical expanse, the bird strike number would be strongly overestimated. Therefore, an average height was determined from the heights of the aircraft's front surfaces prone to bird strikes: the wings, the engines and

Table 3.9: Parameters defining an aircraft's protected volume.

Aircraft category	Reference aircraft type	Radius [m]	Height [m]	Sweep [°]	Sources
widebody	Airbus A380-800	39.88	1.99	33.50	[3, 96]
narrowbody	Boeing 757-200	19.94	1.01	25.00	[29, 96]
regional	Bombardier Dash 8-400	14.2	1.35	0.00	[30, 96]

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the fuselage [57]. This average height represents the height required to be multiplied with the aircraft's wingspan to obtain a rectangle corresponding to the aircraft's relevant front surface. It is calculated by adding the front surfaces of the aircraft's components as provided in Equation 3.1.

$$S_{front} = \underbrace{(b - 2 \cdot r_{fuselage}) * h_{wing}}_{\text{front surface wings}} + \underbrace{n_{engines} \cdot r_{engine}^2 \cdot \pi}_{\text{front surface engines}} + \underbrace{r_{fuselage}^2 \cdot \pi}_{\text{front surface fuselage}} \tag{3.1}$$

where b represents the wingspan, r the radius of the respective components and h the height, all in metres. $n_{engines}$ is the number of engines.

Exemplarily, the resulting protected volume is presented for an Airbus A380-800 in Figure 3.8. The key parameters to determine the dimensions of the protected volume per aircraft category are given in Table 3.9.

3.2.6. SIMULATION SET-UP

This section presents the resulting simulation set-up. In a first step, simulations to verify the simulation environments - *verification simulations* - were performed. To confirm that the results can be reproduced, *Monte Carlo simulations* were run thereafter.

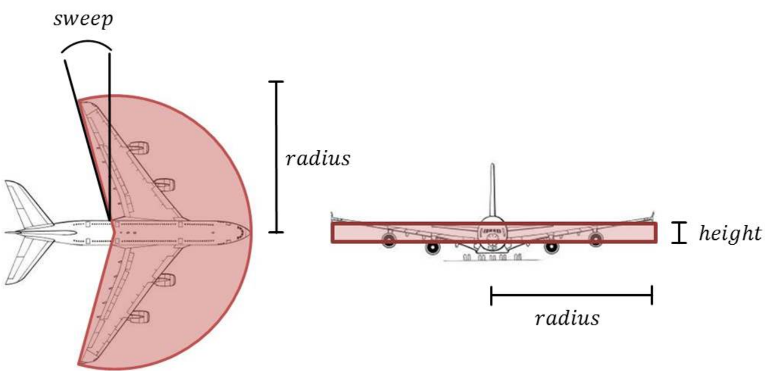


Figure 3.8: Top and front view of an aircraft's protected volume (Airbus A380-800). The resulting front surface corresponds to the aircraft's surface of wings, engines and fuselage.

The number of bird strikes occurring at an airport strongly depends on the season: During migration as well as in summer, when many young and inexperienced birds fly, more strikes take place than in winter [117, 121]. To include seasonal effects within this study, BMP were created for an entire year.

VERIFICATION SIMULATIONS

Regarding the verification simulations, one week per month within the period from October 2015 to September 2016, where radar data was available, was simulated. This kept the simulation effort at a reasonable level while all seasons were covered and the number of days (n = 84 per airport) was representative. The weeks were chosen based on radar availability. The radars ability to detect birds during precipitation is limited [21]. By choosing weeks with little precipitation, a high detection rate and as such representative bird movement information was taken care of.

Each BMP was combined with the flight plans representing high, medium, low and very low traffic volumes to study the effect of different traffic intensities on the bird strike risk. Depending on the airport, the traffic volume varies throughout the year [5]. This variation is implicitly considered by providing flight plans for different traffic intensities. The combination of bird data from 84 days and flight plans covering the four traffic intensities led to a total of 336 simulated traffic days.

By simulating the described scenarios, two goals were pursued. First, a verification, if the developed simulation environment appropriately reflects the risk of bird strikes at an airport, took place. Here, it was expected that more bird strikes would be counted in the simulations than in reality. The main reason is, that the simulated birds are not modelled to show reactions to aircraft whereas in reality, birds often manage to perform last-minute escapes when an aircraft approaches. In addition, the airport of Eindhoven operates at very low traffic intensities. Hence, more birds are expected to be present on and close to the runway than at airports with more aircraft movements, since birds are less disturbed by traffic [4, 85]. Furthermore, not all bird strikes are recognised or reported, especially the ones with very small birds or strikes that did not damage the aircraft involved. Even with the slight reduction of simulated bird strikes due to the filtering of the avian radar data as described in section 3.2.2, the number of bird strikes within the simulation should be higher than in reality. The second goal of the simulation campaign was to acquire data for a baseline scenario for further research involving new ATM procedures to avoid bird strikes.

MONTE CARLO SIMULATIONS

To confirm that the results from the verification simulations are reproducible, additional Monte Carlo Simulations were performed. For this purpose, one BMP per month was selected as a baseline. Thereby, the day with the average number of birds in the respective month was chosen. The BMPs were then randomised 100 times each, resulting in 1,200 BMPs. To maximise the randomness, all parameters which were not fixed by the input data, were randomised for the replications. Considering the birds from the avian radar, where a two-dimensional track is given, the initialisation height was randomised. Regarding the birds from the weather radar, where only the number of birds is contained in the input data, the simulation's initial parameters for height, latitude, longitude, heading and speed were randomised. All randomizations were performed by applying uniform

Table 3.10: Ranges for the randomizations of bird movement parameters within the Monte Carlo simulations. AR: avian radar; WR: weather radar.

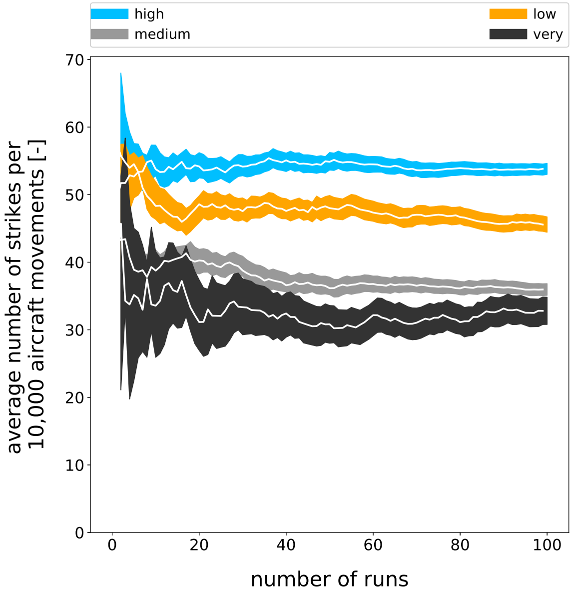
Parameter	Radar source	Range
altitude	AR, WR	within respective altitude band
latitude	WR	within extended airport area
longitude	WR	within extended airport area
speed	WR	$\pm 6\,\frac{m}{s}$
heading	WR	±45°

distributions within the ranges shown in Table 3.10. The uniform distribution was chosen to ensure an even distribution of the bird positions in all degrees of freedom.

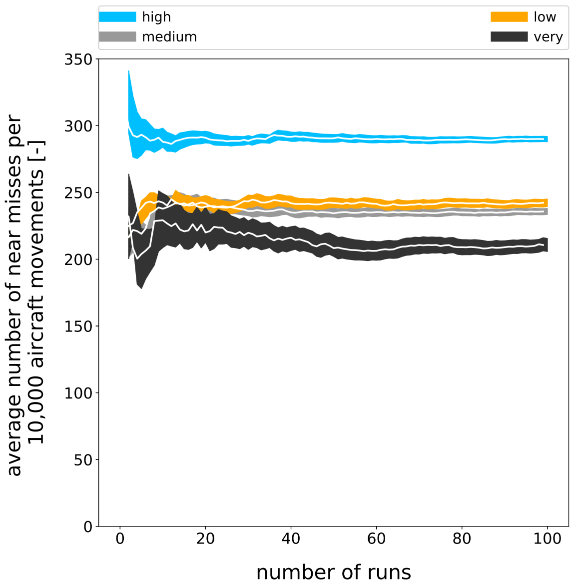
By combining the 1,200 BMPs with the flight plans of the four traffic intensities, 4,800 scenarios resulted. In contrast to the verification simulations, the opening hours were standardised. For this purpose, the shortest opening hours of the four traffic intensities were applied for all scenarios, as described in section 3.2.4.

For consistency and reproducibility, the randomizations per traffic intensity took place with identical randomization seeds. To determine whether this number of replications was sufficient, the convergence of average bird strike and near miss numbers was assessed. Furthermore, the corresponding standard errors were evaluated. A standard error below 5 % over all scenarios was defined as acceptance criterion. It was determined that the number of replications was sufficient, if a standard error below 5 % would be reached. Figure 3.9 illustrates the results. Except for the *very low* scenario considering collisions, all scenarios reached the criterion of a standard error below 5 % within the 100 replications. The *very low* scenario reached a standard error of 6 % from 90 replications in relation to collisions. As this scenario is limited by a small sample size due to the small number of aircraft, the reduction in standard error for this scenario was defined as acceptable as well.

In Figures 3.10 and 3.11, the resulting set-ups of the verification and Monte Carlo simulations are depicted. Adjustments implemented for the Monte Carlo simulations are marked in cyan in Figure 3.11.



(a) Bird strikes



(b) Near misses

Figure 3.9: Convergences of average bird strike and near miss numbers for the Monte Carlo simulations.

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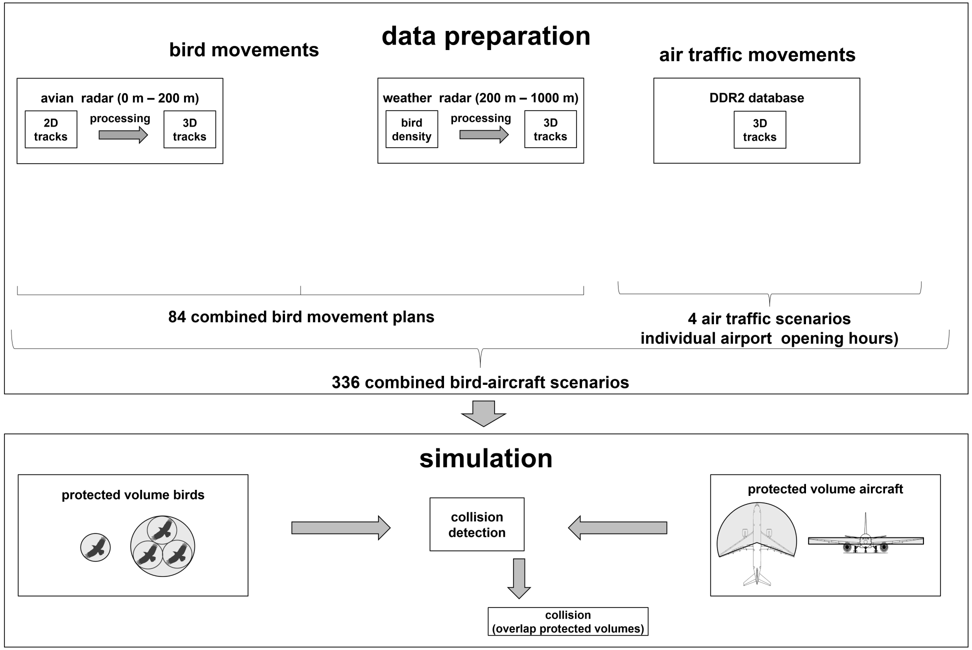

Figure 3.10: Method overview for the verification set-up. Within the data preparation of bird movements, 84 scenarios of bird tracks - 7 per month within a year - are generated from weather and avian radar. Air traffic trajectories from four single-runway airports are retrieved from the DDR2 database of EUROCONTROL and processed to air traffic scenarios. By combining the BMPs with the air traffic scenarios, 336 bird-aircraft scenarios result. These serve as input for the fast-time simulation. Based on the definition of protected volumes, bird strikes are counted and recorded.

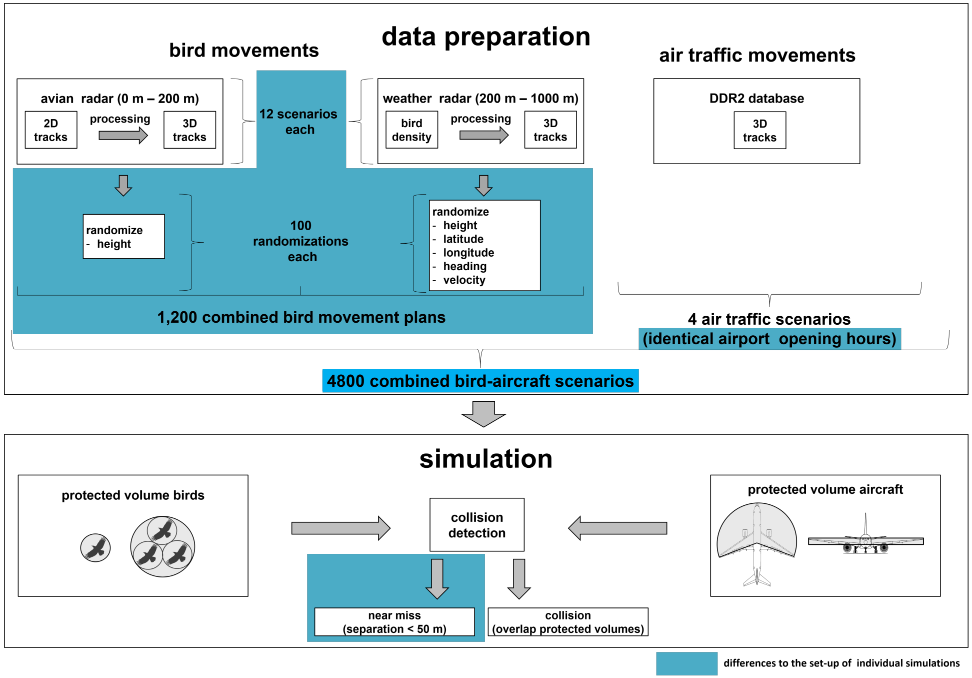

Figure 3.11: Method overview for the Monte Carlo simulation set-up. Within the data preparation of bird movements, 12 scenarios of bird tracks - one per month within a year - are generated from weather and avian radar. By randomizing the input parameters 100 times, 1,200 BMPs result. Air traffic trajectories from four single-runway airports are retrieved from the DDR2 database of EUROCONTROL and processed to air traffic scenarios. By combining the BMPs with the air traffic scenarios, 4,800 bird-aircraft scenarios result. These serve as input for the fast-time simulation. Based on the definition of protected volumes, bird strikes and, additionally, near misses are counted and recorded.

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3.3. RESULTS

Within this chapter, a simulation environment to model and analyse the risk of bird strikes was developed. The resulting set-up enables fast-time simulations of bird and air traffic movements. Collisions between birds and aircraft are registered and counted as bird strike occurrences. The simulation environment's set-up was verified with an initial dataset including bird movement from all seasons and four air traffic intensities. This was followed by Monte Carlo simulations covering 4,800 simulation days to ensure reproducibility of results and to test the robustness of the set-up. The results of the verification and the Monte Carlo simulations are described below.

3.3.1. VERIFICATION SIMULATIONS

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

The results presented in this section deviate from the ones published in [123]. The difference results from an adaptation of the bird model being performed within the Monte Carlo simulations to achieve a more realistic bird representation.

Bird strike rates The bird strike rate of an airport is generally given in number of bird strikes per 10,000 flights [105]. The average ratio of all bird strikes at Eindhoven airport amounted to 12.33 between 2007 and 2016 (RNLAF Bird Strike Database. Hans van Gasteren, personal communication, 3 August 2017). The simulated bird strike rates are higher. They amount to 39.06 for the high, 36.83 for the medium, 41.96 for the low and 43.7 for the very low air traffic intensity. Due to last-minute escapes in reality, which are not modelled in the simulation, as well as unreported strikes, a larger offset would be expected. However, birds were filtered for duration of stay in the altitude band covered by the avian radar as described in section 3.2.2. For this reason, the risk of bird strikes is reduced in this altitude band. This is reflected in the altitude distribution of strikes in the simulation as presented by Figure 3.12. As statistics from across the world consistently suggest, the number of bird strikes decreases exponentially with increasing altitude [54, 57, 90]. With regard to the simulation results displayed in Figure 3.12, a significant decrease can only be found from 201 m upwards – the altitude from which the weather radar data serves as source for bird movements. Between zero and 200 m, where the data from the avian radar was used, the number of bird strikes is only slightly higher than in the altitude band above. By comparing the number of all birds including the ones filtered out to the number of birds considered within the simulation, the theoretical sum of bird strike occurrences was calculated. To ensure the accuracy of scales, the number of birds was weighted with their average duration of stay in the considered area. This calibration (top bars in Figure 3.12) increased the bird strike rate to a reasonable level in comparison to the other altitude bands. Table 3.11 presents the comparison between the simulated and theoretical bird strike rates. The effective bird strike rate in Eindhoven is overestimated by a factor between 3.0 and 3.5 within the simulation results and between 4.4 and 4.8 when considering the theoretical number of strikes. In com-

Table 3.11: Simulated and theoretical bird strike rates (number of strikes per 10,000 flights) resulting from the verification simulations.

Airport	Simulated bird strike rate	Theoretical bird strike rate
high	39.06	58.90
medium	36.83	59.64
low	41.96	58.16
very low	43.70	54.24
Eindhoven (reference)	12.33	

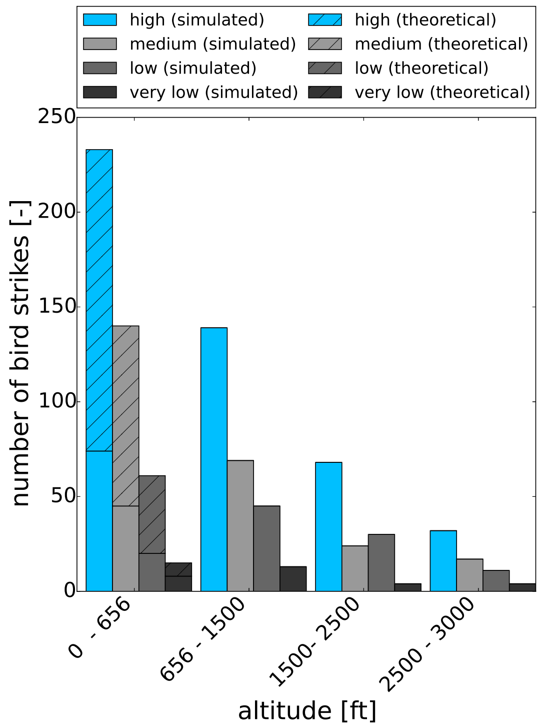
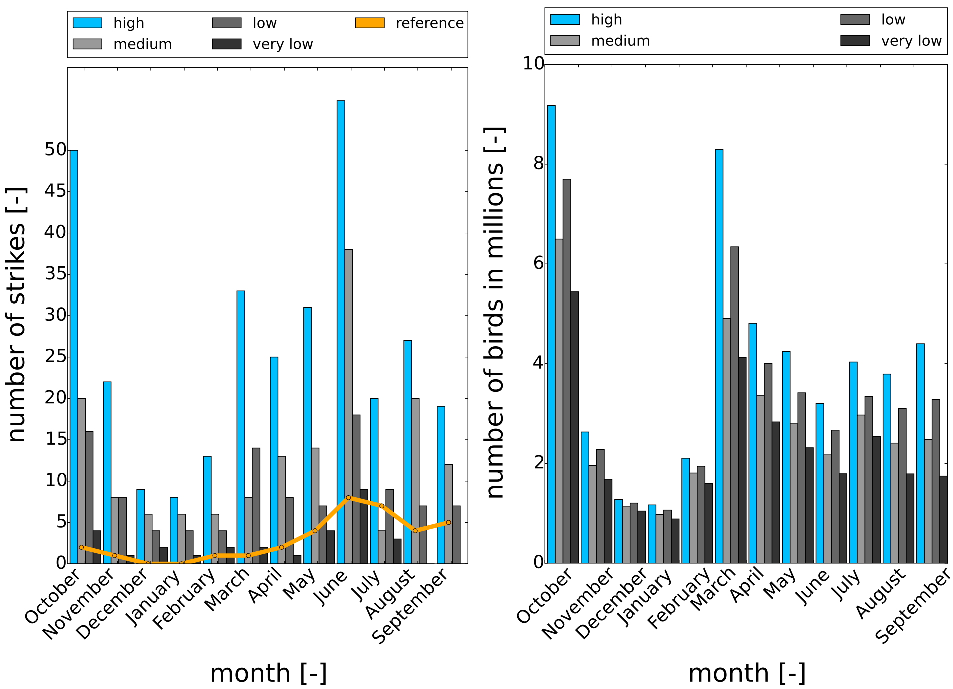


Figure 3.12: Simulated and theoretical bird strike altitude distribution (0-200 m: avian radar, 200 - 1,000 m: weather radar) for the chosen traffic volumes of the verification simulations.

parison to the other scenarios, the rise of the bird strike rate when considering all birds present is relatively small in the very low scenario.



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

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

Figure 3.13: Number of strikes and number of birds per month resulting from the verification simulations.

Seasonal distribution of bird strikes Figure 3.13a shows the distribution of bird strikes per month in the simulation. These differ between the scenarios and mostly correlate with the air traffic volume. However, in five months, at least the same number of strikes occurred in the low as in the medium air traffic intensity scenarios. In Figure 3.13b, the number of birds is given per month and air traffic intensity. In October and March, a high number of birds was present. This corresponds to a relatively high number of bird strikes. In contrast, there are many bird strikes in June, where less birds are present.

In addition to the simulation results, the average number of strikes per month for the period 2007 - 2016 is given for the reference airport in Eindhoven in Figure 3.13a. It has to be noted that the data from Eindhoven reflects all strikes that happened within one month. In contrast, the simulation results cover the number of strikes for one week per month. Comparing the simulation output with the real data, two main differences become apparent. First, the number of strikes at Eindhoven are relatively high in comparison to the simulation results during the summer months. The second deviation can be found in the month of March, where the simulation results increase remarkably, while the number of bird strikes remains at a relatively low level at Eindhoven airport. When comparing the bird strike occurrences in the simulated scenarios with the number of birds as shown in Figure 3.13b, the peak in March is reflected in both statistics. Overall, when comparing the seasonal trends between the simulation and reality, a high similarity can be found: In autumn, the number of bird strikes is relatively high. During the winter months, fewer bird strikes occur. In spring, the number increases again and has a maximum in June. With the named exception of March, the seasonal trends seem to be well reflected within the simulation. This is supported by the number of birds present in the simulation as shown in Figure 3.13b. Most birds fly during migration in autumn and spring. In winter, there is very small bird activity while more birds fly in summer. The only offset between the number of birds and the number of strikes can be found in June: With regards to the number of birds flying, a large number of bird strikes occurred. Therefore, the correlation between the number of strikes and the number of birds in the simulation was calculated for all months and for all months excluding June.

Correlation between the number of birds and the number of strikes The Spearman correlation was applied for this purpose as not all of the considered values are normally distributed. Table 3.12 presents the results. It becomes clear that the exclusion of the values for June, where the high number of bird strikes is not related to a rise in the number of birds, notably increases the correlations. Regarding these values, the high-scenario shows a strong significant correlation ($r(10)$=0.89, $p < .001$) the low scenario a moderate significant correlation ($r(10) = .71, p < .01$). The medium and very low air traffic intensity scenarios do not correlate significantly (medium: $r(10) = .44, p = .088$; very low: $r(10) = .26, p = .281$). The sample size for all airports was twelve weeks, which is relatively small for statistical evaluation. To gain more robust correlation results, Monte Carlo simulations were performed. The corresponding results are presented below.

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Table 3.12: Spearman correlation between number of birds and bird srike occurrences of the verification simulations ($n = 12$ months).

Airport	**r_s all months**	**p – value (one-tailed) all months**	**r_s w/o June**	**p – value (one-tailed) w/o June**
high	0.66	0.001	0.83	< 0.001
medium	0.37	0.118	0.48	0.068
low	0.67	0.009	0.86	< 0.001
very low	0.40	0.097	0.40	0.114

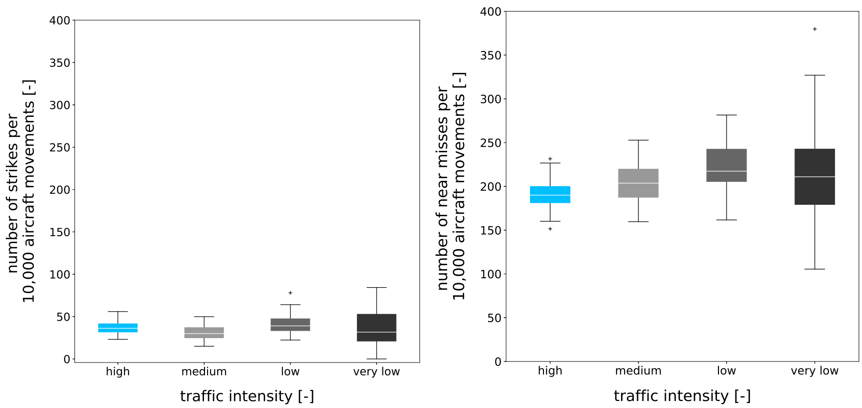
3.3.2. MONTE CARLO SIMULATIONS

Bird strike and near miss rates Within the Monte Carlo simulations, the average bird strike rate lies between 30 and 40 strikes per 10,000 flights for the different traffic intensities. The average near miss rate lies between 190 and 220 near misses per 10,000 flights. Figure 3.14 presents these results. Regarding both, strikes and near misses, simulations including larger air traffic volumes have smaller spreads. The ranges for the near misses are higher than the ones regarding bird strikes.

The comparison of the simulation results to real data from Eindhoven airport reveals an overestimate of bird strike occurrences within the simulation. Between 2007 and 2016, the average bird strike rate amounted to 12.33 for Eindhoven. The simulation results of 30 to 40 strikes per 10.000 flights correspond to an overestimate by factor 2.5 to 3.3.

Seasonal distribution of bird strikes and near misses Figure 3.15 provides an overview of the monthly strike and near miss rates per air traffic intensity. Seasonal variance is more visible for scenarios including larger air traffic volumes. Peaks for bird strikes occur in the migratory months March, April and October. The highest average number of occurrences as well as the largest range occurs in June. As for the annual overview depicted by Figure 3.14, the ranges of the number of occurrences decrease with rising air traffic volumes.

Correlation between the number of birds and the number of strikes / near misses To determine the dependency between the number of birds and the number of collisions / near misses, the respective Spearman correlations were calculated. There is an obvious deviation between the number of birds and the number of events in June. Therefore, the correlations were calculated once for the entire year and once after excluding the June data. In Figure 3.16, the results are presented. Table 3.13 summarises the correlations and their levels of significance for the boxplot values. There are higher correlations for higher air traffic volumes. In addition, the results are more significant for higher air traffic volumes. When comparing the results between collisions and near misses, the number of occurrences is higher for near misses.



(a) Collisions (b) Near misses

Figure 3.14: Collision and near miss rates of the Monte Carlo simulations

Within the *very low* scenarios, no bird strike event took place in seven iterations considering the entire year and in 13 iterations when excluding June. To obtain a valid correlation value, these iterations were therefore removed for the calculations of the correlations between bird strikes and the number of birds.

3.4. DISCUSSION

The simulations presented in this chapter pursued two goals. With the verification simulations, the enhanced fast-time simulation environment was verified. The Monte Carlo simulations aimed at demonstrating the reproducibility of the respective results and at evaluating the robustness of the simulation environment. This section discusses the achieved results of the two simulation campaigns.

3.4.1. VERIFICATION SIMULATIONS

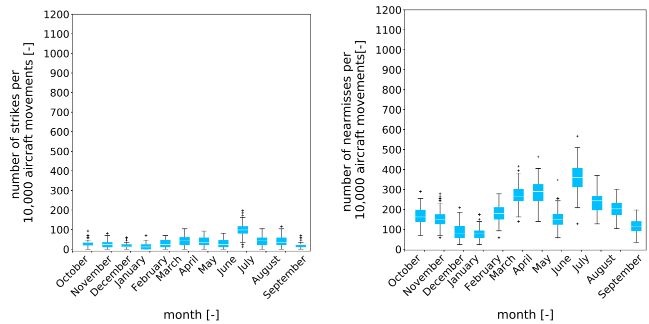
The simulation results of the verification simulations were analysed with regard to bird strike rates as well as distribution by altitude segments and season. Moreover, the correlations between the number of birds present in the airspace and the corresponding risk of bird strikes was analysed.

Bird strike rates The simulated bird strike rates are higher than the ones actually observed at the reference airport of Eindhoven. This is true for both the pure simulation results as well as when including the theoretical number of strikes in the lowest altitude band. Due to a missing model of bird behaviour in the simulation and limited reliability of bird strike reports in reality, this conforms to the expectations.

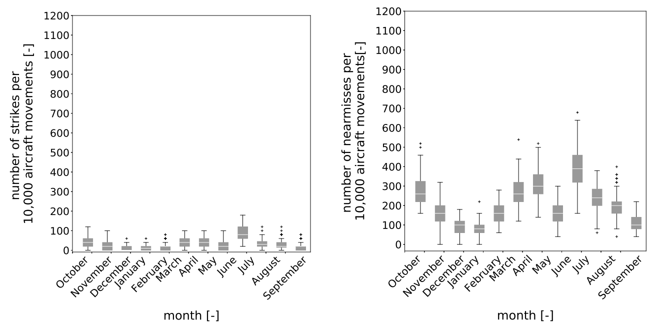
The comparison between simulated and theoretical bird strike rates among airports reveals that the rise for the very low scenario is relatively low. This is mainly caused by the offset between the number of all birds present within the opening hours and the number of birds selected for the simulation, which is much smaller than in the other scenarios.

Table 3.13: Boxplot values regarding the correlations between the number of birds and the number of collisions / near misses for the different traffic volumes of the Monte Carlo simulations.

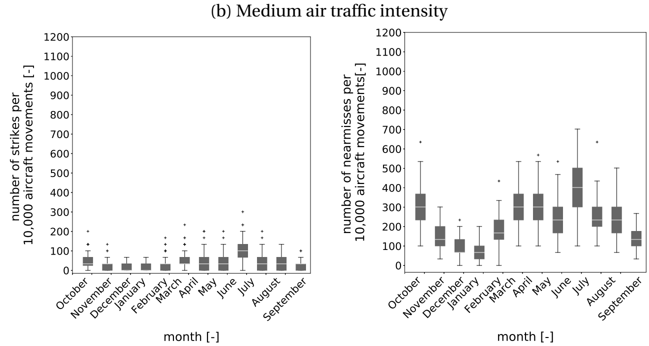
	Q_1		Q_2		Q_3		
	r_s	p	r_s	p	r_2	p	n
collisions, entire year							
high	0.06	0.226	0.28	0.002	0.42	< 0.001	100
medium	0.23	0.011	0.36	< 0.001	0.51	< 0.001	100
low	0.07	0.251	0.21	0.017	0.38	< 0.001	100
very low	-0.14	0.091	0.13	0.108	0.31	0.001	93
collisions, w/o June							
high	0.23	0.01	0.43	< 0.001	0.59	< 0.001	100
medium	0.23	0.010	0.39	< 0.001	0.51	< 0.001	100
low	0.12	0.127	0.31	0.001	0.48	< 0.001	100
very low	0.00	0.5	0.19	0.036	0.40	< 0.001	87
near misses, entire year							
high	0.43	< 0.001	0.52	< 0.001	0.58	< 0.001	100
medium	0.63	< 0.001	0.70	< 0.001	0.77	< 0.001	100
low	0.48	< 0.001	0.53	< 0.001	0.61	< 0.001	100
very low	0.16	0.055	0.30	0.001	0.49	< 0.001	100
near misses, w/o June							
high	0.61	< 0.001	0.72	< 0.001	0.81	< 0.001	100
medium	0.71	< 0.001	0.78	< 0.001	0.85	< 0.001	100
low	0.59	< 0.001	0.66	< 0.001	0.75	< 0.001	100
very low	0.25	0.006	0.42	< 0.001	0.61	< 0.001	100



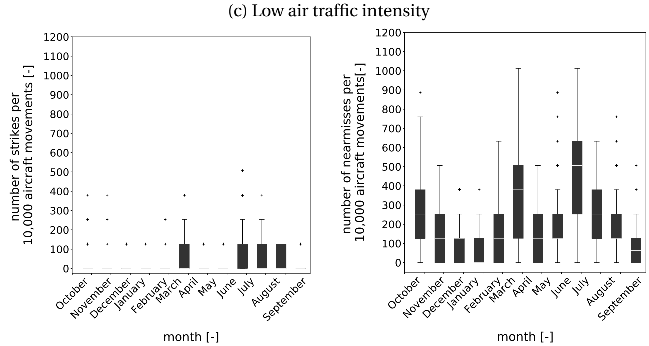
(a) High air traffic intensity



(b) Medium air traffic intensity



(c) Low air traffic intensity



(d) Very low air traffic intensity

Figure 3.15: Monthly collision and near miss rates for the different traffic scenarios of the Monte Carlo simulations

3

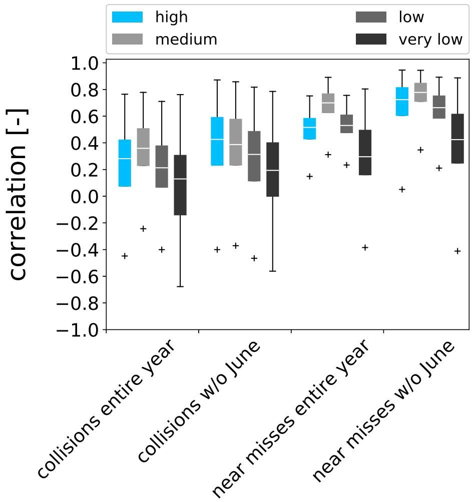


Figure 3.16: Spearman correlations between the number of occurrences and birds of the Monte Carlo simulations

The medium air traffic intensity scenarios have a relatively low number of bird strikes (see Figure 3.14a), especially in contrast to the low air traffic intensities. A possible explanation is the temporal distribution of flights: Between 6 and 7 a.m., where internationally most bird strikes are recorded [15, 90], more flights depart in the low air traffic intensity scenario. In this period, 24 % of all strikes happen in that scenario with 8 % of the daily air traffic movements. In the medium air traffic intensity scenario, only 2 % of all strikes occur with 4 % of the daily traffic in this period.

Seasonal distribution of bird strikes The seasonal comparison between the simulation results and the number of strikes reported at Eindhoven airport revealed some differences. The relatively high number of real strikes in summer is related to increased air traffic in Eindhoven, which takes place in these months. In contrast, average traffic volumes are simulated for the entire year. The second offset is in spring, where the peak in simulated bird strikes takes place in March while the risk is more evenly distributed in reality. Possibly, the majority of spring migration took place in March in the year considered for the simulations. In contrast, the reports from Eindhoven are averaged over ten years. In this period, the exact timing of spring migration could have shifted between the years, leading to a wider distribution of bird movements and thus bird strikes.

The risk distribution of bird strikes is not solely related to the number of birds present in the airspace, as the comparison between the number of strikes and birds present reveals. Especially in June, the correspondence is low - a high number of strikes is caused by a relatively low number of birds. This could be attributed to very high activity of juvenile birds during this month. Due to a lack of experience, they cause significantly more strikes than adult birds. [164]. The peak in real bird strike occurrences at Eindhoven airport in this month supports this assumption.

Correlation between the number of birds and the number of strikes While the high and low scenarios showed significant correlations between the number of birds and the number of bird strike events, the correlations were insignificant for the medium and very low air traffic intensity scenarios. This is most likely connected to the opening hours of the airports where the scenarios originate from: Scenarios with longer opening hours have higher correlations between the number of birds and the bird strike occurrences. Moreover, scenarios with longer opening times have a higher simulated bird strike rate as shown in Table 3.11 . The different opening hours also cause the higher number of birds in the low compared to the medium air traffic intensity as Figure 3.13b illustrates. To increase the comparability among scenarios, the opening hours of all airports were adjusted to represent identical opening hours within the Monte Carlo simulations.

3.4.2. MONTE CARLO SIMULATIONS

The evaluated simulation environment representing bird movement and air traffic is a powerful tool to analyse future concepts for the risk reduction of bird strikes. The results of the initial simulations provide a first approximation on the validity of the simulation environment. However, for future research, the knowledge about the reproducibility of the results is vital. Therefore, Monte Carlo simulations were performed in this study to evaluate the robustness of the simulation environment and the reproducibility of the results. The simulations included bird movement data from one year and air traffic data representing airports with four different traffic volumes. In total, 48 scenarios with 100 replications each were performed. A test of the convergence of the number of occurrences as well as the standard error confirmed that this number was sufficient.

The results of the Monte Carlo simulations were analysed with respect to the variance of bird strikes and near miss rates over the entire year as well as depending on the season. Furthermore, the correlation between the number of birds present in the airspace and the number of bird strike and near miss occurrences was evaluated.

Bird strike and near miss rates As expected, it was found that there was variance in the bird strike rates among the verification simulation runs. The ranges decreased and the correlations increased with increasing number of occurrences for bird strikes and near misses with the latter producing more robust results. However, when comparing the number of bird strikes and near misses for the same traffic intensities in Figure 3.14, the ranges regarding the near misses are higher. This is related to the higher number of occurrences as well as a higher range of the number of near misses.

Seasonal distribution of bird strikes and near misses The results considering bird strike and near miss rates are reflected in the seasonal overview presented in Figure 3.15. The ranges decreased with higher traffic volume for both, bird strike and near miss rate. Regarding the same traffic volumes, the ranges were higher for near misses than for bird strikes. The correlation results of the verification simulations are relatively high in comparison with the outcome of the Monte Carlo simulations. However, they still lie within a reasonable range.

3

Correlation between the number of birds and the number of strikes / near misses
The analysis of the Spearman correlation between the number of birds and the number of collisions / near misses revealed that, as in the verification simulations, there is a coherence between these parameters when excluding June. In this month, a high number of events takes place in the simulation, while a relatively low number of birds is active in the entire airspace. This was confirmed by an in-depth analysis of the data. It revealed that the majority of bird strikes in June occur below a height of 200 m, between 66 % and 85 % of all bird strikes[2]. This is the area which is covered by the avian radar. Of all strikes below 200 m throughout the year, between 58 % and 78 % [3] take place in June. This is only partly reflected by an increase of bird movements below 200 m. The number of birds present in the lowest altitude band lies only slightly above the average number of birds present per year[4]. Hence, the reason for this significant increase in bird strikes is related to the geographical distribution of tracks rather than to the number of birds. This corresponds to international bird strike data revealing that the fledging of young birds, which takes place in summer, leads to the highest risk of bird strikes. In the Netherlands, where the bird data originates from, most birds fledge in June [60, 164, 166]. Another contributing factor could be a contamination of the avian radar data by insect echoes. However, as no similar effect was observed for the other summer months, this seems unlikely. When excluding June for the analysis, the correlations between bird strikes and the number of birds increase and become significant. As such, the Monte Carlo simulations confirm the results of the initial simulation. With regards to near misses, where a higher number of occurrences is available for analysis, the correlations become significant. Except for the *very low* scenario, the average correlations become moderate. With the exception of June, this indicates that there might indeed be a higher risk of bird strikes with rising bird numbers throughout the year.

The large ranges of the number of occurrences as well as for the correlation between the number of birds and the number of occurrences for the *very low* traffic volume indicate that the number of occurrences is too low to gain representative and reproducible results in this scenario. Hence, for further studies, only the *high*, *medium* and *low* scenarios should be considered. Moreover, due to the expected variance in the results of these scenarios, a minimum of runs should be performed to achieve stable outcomes. Alternatively, scenarios generating results close to the overall average could be used.

Compared to real data, the risk of bird strike is overestimated by a factor of 2.5 to 3.4 in both the initial and the Monte Carlo simulations, when excluding the theoretical bird strikes. This can be attributed to missing escape behaviour of birds within the simulation and high bird presence on the runway. In the simulation, however, neither general behaviour nor escape reactions of birds was modelled. Hence, a higher number of strikes had been hypothesised and had occurred as well. Therefore, the effects that a bird strike advisory system would cause, will be overestimated when using this simulation environment. By considering this factor as well as the requirement for a minimum number of simulation runs, this simulation environment can serve as a beneficial tool for future research on bird strike occurrences.

[2] *high*: 81 %, *medium*: 78%, *low*: 66 %, *very low*. 85 %
[3] *high*: 65 %, *medium*: 58 %, *low*: 66 %, *very low*. 78 %
[4] approximately 10 % of all bird movements in the different scenarios

3.5. CONCLUSIONS

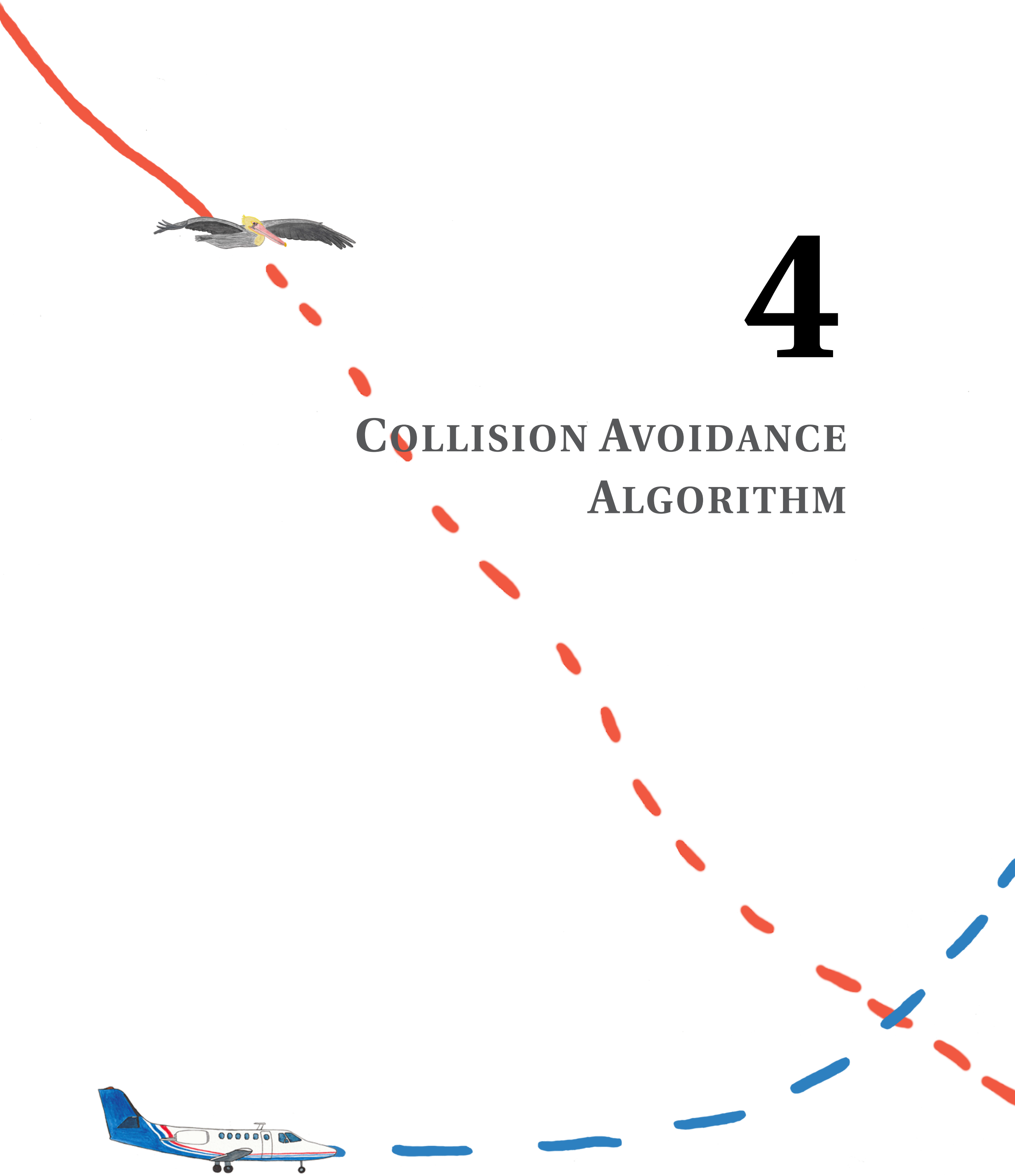
The aim of the presented work was to develop and verify a fast-time simulation environment to analyse the risk of bird strikes in the arrival and departure corridors of an airport. Furthermore, it was evaluated whether the results are reproducible. Finally, the robustness of the simulation environment were evaluated with Monte Carlo simulations.

An existing air traffic simulator was enhanced with modules to represent bird movement and to recognise bird strikes as well as near misses between birds and aircraft. To generate bird movement, information from two different radar types was merged. By combining the BMP and the aircraft flight plans, the risk of bird strikes can be simulated in fast-time in the resulting simulation environment. Up to the author's knowledge, this simulation set-up is unique. The verification of the set-up as well as the Monte Carlo simulations revealed that the simulated bird strike rate is 2.5 to 3.4 times higher than in reality. Due to last-minutes escapes often occurring in reality but not modelled within the simulation, this conforms to the expectations. Especially if respecting all birds present in the lowest altitude band, the altitude distribution of bird strikes reflects international statistics appropriately. The seasonal effects on the bird strike risk are covered adequately as the comparison to real data from Eindhoven airport demonstrates. In conclusion, the verification with real data demonstrates that the developed simulation environment reflects the risk for bird strikes decently with the initial data set. The correlation between the number of bird strikes and the number of birds seems to depend on airport opening hours and was addressed in the following Monte Carlo simulations. These revealed that when considering a sufficient air traffic intensity, the requirements for reproducibility are met. With regards to this study, this pertains to the air traffic intensities low, medium and high.

By considering the limitations of missing reaction of birds to aircraft and the resulting overestimate in number of bird strikes, the simulation environment can serve as a tool for bird strike-related studies. The range of potential applications is wide. For example, long-term effects of additional management measures can be studied and quantified by using avian radar data from prior and after implementing these measures as input for the simulation. In the next chapters, algorithms that delay departing air traffic in case of a predicted bird strike are implemented into the simulation environment. The goal is to evaluate the effects on an airport's runway capacity and safety when applying such a concept. Next to an algorithm considering deterministic bird trajectories, an algorithm including uncertainties in bird movement will be implemented.

4

Collision Avoidance Algorithm



This chapter is based on the publications

I. Metz, T. Mühlhausen, J. Ellerbroek, D. Kügler and J. M. Hoekstra, *What is the Potential of a Bird Strike Advisory System?,* Proceedings of 13th USA/Europe Air Traffic Management Research and Development Seminar, Vienna, Austria, 2019 [129].

I.C. Metz, J. Ellerbroek, T. Mühlhausen, D. Kügler, S. Kern and J.M. Hoekstra, *The Efficacy of Operational Bird Strike Prevention*, Aerospace **8**, 17 (2021) [126].

SUMMARY

In this chapter, the collision avoidance algorithm underlying the bird strike advisory system is introduced. The algorithm targets at preventing bird strikes for aircraft departing from an airport. Collision detection is performed by comparing the trajectories of these aircraft and the birds in the surrounding environment. Collision avoidance is achieved by delaying departures until they can follow a collision-free trajectory. To research the maximum safety benefit at minimal capacity and delay costs, perfect predictability of bird movement is assumed. The resulting algorithm was verified with an initial data set. Thereafter, it was validated with Monte Carlo simulations involving different air traffic intensities and bird movement from all seasons to analyse the effect of the algorithm on the safety and the traffic flows of an airport. The results reveal that the system is capable to prevent almost all bird strikes. However, the induced delays sometimes exceed tolerable limits. Nevertheless, when comparing arising delay costs against costs saved by preventing bird strikes in an initial analysis, a strong saving potential can be shown.

4.1. INTRODUCTION

To consider an implementation of a bird strike advisory system, its ability to actually prevent collisions between aircraft and birds has to be evaluated first. Moreover, potential impacts on airport operations and runway capacity have to be analysed. Controller interventions are most feasible for departures [68, 117], which are in addition most prone to bird strike damage [19, 46]. Hence, the algorithm targets at delaying take-offs to prevent strikes. This chapter describes the set-up of the resulting implementation. It was verified with an initial data set of air traffic flight plans and bird movement information. Thereafter, large-scale fast-time Monte Carlo simulations were performed to gain a comprising insight on potential effects of the algorithm on airport safety and capacity. This provides a first assessment of the feasibility of operational bird strike control.

In this study, perfect predictability of bird movement is assumed for two reasons. First, it is necessary to exclude side-effects from predicting bird movements when verifying the correct implementation of the algorithm. Second, to achieve a benchmark for the potential of the concept of operational bird strike prevention, the outcome of the algorithm under perfect conditions is required. A more realistic implementation including the limited predictability of bird movement, as introduced in chapter 5, can subsequently be compared and judged against the results presented in this chapter.

It is hypothesised that the algorithm strongly reduces bird strikes since it assumes perfect predictability of bird movements. Considering runway capacity, an increasing impact with rising intensities of air traffic and bird movements is expected. However, due to the optimised implementation, it is anticipated that runway capacity can be maintained and the delays for all air traffic scenarios remain within acceptable limits.

4.2. METHOD

By considering flight paths of aircraft and birds, the collision avoidance algorithm revises air traffic scenarios until all departing aircraft are calculated to have a collision-free trajectory. By simulating the resulting rescheduled traffic scenarios alongside the bird movement, the number of correctly prevented strikes was analysed.

An initial data set of different air traffic intensities and bird movement from all seasons served as input for the verification of the algorithm to ensure its correct implementation. Moreover, sampling rates of trajectory positions for the collision detection satisfying both, requirements of precision and computational performance were identified. Finally, an initial comparison of the costs caused by imposed delays against the savings from prevented bird strikes was performed.

To validate the algorithm, Monte Carlo simulations involving different air traffic intensities, flight plan patterns as well as variation in bird abundance were performed in a second step. The validation results served as input for a thorough study of the consequences on runway safety as well as traffic flows when implementing a bird strike advisory system for airport air traffic control. This section first introduces the logic of the collision avoidance algorithm underlying the bird strike advisory system. Thereafter, the configurations of the verification and validation experiments as well as the applied specifications are described.

4.2.1. COLLISION AVOIDANCE ALGORITHM

The presented collision avoidance algorithm is conceptually comparable to the Airborne Collision Avoidance System (ACAS) which aims at the prevention of mid-air collisions between aircraft [75]. Based on an information received from the Secondary Surveillance Radar (SSR) transponders of the aircraft, the time to and minimum distance at the Closest Point of Approach (CPA) between the two trajectories are predicted. Every aircraft is surrounded by a protected volume which is depending on the time to the CPA and fixed altitude thresholds. Protected volumes are divided into a caution, a warning and a collision area. If the caution area is predicted to be intruded by another aircraft, a traffic advisory is issued to both aircraft. In case of a penetration of the warning area, resolution advisories to eliminate the conflict are provided [75].

When considering collision avoidance between birds and aircraft, this logic can be applied as well. However, due to the differences in size, velocity and number of opponents in aircraft-bird collision avoidance, some adaptations have to be considered for the implementation of a respective algorithm.

First, the requirement for the number of potential opponents to process is limited in ACAS. Implementations have to be able to process up to 24 aircraft in a ten-kilometre radius [75]. In contrast, thousands of birds and thus potential opponents can be airborne in the departure corridors of an airport [167]. Hence, strong filtering for critical opponents has to be performed to comply with run-time and memory limitations.

Second, the required protected volumes around the opponents are much smaller in bird strike prevention than in aircraft-aircraft collision avoidance. In ACAS, the horizontal size of protected volumes can extend to 26 km to account for the high approaching speeds of opponents [75]. In contrast, tens of metres are required in collision avoidance between aircraft and birds. Consequently, high precision of the predicted trajectories is required to enable correct collision identification.

The protected volumes defined in ACAS consist of a caution, a warning and a collision area [75]. Due to the small sizes of the protected volumes defined for the collision detection between birds and aircraft, only the collision area is included here.

ACAS relies on an information exchange between on-board transponders. For area-covering and real-time movement information of birds in the extended airport environment, ground-based sensors such as radar, visual or infrared video have to be used. Hence, the spatial extension as well as the look ahead time are limited by the range of the chosen sensor. Since the intentions of birds are unknown, an estimate of their future flight path has to be made. Thereby, their potential reactions to aircraft have to be taken into account [106]. As the kinetic energy of the impact of a collision with a bird increases with increasing involved biomass, especially large individuals and flocks of birds are threatening. For prioritisation, the chosen sensors acquiring bird movement information should be able to classify birds in weight categories.

STRUCTURE

The resulting structure of the collision avoidance algorithm takes the above described requirements into account. Based on the concept introduced by Kuenz [110], the algorithm is optimised to compare large numbers of opponents, as required for the implementation targeting the prevention of collisions between aircraft and birds. The optimisation is achieved by dividing the collision detection into two phases. In the first, the *broad phase*, the airspace is filtered for birds that are likely to conflict with the aircraft. For this purpose, the airspace is split into a grid consisting of n-dimensional tiles during a preprocessing phase. Only if the trajectories of the birds and the aircraft cross identical or neighbouring tiles, the birds are considered as potential opponent. In the second, the *narrow phase*, a high-precision trajectory comparison is performed for the effective collision detection on the filtered birds only.

Figure 4.1 shows the steps performed by the algorithm. The algorithm is provided with flight plans as well as bird movement information of entire days. The latter is represented within the Bird Movement Plans (BMP) introduced in section 3.2.2. Within the preprocessing, the airspace is discretised in the four dimensions time, latitude, longitude and altitude. Based on their positions in the BMP, birds are stored in the tiles of the grid in the preprocessing step. Each scheduled departure is tested against the birds present at the intended take-off time. For this purpose, the tiles which will be crossed by the aircraft, are determined based on its trajectory in the *broad phase*. Only birds stored in these or in their neighbouring tiles will be considered for collision-detection in the *narrow phase*. The latter are included to account for aircraft and birds flying close to the boundaries of their tiles (cf. [110]). To identify collisions, the trajectories of the respective birds and the aircraft are compared. If the comparison reveals that they will penetrate the protected volume of each other, the aircraft receives a take-off delay to avoid the collision. Thereby, separation minima to subsequent aircraft are considered. To avoid go-arounds for arrivals, they are given priority. If the delay of a departure leads to a loss of separation with the subsequent arrival, the departing aircraft is scheduled to depart behind the arrival. This can result in domino effects for following departures. The output of the algorithm is a rescheduled flight plan for the considered traffic day.

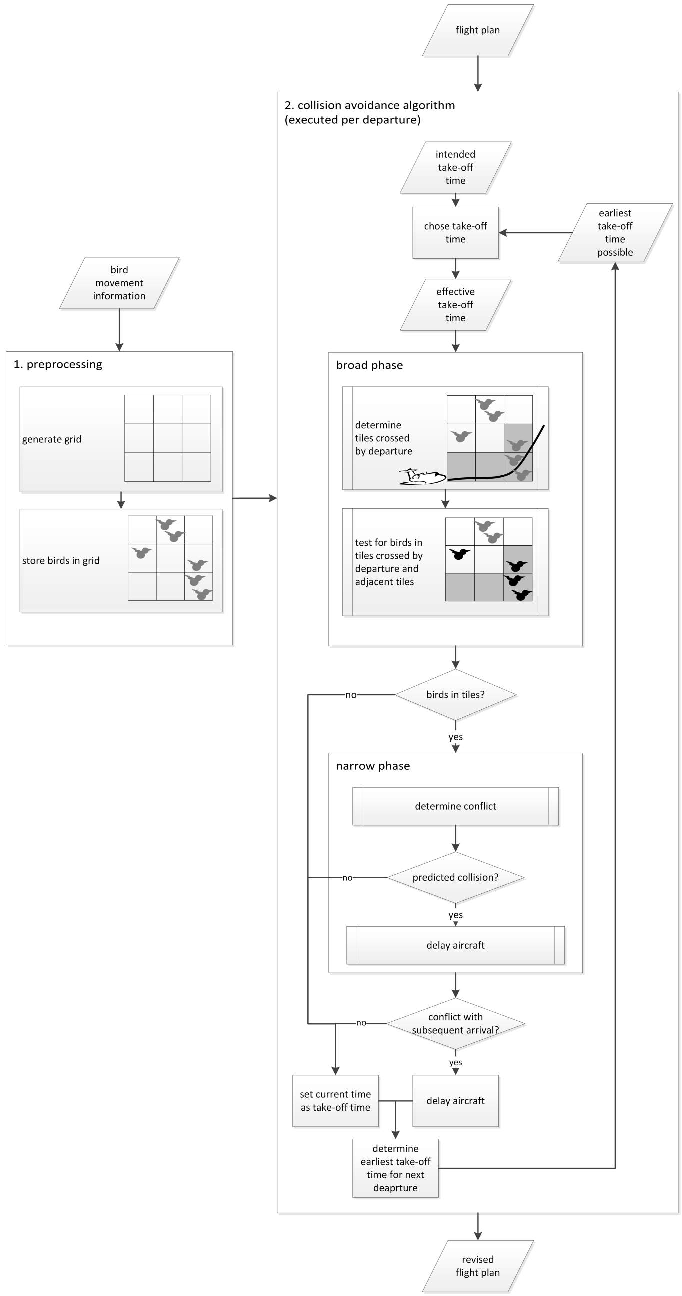


Figure 4.1: Set-up of the collision avoidance algorithm.

Table 4.1: Grid and tile sizes.

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

SPECIFICATIONS

The collision avoidance algorithm is set up to evaluate the maximum potential of its effects in terms of maximum number of prevented strikes at a minimum delay cost. Therefore, all bird and aircraft trajectories are given and do not include uncertainties.

The tile-widths of the considered grid-dimensions used for filtering relevant bird trajectories are summarised in Table 4.1. The dimensions of the entire grid result from the temporal and geographical boundary conditions set for the study. In the time dimension, the grid covers the airport opening hours of 17 hours. The lateral widths correspond to the study area around Eindhoven airport (see Figure 3.4). The altitude boundary refers to the limit defined in chapter 3.

Birds were filled into the grid based on their trajectory information. Between the given positions, linear interpolation was applied. This was defined as appropriate, as the differences to distances calculated with a more sophisticated definition including e.g. the haversine formula [154], are small.

The protected volumes defined to identify collisions in the *narrow phase* are identical to the one described in section 3.2.5. The identical definition of protected volumes within the simulation environment and the collision avoidance algorithm ensures comparability of results which is relevant for the verification and validation of the algorithm.

Due to the high aircraft speeds and the small sizes of the protected volumes, trajectory comparison should be performed with a high sampling rate in order to capture all strikes. Considering runtime and memory requirements, a sampling rate enabling to detect strikes with high risk of damage at least should be implemented. Highest risk of damage occurs at high velocities and close to the core of the aircraft [46, 54]. Therefore, a minimum sampling frequency to detect head-on collisions between aircraft of the smallest category and birds of all sizes at the highest observed speed at half of the aircraft's wingspan as visualised in Equation 4.1 was defined as minimum.

$$f_s = \frac{v_{ac} + v_{bird}}{r_{ac} - r_{bird}} \tag{4.1}$$

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

By applying the smallest aircraft radius of 14.2 m, the smallest bird radius of 0.32 m, the largest aircraft velocity of 113.18 m/s as defined in the flight plans and a maximum bird velocity of 16.22 m/s, a sampling rate of 9.32 Hz results. Distance measures were performed using the local flat earth approximation [154]. For compatibility with BlueSky, which was used to evaluate the results, the rate was increased to 20 Hz. Consequently, collisions where the penetration of protected volumes lasts at least 50 ms are captured.

In case of a detected collision, the aircraft is delayed in five-second increments. If this leads to the loss of separation to an arriving aircraft, the departure is further delayed until it has a sufficient separation to the previous and following arriving aircraft. Occurring delays are transferred to subsequent departures. For simplicity, an average minimum separation of 66 seconds was applied between all aircraft in all scenarios. This separation corresponds to 55 take-offs per hour which is achieved at Europe's most frequented single-runway operated airport of London Gatwick [5, 10].

All simulated aircraft were of the type A320-200 and their performance was calculated using the Base of Aircraft Data (BADA) model, version 3.12 [67].

4.2.2. ANALYSIS

To analyse the outcome of the collision avoidance algorithm, the following steps depicted in Figure 4.2 were performed for the verification as well as for the validation. First, the air traffic flight plans were simulated alongside the BMPs in fast-time as described in chapter 3. The number of strikes recorded indicate, how many strikes can be prevented and as such represent the safety potential of the algorithm.

Second, the collision algorithm was applied on all combinations of flight plans and BMPs, rescheduling departures where necessary. Third, the revised flight plans were simulated alongside the BMPs in BlueSky to test for collisions undetected by the algorithm. To test for superfluous warnings, it was checked in the fourth step whether the collisions prevented by the algorithm actually did take place in the baseline.

Next to evaluating the effect on airport safety, the impact on capacity and the delays imposed by the algorithm were analysed. In real operations, Air Traffic Flow Management (ATFM) slots can be assigned to departing aircraft if the number of airspace users is forecasted to exceed the airport or en-route capacity. The so-called slot tolerance window starts five minutes prior and ends ten minutes after the assigned departure time [68]. To comply with potential ATFM slots, the maximum tolerable delay due to bird strike prevention amounts to ten minutes. The number of delays exceeding ten minutes as well as their duration were counted as a performance indicator. Shifts of flights to beyond the opening hours indicate that the airport cannot keep up its capacity. Therefore, all aircraft should be able to depart within the assigned airport opening hours.

Aircraft delays within the revised flight plan have three potential sources which are displayed in Figure 4.3. They can result from an intervention of the collision avoidance algorithm (*bird delay*) or a domino effect of a previously delayed departure (*transferred delay*). If an aircraft with a *transferred delay* has to be further delayed due to bird presence, it experiences a *combined delay*.

To evaluate the impact on capacity, the delays generated by the collision avoidance algorithm to avoid bird strikes as well as transferred delays for subsequent departures were stored. The specifications differing between the verification and validation experiments are described in the subsequent sections.

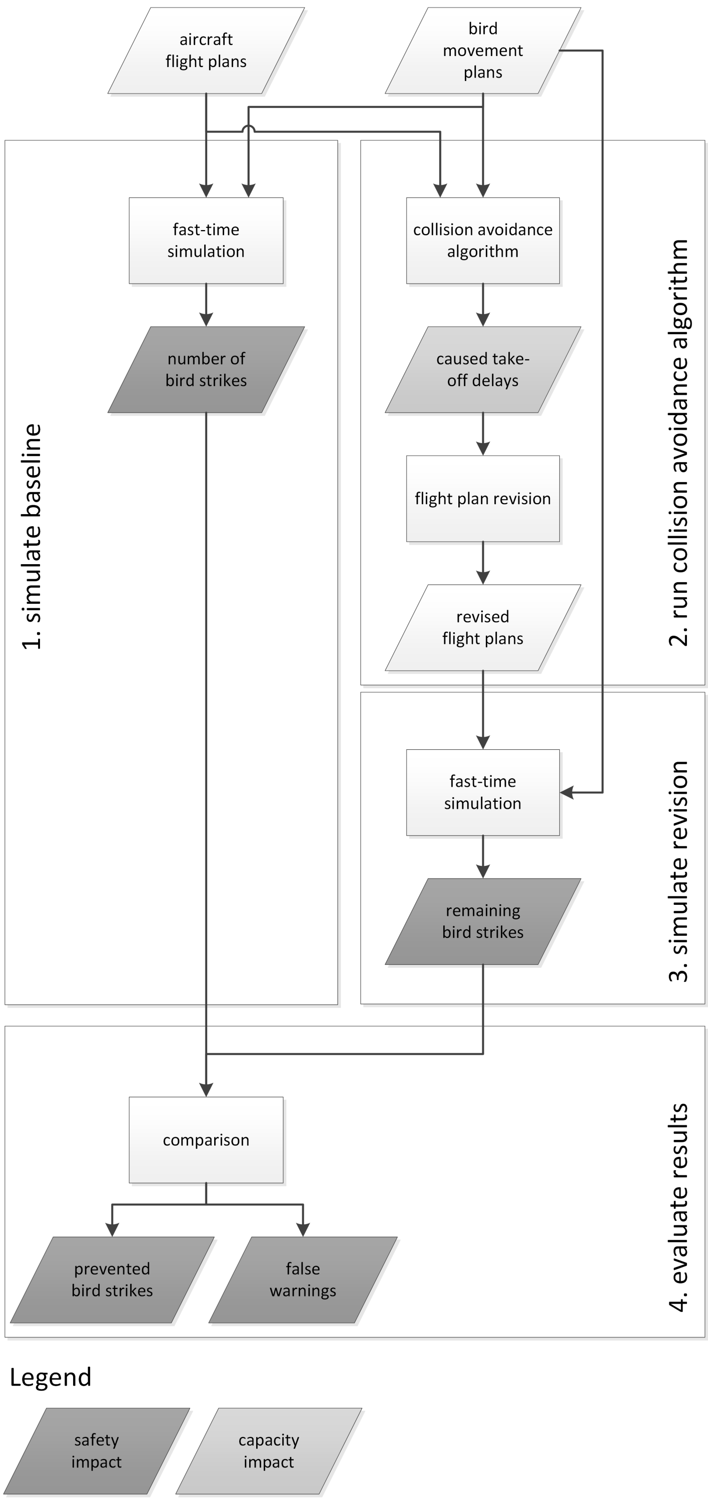


Figure 4.2: Procedure to validate the collision avoidance algorithm

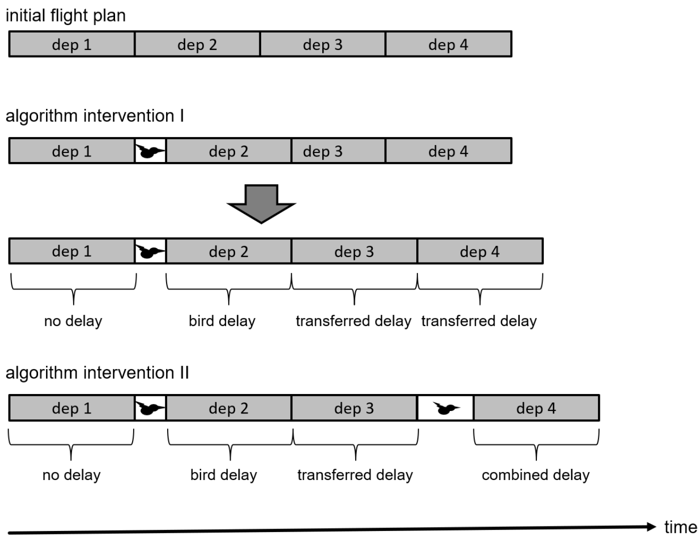


Figure 4.3: Types of delays generated by the algorithm (dep: departure).

4.2.3. VERIFICATION EXPERIMENT

The main goal of the verification experiment was to ensure the correct implementation of the collision avoidance algorithm. In addition, three different sampling rates to record aircraft trajectories were compared regarding their precision in collision detection. Lastly, an initial study on the costs arising from delaying departures as well as the potential savings from preventing bird strikes was performed.

To verify the algorithm, the same data sets as for the verification of the simulation environment described in section 3.2.6 were used. BMPs of one week per month between October 2015 and September 2016 were combined with flight plans representing high (954 daily movements), medium (501 daily movements) and low (305 daily movements) air traffic intensities. The very low traffic intensity was skipped since it had been shown to lead to results hardly to reproduce in section 3.3.2. By merging the 84 BMPs with the three traffic intensities, 252 scenarios resulted.

To generate the aircraft trajectories, the flight plans were simulated and the trajectories were logged in BlueSky. With increasing logging frequency, trajectories can be rebuilt more precisely for analysis. On the other hand, this results in larger datasets and thus higher memory requirements for the processing within the collision avoidance algorithm. Therefore, a logging frequency with sufficient precision at minimum cost of memory had to be determined. Initial evaluations revealed that a higher sampling rate is necessary during the lift-off phase between 0 m and 15 m to account for the rapid changes in vertical speed in this phase. During the remaining flight, a smaller sampling rate is sufficient. Within the collision avoidance algorithm, linear interpolation was applied between recorded aircraft positions. The collision avoidance algorithm was executed for three combinations of logging frequencies. These can be found in Table 4.2.

Table 4.2: Tested logging frequencies of aircraft trajectories.

Iteration identifier	Logging frequency lift-off [Hz]	Logging frequency other flight phases [Hz]
I	10	2
II	20	1
III	20	2

The determining criteria for a correct implementation of the collision avoidance algorithm are the number of false warnings and the number of strikes still taking place after revising the flight plans. As aircraft and bird trajectories are perfectly predictable, all collisions of departing traffic should be prevented and no false warnings be generated. However, due to the chosen sampling rate of the trajectories, the collision avoidance is defined as correctly implemented if a maximum of 5 % of strikes remain after rescheduling and a maximum of 5 % of false alerts is generated.

Finally, an initial study on the economic consequences resulting from operational bird strike prevention was performed. On the one hand, bird strikes cause substantial costs to the aviation industry [9, 55]. On the other hand, the take-off delays generated by the collision avoidance algorithm cause costs as well [32]. Direct costs resulting from a bird strike mainly concern the operator of the affected aircraft. However, the economic impact caused by the impairing of operations also influence the other parties involved in the ATM process [149]. For this analysis, FAA data considering bird strike related costs for airlines in the US could be obtained [55]. Based on reports from 1990 to 2015, average repair costs of US$164,595 (3,945 reports) and average indirect costs of US$27,599 (2,962 reports) per bird strike were determined. Indirect costs include expenses resulting from lost revenues, passenger costs, rescheduling of aircraft and flight cancellations. The resulting costs of US$192,194 represent average costs per strike, where an adverse effect on the flight was reported (24,473 reports). When mapping them to all 169,856 reported strikes, average costs of US$27,691 (about €24,947 [1]) per strike result. These are inflation-adjusted to 2015. Due to incomplete reporting, these costs are considered to underestimate real costs by a factor of two to three [55].

Regarding delay costs, data is available for Europe. In [32], reference values are presented for the year 2014. Airline costs are calculated for different phases of flight and include the costs of fuel, maintenance, fleet, crew, passengers and reactionary delays. By considering all aircraft types for the taxi phase (cf. [32], Table 27, p.12), average delay costs of €175 per five minutes, respective €35 per minute result.

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

[1] based on the exchange rate of 1.11 from 2015 [156]

Table 4.3: Chosen distributions and parameters to create the air traffic flight plans for the validation experiment with the tool *Computing Runway Capacity Enhancements*.

Traffic intensity	**Number of flights**	**Separation buffer**	**Reaction time buffer**
high	900	Normal distribution: $\sigma = 0.1$ NM /0.4 s, $underrun = 5\%$	Weibull distribution: $k = 1.5$, $\lambda = 0.18$
medium	500	Weibull distribution[a]: $k = 5$, $\lambda = 0.04$	Weibull distribution: $k = 5$, $\lambda = 0.07$

[a] The Weibull distribution is a continuous probability function. Its shape strongly depends on the underlying shape parameter k and the scale parameter λ [147].

4

4.2.4. VALIDATION EXPERIMENT

The focus of the validation experiment was to gain a comprising insight on the potential effects of the airport on airport safety and traffic flows to provide first implications on the feasibility of operational bird strike control.

For the validation experiment, Monte Carlo simulations with randomised air traffic flight plans were performed. Since the air traffic intensities high and medium are most critical, these were selected as foundation of the randomisations. The randomised flight plans were created with the tool *Computing Runway Capacity Enhancements* [108]. The main focus of this tool lies on runway capacity analysis. For this study, its module to randomise flight plans for a defined number of aircraft was used. To randomise flight plans, the sequence of departures and arrivals is defined in a first step. Subsequently, separations between the aircraft are calculated based on various parameters such as minimum separation, aircraft and airport characteristics and human factors. An overview of all parameters and applied distributions can be found in [109]. For this study, the flights were spread over the opening hours used for the verification flight plans as described in section 3.2.4, with the identical minimum separation of 66 seconds for comparability. To generate sequences meeting these requirements, specific distributions for the parameters *separation buffer in aircraft separation* and *reaction time of controller or pilots* were applied. These can be found in Table 4.3. Following this procedure, 1,000 scenarios for each of the departure shares 25 %, 50 %, 75 % and 100 %, were generated, leading to 4,000 scenarios for the high and medium traffic intensities, respectively.

The randomised flight plans were combined with three BMP representing various levels of bird strike risk. It was shown in chapter 3 that higher bird abundance does not necessarily lead to a higher risk of strikes. Hence, the scenarios leading to the maximum, median and average number of bird strikes in these simulations were selected as input for the BMPs. The dates of which they originate from are shown in Table 4.4.

Combining the three BMPs with the 8,000 flight plans from the two air traffic intensities leads to 24,000 scenarios for the validation experiment.

As the evaluation of different sampling rates described in section 4.3.1, the sampling rate III, logging the lift-off part of the aircraft trajectory with 10 Hz and the remaining flight phases with 2 Hz (Table 4.2), was the only one to meet the precision requirements. Hence these sampling rates were applied for the validation experiment.

Table 4.4: Days selected to create BMP for the validation experiment.

Observed number of bird strikes	Scenario name	High air traffic intensity	Medium air traffic intensity
maximum	high	5/6/2016	5/6/2016
median	medium	14/10/2015	25/08/2016
minimum	low	10/01/2016	11/01/2016

4.3. RESULTS

To evaluate the collision avoidance algorithm introduced in this chapter, the following steps were performed. First, the correct implementation of the algorithm was verified with initial data sets and a suitable logging sampling rate of aircraft trajectories for the collision detection determined. In addition, an initial cost-study was performed.

Thereafter, the algorithm was validated with Monte Carlo simulations and an in-depth analysis on the effects on capacity and safety of the algorithm was performed.

In both the verification and the validation experiments, a maximum of 5 % of strikes remaining and a maximum of 5 % of false alerts are tolerated to account for inaccuracies resulting from the selected sample rates. Since the algorithm focuses on departures, only strikes involving these aircraft were included in the analyses.

4.3.1. VERIFICATION EXPERIMENT

The correct implementation of the collision avoidance algorithm was tested in two steps. First, the flight plans rescheduled by the collision avoidance algorithm were simulated alongside the BMPs in BlueSky. The results were compared against the results obtained in chapter 3, where the original flight plans had been simulated alongside the BMPs.

Strikes occurring to departures of the revised flight plans served as verification criterion. Second, the algorithm's output was evaluated regarding false warnings. To calculate the share of these false alerts, the aircraft with a *bird delay* in the revised flight plans were compared to the collisions taking place in the initial flight plan. Departures that did not encounter a collision there but received a *bird delay* by the algorithm were counted as false alerts. For that comparison aircraft that were only delayed because of birds (i.e. without having received a *transferred delay*), were included. Only these aircraft encountered the same birds in the original as well as the revised flight plan and are therefore comparable. This applied to 50 % of strikes of the high, 78% of the medium and 100 % of the low traffic intensities. Aircraft which already had an initial delay in the revised scenario were excluded.

Table 4.5: Total number of strikes missed by the algorithm and false alerts for the different sampling rates tested in the verification experiment. Values exceeding the tolerance are marked in bold.

Traffic intensity	**Number of strikes before**	**Tolerated remaining strikes and false warnings**	**Missed strikes**			**False warnings**		
			iteration I	***iteration II***	***iteration III***	***iteration I***	***iteration II***	***iteration III***
high	155	7.75 (5.00 %)	***9 (5.81 %)***	6 (3.87 %)	6 (3.87 %)	3 (1.94 %)	3 (1.94 %)	3 (1.94 %)
medium	70	3.50 (5.00 %)	2 (2.86 %)	2 (2.86 %)	2 (2.86 %)	1 (1.43 %)	1 (1.43 %)	1 (1.43 %)
low	54	2.70 (5.00 %)	1 (1.85 %)	1 (1.85 %)	1 (1.85 %)	2 (3.70 %)	***3 (5.56 %)***	2 (3.70 %)

Table 4.6: Bird strike rates prior and after the algorithm intervention with the sampling rates of iteration III in the verification simulations. Note that prior bird strike rates corresponds to the verification results of chapter 3.

Traffic intensity	**Initial bird strike rates**	**Bird strike rates after intervention**
high	39.06	0.7
medium	36.83	0.4
low	41.96	0.4

The collision avoidance algorithm was executed with aircraft trajectories recorded at three combinations of sampling frequencies (cf. Table 4.2). The outcome from simulating the scenarios with the different frequencies is shown in Table 4.5. Slight variations in number of remaining strikes and false warnings are present for the high and low traffic intensities. When applying the selected tolerance of 5 % to remaining collisions and false warnings restrictively by rounding them down, only iteration III fulfils all requirements. Hence, this iteration was selected to be evaluated regarding the algorithm's impact in the verification experiment and for the execution of the validation experiment.

The effect of the algorithm on the bird strike rate, expressed in number of strikes per 10,000 departures, can be found in Table 4.6. As expected, a strong decrease resulted.

The number of flights affected by the algorithm is very small in all traffic intensities, with a maximum of 3.14% in the *high* intensity, as shown in Table 4.7. The weighted average of the results of the high and medium traffic intensity scenarios is provided for comparability to the corresponding validation results which are provided in Table 4.11.

With decreasing traffic intensity, the effect of the collision avoidance algorithm decreases as well for all considered parameters. This becomes most visible, when considering how many delays followed an intervention of the algorithm. For the high air traffic intensity, eight *transferred delays* resulted from one imposed *bird delay*. For the medium and low air traffic intensities, the values are much lower (two and one, respectively). This indicates the strong influence of the tightness of the traffic schedule on the results.

The maximum observed delay amounted to 396 s in the high air traffic intensity scenarios. This lies well below the defined critical delay of 10 minutes (600 s). Moreover, all aircraft of all scenarios could depart within the airport opening hours.

Table 4.8 summarises the potential savings due to the prevention of strikes and costs resulting from the applied delays. In all traffic intensities, the monetary benefits outnumber the costs considerably. Thereby, the ratio between benefits and expenses strongly increases with decreasing traffic intensity. The monetary quantification of the costs and benefits of implementing a collision avoidance concept as presented here has to be performed carefully, as the sources for the costs of bird strikes and delay minutes originate from different countries. Furthermore, the data set serving as input for the costs of bird strikes is considered as incomplete and the resulting costs are expected to underestimate the effective expenses. Therefore, the numbers presented here serve as an initial estimate of the monetary impact on the airlines.

Table 4.7: Analysed delay parameters for the three traffic intensities within the verification experiment (weighted average of high and medium traffic intensity for comparability to validation experiment).

Traffic intensity	**Delayed flights [%]**	***Transferred delay* caused by *bird delay* [-]**	**Average delay per affected aircraft [s]**	**Maximum observed delay [s]**
high	3.1	8	123	396
medium	0.6	2	76	294
weighted average	**2.3**	**5.7**	**119**	**396**
low	0.5	1	19	167

Table 4.8: Daily averages of savings and costs resulting from the verification experiment.

Traffic intensity	**Number of prevented Strikes[a] [-]**	**Costs saved[b] [€]**	**Sum delay [min]**	**Delay costs[c] [€]**	**Saved per caused costs [-]**
high	1.77	44,251	29.22	1022.90	43.26
medium	0.81	20,195	1.78	62.36	323.83
low	0.63	15,740	0.23	8.04	1956.74

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

[b] € 24,947 per strike

[c] € 35 per minute

Table 4.9: Average daily number of strikes remaining after rescheduling flight plans as well as average daily number of false alerts within the validation experiment.

Traffic intensity	**Number of strikes before**	**Tolerated remaining strikes and false warnings**	**Remaining strikes**
high	4.26	0.21 (5.00 %)	0.11 (2.55%)
medium	1.94	0.10 (5.00 %)	0.04(2.31 %)

4.3.2. VALIDATION EXPERIMENT

The validation experiment aimed at the thorough study of the effects of the collision avoidance algorithm on safety and traffic flows of an airport. To obtain representative results for different conditions, Monte Carlo simulations involving 24,000 scenarios of varying air traffic flight plans and three bird movement densities were performed. As for the verification experiment, the reduction of bird strikes by the algorithm was assessed. The results are shown in Table 4.9. The share of remaining strikes remains well below the tolerance criterion of 5 %, which strengthens the verification results.

The overall effect on the bird strike rate observed within the validation experiment is visualised for the different combinations of air traffic intensities and BMPs in Figure 4.4. The initial rates are proportional to the number of air traffic and birds. The algorithm reduces the rates notably but with different efficacy for the individual scenarios, as can be seen in Figure 4.4. When considering the weighted average of all scenarios, the algorithm lowers the bird strike rate from 63.26 to 1.76 strikes per 10,000 departures. As such and in accordance with the verification results, the anticipated strong decrease in bird strike rate was observed.

The reduction in number of bird strikes resulting from rescheduling flight plans has two potential sources. First, there are strikes which are deliberately prevented by the algorithm. In this case, the respective flight receives a *bird delay*. Second, the shift in departure time of aircraft having received a *transferred delay* can cause an aircraft to miss a bird which it encountered with the original departure time. However, these occurrences are not because of the algorithm actively preventing the strike but due to the domino effect of delays inherited from previous departures. Hence, in addition to the total reduction of strikes, it is of interest, how many strikes were deliberately prevented by the algorithm. For this analysis, only the aircraft having received a *bird delay* were included. Only for them, the difference in number of bird strikes was actively caused by the algorithm. This applied to 92 % of aircraft in the revised flight plans, which can be regarded as representative. Considering this share, 99.33 % of strikes were prevented for departing aircraft in all scenarios, as depicted in Table 4.10. Hence, also the deliberately prevented share of bird strikes exceeds the requirement of 95 % of prevented strikes. Next to the averages of the three bird movement densities per air traffic intensity, the weighted average for the entity of scenarios was calculated, where the number of flights per scenario

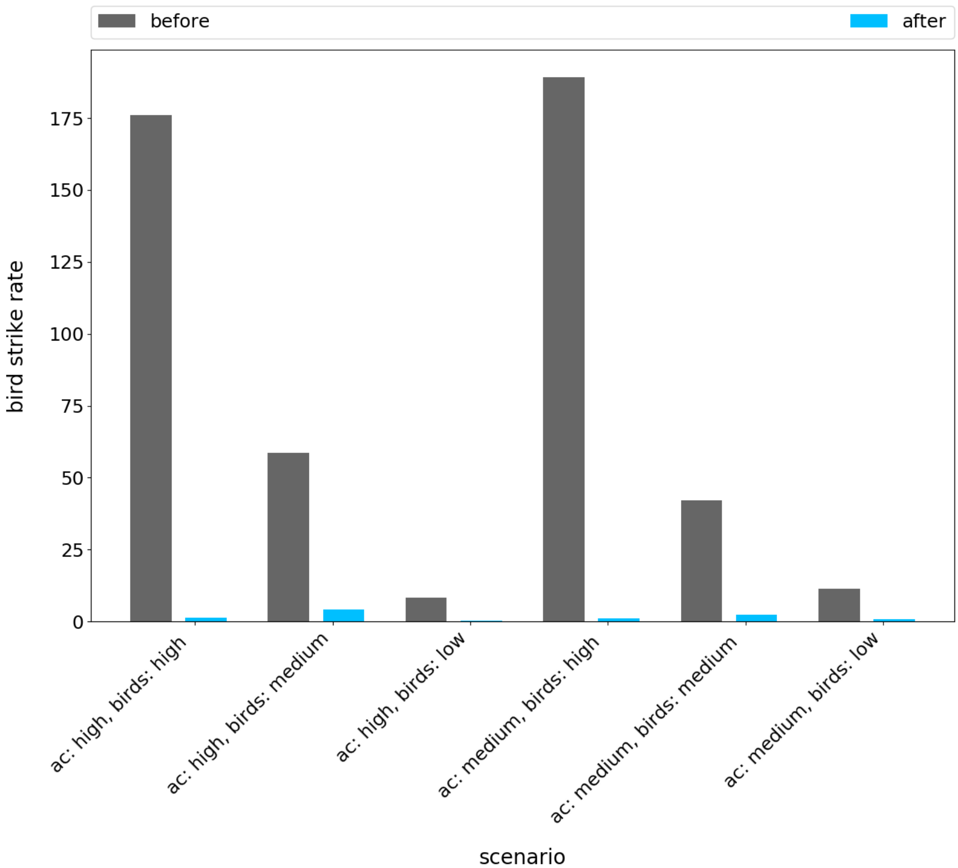


Figure 4.4: Bird strike rates before and after the intervention of the algorithm in the validation experiment.

Table 4.10: Analysed strike parameters for all scenarios of the validation experiment, averaged per air traffic intensity as well as averages weighted by number of flights over all scenarios when considering flights with *bird delays*.

Traffic intensity	Bird movement intensity	Prevented strikes [%]	False alerts [%]
high	*high*	99.15	0.07
high	*medium*	98.88	0.04
high	*low*	100.00	0.01
high	***average***	**99.34**	**0.04**
medium	*high*	99.74	0.06
medium	*medium*	99.24	0.02
medium	*low*	99.82	0.01
medium	***average***	**99.27**	**0.03**
weighted average		**99.33**	**0.04**

4

served as weighting factor. Therefore, the results lies closer to the values of the *high* air traffic intensity scenarios. In all cases, the share of false alerts lies well below the tolerance criterion of 5 %.

To calculate the share of false alerts, aircraft with a *bird delay* in the revised flight plans were compared to collisions taking place prior to the intervention of the algorithm. This procedure corresponds to the one performed in the verification. Aircraft that did not encounter a collision but were delayed due to birds by the algorithm were counted as false alerts. The algorithm generated 0.04 % false alerts. The individual values per scenario as well as the weighted average of all scenarios can be found alongside the shares of prevented strikes in Table 4.10.

While the number of strikes prevented serves as measure for the safety effect of the collision avoidance algorithm, the generated delays indicate the impact on runway capacity. Table 4.11 provides an overview of the delays per scenario as well as for the consolidation of all scenarios. In contrast to the verification, the observed impact on capacity is higher. In the verification, 3 % of flights were affected in the *high* and 0.5 % in the *medium* scenarios. In contrast, the shares amounted to 6 % and 1 % in the validation.

The share of affected aircraft as well as the delay duration decreases with decreasing bird and air traffic. In all scenarios, a limited number of aircraft is affected and the average experienced delay lies well below the tolerance of ten minutes. However, in contrast to the verification, individual delays exceeding this tolerance were observed for high air traffic combined with high and medium bird movement intensity. Hence, the hypothesis of acceptable delays in all scenarios cannot be fully supported.

Table 4.11: Delays resulting from the intervention of the collision avoidance algorithm per individual scenario, averaged per air traffic intensity as well as averages weighted by number of flights over all scenarios of the validation experiment.

Traffic intensity	**Bird movement intensity**	**Delayed flights [%]**	***Transferred delay* caused by *bird delay* [-]**	**Average delay per affected aircraft [s]**	**Maximum observed delay [s]**
high	*high*	15	14	192	2,135
high	*medium*	3	7	70	704
high	*low*	< 1	6	59	350
high	***average***	**6**	**9**	**107**	**2,135**
medium	*high*	3	2	35	486
medium	*medium*	< 1	2	29	320
medium	*low*	< 1	2	23	295
medium	***average***	**1**	**2**	**29**	**486**
weighted average		**4**	**8**	**158**	**2,135**

The distribution of delays among the different types *bird delay*, *transferred delay* and *combined delay* is displayed in Figure 4.5 for all scenarios. While the *transferred delays* dominate for the high traffic intensity, *bird delays* build the majority for the medium air traffic scenarios. *Combined delays* play a minor role in all scenarios. Over all scenarios, only two aircraft would depart after the assigned opening hours, both when merging medium air traffic with high bird movement intensity. In both cases, the last aircraft of the day was delayed due to bird strike risk, leading to a departure just after the closing hour (99 s and 109 s). Hence, they can be considered as outliers and the requirement of all take-offs remaining within the airport opening hours regarded as fulfilled.

4.4. DISCUSSION

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

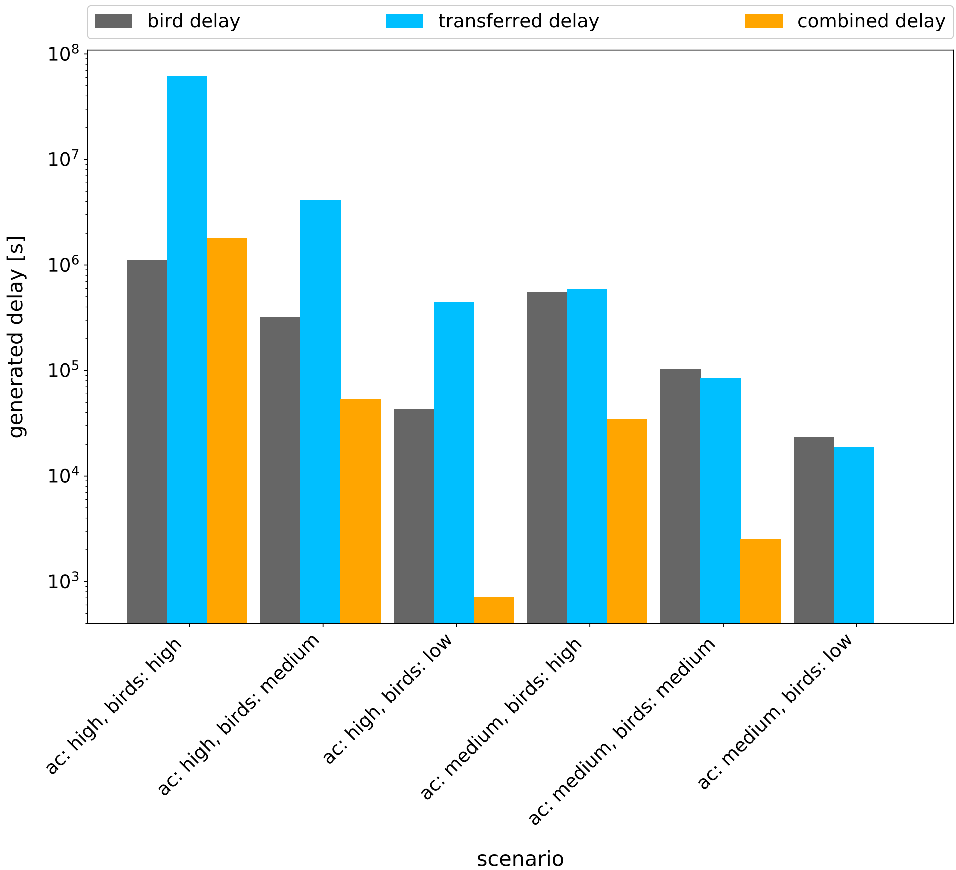


Figure 4.5: Number of the different delay types per traffic day of the validation experiment (note logarithmic scale).

4.4.1. VERIFICATION EXPERIMENT

For the verification of the algorithm, an initial data set including flight plans from three air traffic intensities were run alongside bird movement information from one week per month of one year, resulting in 252 scenarios.

The correct implementation of the collision avoidance algorithm was verified by considering still occurring aircraft-bird collisions and generated false warnings. Three combinations of logging frequencies for aircraft trajectories were tested. It was found that the combination of 20 Hz during lift-off and 2 Hz during the remaining flight phases fulfils the verification requirements. Hence, the corresponding iteration III was selected for further evaluation. This included aircraft flight plans of high, medium and low traffic intensities and bird movements from all seasons. A safety benefit in terms of prevented collisions of 96 % to 98 % of prevented bird strikes resulted, while 1 % - 4 % of false warnings were generated. The false alerts were obtained for aircraft having received a *bird delay*. This applied for 50 % in the high, 75 % in the medium and 100 % of flights in the low air traffic intensity scenarios. The share for the high scenario is not necessarily representative. However, since the results were confirmed in the validation experiment (cf. section 4.4.2), they are considered as valid here as well.

To assess the impact on runway capacity, the resulting delays caused by the collision avoidance algorithm were analysed. Delays above 10 minutes, leading to a loss of an ATFM slot, were defined as critical as well as delays causing departures to be shifted after the airport opening hours. No critical delay took place in any of the scenarios. Even in the *high* traffic intensity scenarios containing 954 flights in 17 hours, the resulting delays and the loss of 27 departure slots could be compensated for. The maximum delay amounted to just above six minutes and all flights could depart within the airport opening hours. Moreover, the amount of flights which were influenced by the algorithm was extremely small with a maximum of 3 % in the *high* traffic scenario.

The initial cost estimation performed within the verification revealed a strong potential to save direct costs for the airlines when implementing a collision avoidance algorithm. In all scenarios, airlines would profit from the implementation. The benefit increases with decreasing traffic intensity. The simulation overestimates the number of bird strikes (cf. chapter 3). Therefore, also the number of interventions and thus the impact of the collision avoidance algorithm should be interpreted as a maximum estimate. Still, the ratio between savings and costs remains strongly beneficial when assuming a linear coherence between prevented bird strikes and caused delays as a first approximate. The cost-analysis focused on the aircraft operators. To receive a more elaborate picture of the economic consequences for all parties involved in the ATM process, more complete data is required.

4.4.2. VALIDATION EXPERIMENT

The performed Monte Carlo simulations in the validation experiment including various bird movement and air traffic patterns demonstrated the potential to remarkably lower the bird strike rate for departing aircraft in case of perfect predictability of bird movement. Hence, the hypothesis of a strong cut in bird strikes can be accepted. Furthermore, the target of a maximum of 5 % of remaining strikes and a maximum of 5 % false alerts were fully met for all simulated scenarios.

The impact of the algorithm, both in prevented strikes and consequently in generated delays, was higher than in the verification. Contributing factors might be the variability in flight plans per traffic density, which was not included in the verification. Moreover, the verification only used a limited sample of replications. In contrast, the here obtained results are based on a representative number of scenarios.

The variable efficacy of the algorithm in preventing bird-aircraft collisions per scenario is related to the timing of bird and aircraft departures. In those scenarios where a slightly higher strike rate remained, more birds causing collisions took off after the considered aircraft than in the other scenarios. Since the algorithm only considers birds airborne at the time of intended take-off, these strikes were unpreventable, leading to these somewhat higher final strike rates. However, this would also occur in a real-life implementation. Therefore, even with an optimised system as presented here, bird strike rates can be reduced but never eliminated.

The second hypothesis focused on the effect on capacity. Since the algorithm was expected – and has proven – to prevent bird strikes with high precision, the resulting delays were hypothesised to stay within reasonable limits. As a benchmark, ten minutes were set as a maximum acceptable delay to comply with the slot tolerance window of ATFM. In all scenarios, the average delay per affected aircraft stayed well below this limit. However, in some cases considering high air traffic intensity, it was overrun by individual flights by up to 25 minutes. Here, the results are in contrast to the ones obtained in the verification experiment, where all delays stayed within acceptable limits. This discrepancy stresses the importance of including a sufficient number of scenarios for representative results as performed in the validation. The exceeding of the tolerable delay minutes was caused by *transferred delays* to later aircraft. Since the schedule was very tight in these scenarios, even a small bird delay could already lead to a domino effect for following aircraft including large delays. This is reflected in Figure 4.5 which illustrates the high share of transferred delays, exceeding the share of bird delays in the scenarios involving high air traffic density. Consequently, the hypothesis of capacity impact can only be accepted for the medium air traffic scenarios as well as for the high air traffic scenario encountering low bird movement intensity. However, the bird strike rates in these simulations are overestimated by a factor of three, as demonstrated in chapter 3, leading to more algorithm interventions than would be expected in reality. Still, the here analysed algorithm is optimised to prevent all strikes at minimum delay when assuming perfect predictability of bird movement. More realistic implementations that actually forecast bird tracks are expected to generate higher delays due to increased safety buffers. Since individual delays already exceed acceptable ranges in the validation experiment, future implementations should be restricted to avoid potentially hazardous strikes only. Thus, the impact on the capacity of airports is limited, especially for airports which are operating at high air traffic intensities. The performance of the algorithm when considering limited predictability of bird movement and implementing kinetic energy thresholds is addressed in chapter 5.

4.5. Conclusions

Within this chapter, a collision avoidance algorithm for the prevention of bird strikes by delaying aircraft departing from an airport was verified and its impact on the airport's safety and capacity as well as the economic consequences for the airlines evaluated. The analysis revealed strong safety benefits in terms of prevented bird strikes at a reasonable number of generated delays for departing aircraft within the verification as well as the validation experiment. A rough cost-estimate performed on the verification data set even implied the potential for cost-savings for the airlines.

This study demonstrates the potential of and identified preconditions for implementing operational bird strike prevention in form of a bird strike advisory system for air traffic control. As such it provides a foundation for further research on the operational feasibility of the concept. A first approach is performed in the next chapter. In the there described study, the uncertainty in bird movement is considered and a method to predict future bird tracks is developed.

5

Bird Strike Risk Algorithm

This chapter is based on the publication

I.C. Metz, J. Ellerbroek, T. Mühlhausen, D. Kügler and J.M. Hoekstra, *Analysis of Risk-Based Operational Bird Strike Prevention*, Aerospace **8**, 32 (2021) [125].

SUMMARY

The study of the collision avoidance algorithm in chapter 4 has shown the strong safety potential of a bird strike advisory system in case of perfect bird movement prediction. This chapter takes the research to the next level by taking into account the limited predictability of bird tracks. As such, the collision avoidance algorithm is extended to a bird strike risk algorithm. The risk of bird strikes is calculated for birds expected to cross the trajectory of the departing aircraft and to cause aircraft damage upon impact. By specifically targeting these birds and excluding birds lingering on the runway which are taken care of by the local wildlife control, capacity reductions should be limited and the implementation remain feasible. The extrapolation of bird tracks is performed by simple linear regression based on the bird positions known at the intended aircraft take-off times. To calculate the probability of collision, uncertainties resulting from variability in bird velocity and track are included. The effects of the resulting bird strike algorithm are tested in Monte Carlo simulations including different air traffic intensities and bird movement densities. The imposed departure delays remain tolerable even for high air traffic intensities. However, to achieve a safety-benefit, predicting bird movements based on simple linear regression without considering individual bird behaviour proves insufficient. Hence, in-depth studies of multi-year bird data to develop bird behaviour models and reliable predictions are recommended for future research. This is expected to facilitate an implementation of a bird strike advisory system satisfying both safety and capacity aspects.

5

5.1. INTRODUCTION

The previous chapter researched the influence on traffic flows and the hypothetical maximum safety potential of a bird strike advisory system independent of the effectiveness of any predicting algorithm. For this purpose, perfect predictability of bird movement was assumed. In this chapter, the next step is taken by abandoning the assumption of perfect predictability, and replacing it by a prediction logic. A concept is proposed that calculates the risk of bird strikes, based on the currently detected presence and movements of birds. As such, the collision avoidance algorithm introduced in chapter 4 is extended to a bird strike risk algorithm.

5.2. METHOD

In chapter 4, perfect predictability of bird movement was assumed when developing the collision avoidance algorithm. In this chapter, the outcomes of a more realistic setting including the limited predictability of bird movement are analysed. Therefore, modules for bird movement prediction as well as the calculation of probability and severity of bird strikes were developed. These were implemented in the initial collision avoidance algorithm presented in chapter 4, enhancing it to a bird strike risk algorithm. To evaluate the effects of the resulting algorithm, it was executed for different air traffic patterns and volumes, combining them with historic bird movements from various days throughout the four seasons. The scenarios rescheduled by the algorithm were simulated in fast-time to analyse, how many bird strikes occurring in the initial flight plans the algorithm had prevented. This methodology corresponds to the evaluation procedure of the validation experiment described in chapter 4.2.4.

This section firstly introduces the set-up of the bird strike risk algorithm as well as the method to categorise and to predict bird movement. Thereafter, the evaluation experiment to evaluate the algorithm is described.

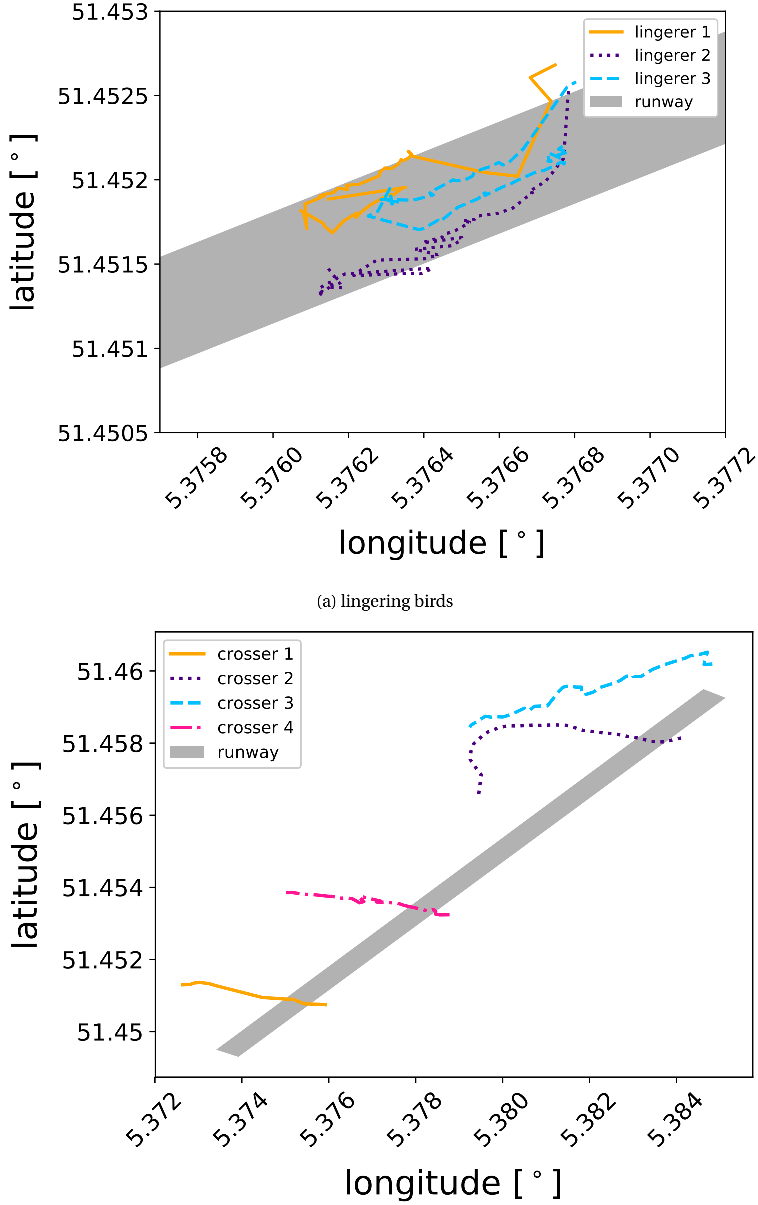
5.2.1. BIRD STRIKE RISK ALGORITHM

To enhance the collision avoidance algorithm to the bird strike risk algorithm, modules to predict bird movement and to calculate risk of collisions were added to the existing module for collision detection and avoidance.

The study in chapter 4 demonstrated that the concept of a bird strike advisory system has the potential to reduce the number of bird strikes while keeping runway capacity when assuming perfect predictability of bird movement. The imposed delays remain acceptable for almost all combinations of air traffic and bird movement mixes. Only when combining very high densities of air traffic and birds, some of the generated delays exceeded an acceptable value. The acceptability threshold was set to ten minutes to keep the ability to comply with potentially imposed ATFM slots [68]. Since it is expected that the number of alerts, and consequently delays, rise when considering the uncertainty in bird predictability, a prioritisation of interventions was recommended.

For this reason, the bird strike risk algorithm presented here targets birds outside the reach of action of Wildlife Control Unit (WCU). An initial analysis on the radar data used for this study revealed two main categories of birds. The first kind is birds lingering close or on the runway centre line, showing erratic flight behaviour. The second one includes birds which cross the runway centre line or its extension and as such the flight path of departing aircraft. Representative tracks for both categories are depicted in Figure 5.1.

In reality, lingering birds as depicted in Figure 5.1a are taken care of by the WCU of the airport. In addition, the bird data which serves as input for this study originates from Eindhoven airport in the Netherlands, which handles very low traffic densities. In the years 2015 and 2016, in which the data was gathered, 80 to 120 military and civil movements took place per day (RNLAF Bird Strike Database. Hans van Gasteren, personal communication, 20 October 2020). On airports with low aircraft activity, more bird activity on or close to the runway is to be anticipated – also with comparable efforts of WCU, as impressively demonstrated during the heavy traffic reductions during the COVID-19 pandemic [4, 59, 85]. However, the scope of this study lies on airports with medium and high traffic intensities where less birds would be expected around the runway. Hence, these lingering birds are considered as over-represented in the input data. Since bird reaction to nearing aircraft is not accounted for in the algorithm, a high number of alerts for these birds and thus a bias in the results is expected. Therefore, lingering birds are disregarded by the bird strike risk algorithm. The second category of birds contains the ones that cross the the trajectory of the departing aircraft. The aircraft follows the runway centre line and its extension until reaching the upper limit of 1,000 m. Hence, on the airport grounds, a crossing of the aircraft trajectory corresponds to a crossing of the runway as illustrated in Figure 5.1b. These are the birds which can hardly be reached by the measures of WCU and where the expected safety benefit of a bird strike risk algorithm is. Consequently, the algorithm focuses on preventing strikes with these crossing birds. Moreover, it targets strikes that are likely to cause damage to aircraft since these impact aviation safety and operations the most.



(a) lingering birds

(b) crossing birds

Figure 5.1: Exemplary bird tracks representative for the categories lingering birds (top) and crossing birds (bottom). Source: avian radar data, recorded at Eindhoven Airport, the Netherlands.

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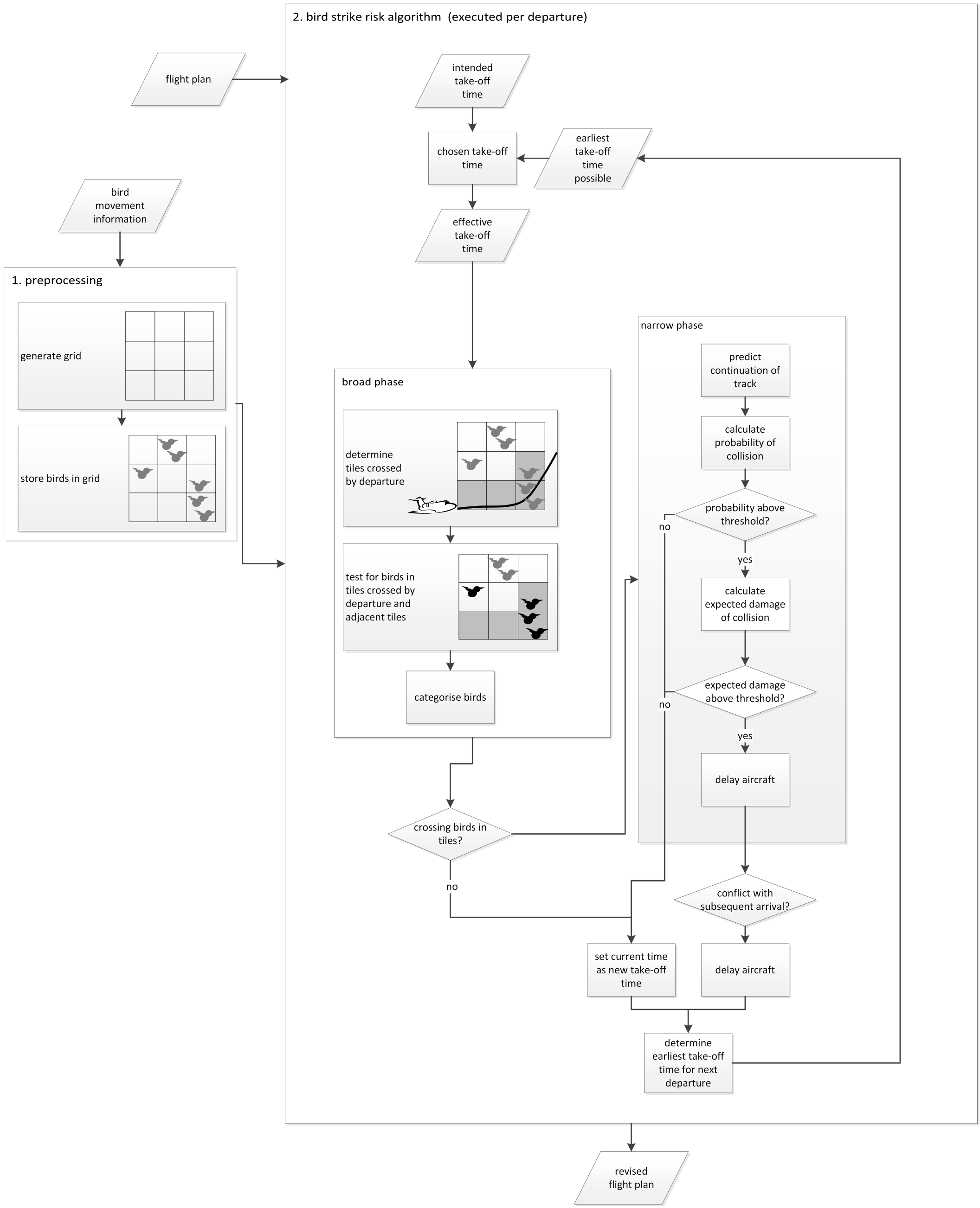

Figure 5.2: Steps of the collision detection and resolution.

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STRUCTURE

The structure of the bird strike risk algorithm is based on the one of the collision avoidance algorithm introduced in section 4.2.1 and is illustrated in Figure 5.2. In an initial step, the grid used for filtering within the *broad phase* is set up and the bird positions of all birds present on the current day are stored. Within the algorithm, only the bird information available at the time of intended take-off will be made available to the algorithm. As for the collision avoidance algorithm, the grid consists of the dimensions latitude, longitude, altitude and time. The filled grid as well as the air traffic flight plan serve as input for the bird strike risk algorithm which is executed per departing aircraft.

The process to calculate the risk of bird strikes is structured into a filtering *broad phase* and a *narrow phase*. In the *narrow phase*, the prediction of bird movement, the calculation of risk and the actual collision detection and resolution take place.

In the *broad phase*, the algorithm determines which tiles the departing aircraft will cross along its flight path. Thereafter, the birds with positions in these as well as adjacent tiles are categorised and filtered for crossing birds. To qualify as crossing, a bird needs at least two position recordings and a heading towards the runway respective the extended runway center line to be classified respectively. This is a relatively open criterion to ensure that all potentially threatening birds are considered. The birds identified as crossing birds are forwarded to the *narrow phase* for the actual collision resolution. If there are no crossing birds in the relevant tiles, the aircraft takes off as intended. Within the *narrow phase*, the tracks of the crossing birds are extrapolated and the CPA to the aircraft trajectory is determined. This step is described in detail in section 5.2.1.

Thereafter, the probability of interference with the aircraft trajectory and the expected impact of the collision are calculated. These steps are described in section 5.2.1. If both probability and severity as well as their product which corresponds to risk exceed previously defined thresholds, the aircraft is delayed until the critical crossing bird passed the runway or turned away. This implementation corresponds to the situation where the aircraft stands at the threshold, ready for departure. The controller, based on the information from the bird strike advisory system, clears the pilots for take-off or delays the provision of the clearance.

This step-by-step implementation of the risk elements probability and severity are beneficial for runtime-efficiency. In addition, it allows to analyse which consequences result from which element. The implementation corresponds to the definition of risk as product of severity and probability. Warnings are generated if both elements exceed their individual thresholds and the risk is larger than their product.

After each delay imposed due to bird strike risk, the algorithm tests whether separation minima to subsequent arrivals are still reached. If this is not the case, a departure is shifted to after the arrival and tested again for potential collisions until the risk of collision with a crossing bird stays below the acceptable limit. Subsequent departures inherit *transferred delays* from their predecessors if their departure times come below the separation minimum to arrivals or previous departures.

FLIGHT PATH PREDICTION

To extrapolate the currently known part of bird trajectories in the *narrow phase* and to determine the CPA, simple linear regression is applied in the horizontal plane. The altitude is constant for each bird since the radar sources do not provide this information. As described in chapter 3.2.2, each bird track is assigned to a constant altitude based on empirically determined distributions [151] in the preprocessing of the data. Consequently, and in correspondence to the input for the BMPs introduced in chapter 3, the bird track relevant for the predictor consists of the dimensions of time, latitude and longitude.

PROBABILITY CALCULATION

To evaluate whether a departure should be delayed due to the presence of crossing birds, the risk of a collision with each relevant crossing bird was calculated. The ICAO defines risk and particularly safety risk as *"the predicted probability and severity of the consequences or outcomes of a hazard"* [101].

Hence, the probability of the collision was determined first, followed by the calculation of the expected severity. If both values exceed given thresholds, the aircraft is delayed by the bird strike risk algorithm. This section describes the probability calculation while the subsequent section addresses the damaging aspect.

As within the collision avoidance algorithm, a collision is defined to take place, when a bird and an aircraft intrude each other's protected volume. The definitions of the protected volumes of bird are identical for the collision avoidance and the bird strike risk algorithms and are first described in section 3.2.5. The implementation of protected volumes of aircraft in the two algorithms mainly correspond. The only difference concerns the rear part of the aircraft. Within the collision avoidance algorithm, it was cut from the protected volume since it barely gets hit by birds [15, 54] (see section 3.2.5). Here, it was included to reduce the number of variables in the analysis of the probability.

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The probability of a collision was calculated as illustrated in Figure 5.3 and as described below. It depends on the expected positions of aircraft and bird at the CPA as well as on the uncertainty of the actual bird location. To account for variability in bird speed, an uncertainty in arrival time at the CPA was added. Lateral deviations along the trajectory were considered by adding uncertainties to the predicted location of the CPA.

The aircraft is set as point mass moving along the runway center line and its extension. Both the protected volumes of the aircraft and the bird are drawn around the bird, resulting in a circle with radius r. The bird is expected at its center, at the Predicted Bird Position (PBP). The actual bird position is defined as Actual Bird Position (ABP). The probability calculation is separated into *parallel* in the direction of the relative speed between bird and aircraft as well as in a *perpendicular* direction. Hence, the respective distances are divided in the respective components as well. The expected offset between the PBP and the ABP is expressed as uncertainty u. The distance between PBP at the time when the CPA is reached by the aircraft is called d_{CPA}.

The probability of collision is then expressed as

$$P = \underbrace{\left(\frac{r - d_{CPA_{parallel}}}{u_{parallel}}\right)}_{\text{parallel}} \cdot \underbrace{\left(\frac{r - d_{CPA_{perp}}}{u_{perp}}\right)}_{\text{perpendicular}} \tag{5.1}$$

Here, the uncertainty $u_{parallel}$ refers to the maximum observed parallel offset between the bird's past trajectory and the corresponding regression line d_{max}, or 20 m, whichever is less. The uncertainty u_{perp} in perpendicular direction is determined by the

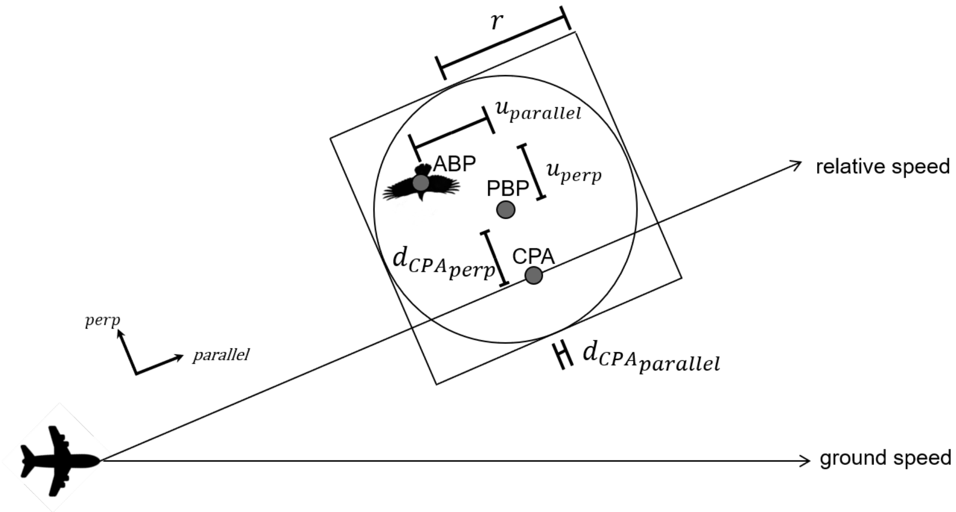

Figure 5.3: Model to calculate the probability of a collision (ABP: Actual Bird Position; CPA: Closest Point of Approach; PBP: Predicted Bird Position; $_{perp}$: perpendicular).

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variability in bird speed. Therefore, the time required to reach the runway from the current position at minimum and maximum speed observed along the trajectory is calculated. The difference is then multiplied by the current bird speed referred to as $v_{bird_{nom}}$ to obtain a distance.

With

$$u_{parallel} = min(d_{max}, 20m) \tag{5.2}$$

and

$$u_{perp} = v_{bird_{nom}} \cdot (t_{max} - t_{min}) \tag{5.3}$$

and

$$r = \underbrace{r_{PV_{ac}}}_{\text{protected volume aircraft}} + \underbrace{r_{PV_{bird}}}_{\text{protected volume bird}} \tag{5.4}$$

the probability of collision is calculated as

$$P = \underbrace{\left(\frac{(r_{PV_{ac}} + r_{PV_{bird}}) - d_{CPA_{parallel}}}{d_{max}}\right)}_{\text{parallel}} \cdot \underbrace{\left(\frac{(r_{PV_{ac}} + r_{PV_{bird}}) - d_{CPA_{perp}}}{v_{bird_{nom}} \cdot (t_{max} - t_{min})}\right)}_{\text{perpendicular}} \tag{5.5}$$

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Since the regression line of the bird crosses the aircraft trajectory and thus passes the CPA, the distance between PBP and CPA is zero at the expected time of collision. Consequently, the equation simplifies to

$$P = \underbrace{(\frac{(r_{PV_{ac}} + r_{PV_bird})}{d_{max}})}_{\text{parallel}} \cdot \underbrace{(\frac{(r_{PV_{ac}} + r_{PV_{bird}})}{v_{bird_{nom}} \cdot (t_{max} - t_{min})})}_{\text{perpendicular}} \tag{5.6}$$

SEVERITY CALCULATION

To prove their airworthiness, various aircraft components have to demonstrate resistance towards the impact of bird strike before being certified by the aviation authorities [76]. For all components to be tested, the determining criterion to pass the tests is represented as a kinetic energy. Therefore, kinetic energy served as input for the calculation of expected severity in this study. The certification requirements by the EASA were used as reference as they provide a benchmark for comparison. Since the focus of the study lies on commercial aircraft, the requirements for *Large Aeroplanes* [64] were referred to. Impact resistance to different numbers and sizes of birds has to be demonstrated for windshields and the structure. In addition, the engines have to undergo engine ingestion tests, as described in section 2.5.3. The criteria for the different aircraft components are presented in Table 5.1.

The strictest regulations concern the engines. These have to withstand the kinetic energy defined in Table A.2 without resulting in a *Hazardous Engine Effect*. This definition includes, among others, uncontrolled fire, significant thrust in the direction opposite to that requested by the pilot or complete inability to shut the engine down [63]. The complete definition of *Hazardous Engine Effects* is provided in Appendix A.

Kinetic energy is defined as

$$E_{kin} = \frac{1}{2} \cdot m \cdot (v)^2 \tag{5.7}$$

with m equals mass in kilograms and v equals velocity in metres per second.

In the context of the certification requirements, the mass of the bird(s) involved and the aircraft velocity are relevant. The bird mass to be used within the certification require-

Table 5.1: Kinetic energy criteria as defined by CS 25 / 14 CFR part 25 [65, 78]. 8,000 ft correspond to 2,438 m, 200 kts equal 103 m/s.

Component	**Kinetic energy criterion**
Windshield	$E_{kin} = \frac{1}{2} \cdot 4lb \cdot (v_{reference})^2$
Structure	$E_{kin} = \frac{1}{2} \cdot 4lb \cdot (0.85 \cdot v_{reference_{8000ft}})^2$ $E_{kin} = \frac{1}{2} \cdot 4lb \cdot (v_{reference_{sealevel}})^2$
Engine	$E_{kin} = \frac{1}{2} \cdot m_b \cdot (200kts)^2$

ment test depends on the specific test conditions, i.e. the size of birds and whether individual or flocking birds are considered. Moreover, the surface of the engine inlet throat is relevant. The highest and thus most critical test mass from the EASA test conditions of 2.7 kg was selected as reference for this study. [63].

To determine the expected kinetic energy and thus the severity of a predicted bird strike within this study, the expected aircraft velocity at the CPA and the bird mass obtained from the processing of bird information served as inputs.

5.2.2. SPECIFICATIONS

The bird strike risk algorithm was configured as follows. Since aircraft trajectories are expected to be perfectly predictable, they were logged in BlueSky. All simulated aircraft were of the type A320-200. Their performance was calculated using the BADA model, version 3.12 [67]. During lift-off between 0 m and 15 m altitude, trajectories were logged with a frequency of 10 Hz, to account for rapid changes in altitude occurring in that phase. The remaining part of the trajectories was logged with a frequency of 2 Hz. Between logged positions, linear interpolation was performed for both aircraft and birds. This procedure corresponds to the one used for the verification and validation of the collision avoidance algorithm described in section 4.2.3. The logging frequencies conform with the ones which were found to balance the requirements on precision and runtime efficiency best (compare 4.3.1).

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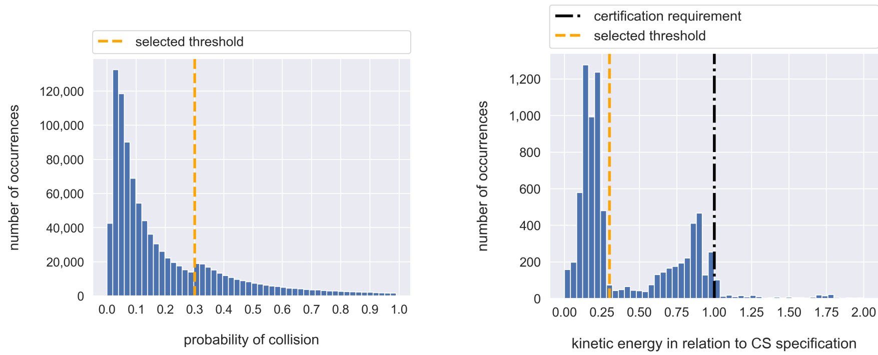
The tile dimensions of the grid used to filter birds in the *broad phase* amounted to 1,000 m in lateral width, 33 m in height and 60 s in time. Recordings of bird tracks from an avian and a weather radar were used as inputs and stored in the respective tiles (cf. section 5.2.3). According to the manufacturer of the avian radar, tracked birds are expected to have landed if not observed for the past five seconds (Remco Kabos, Robin Radar, personal communication, 26 May 2020). Within the implementation of the algorithm, a safety buffer of five seconds was added. Birds recorded by weather radar were considered if they have appeared at least once within the last ten minutes to account for their low update rate of five minutes on average.

To determine a threshold for the probability from which aircraft would be delayed, the probabilities of conflicts for one million combinations of the parameters involved in equation 5.6 were performed. The ranges of individual parameters were obtained from historical data. The resulting probabilities are depicted in Figure 5.4a. It was decided for a probability threshold of 0.3. With this setting, about 25 % of strikes involving crossing birds would exceed the threshold.

To define a reasonable severity threshold, the magnitude of impacts observed in the validation simulations performed in chapter 3 was evaluated. Therefore, the kinetic impact of these strikes was normalised with the kinetic energy aircraft engines have to withstand to comply with the EASA regulations. The resulting distributions are shown in Figure 5.4b. As for the probability criterion, 0.3 was selected as threshold which can be considered as highly conservative. However, since even minor strikes cause operational and repair costs [52], these should be considered by the algorithm.



(a) observed probabilities

(b) observed kinetic energy, normalised to the impact criterion of the aviation authorities

Figure 5.4: Distributions of probability (left) and kinetic energy as well as the selected thresholds (right). Note the different scaling.

When multiplying the factors of probability and severity, a risk threshold of 0.09 results. Consequently, aircraft are held back, if the probability and severity of a strike each exceed values of 0.3 and the resulting risk is higher than 0.09. The thresholds are all set relatively low to ensure a sufficient number of algorithm interventions to be evaluated.

5.2.3. EVALUATION EXPERIMENTS

To evaluate the bird strike risk algorithm , an approach involving Monte Carlo simulations was pursued. Its description is followed by the presentation of the input data as well as the specifications of the simulations.

ANALYSIS

The following three steps were performed for the analysis of the bird strike risk algorithm. They correspond to the steps to evaluate the collision avoidance algorithm (cf. section 4.2.2). First, initial flight plans with various traffic intensities and patterns were simulated alongside bird movement from various days in fast-time in BlueSky. With this step, the strikes to be prevented and as such the safety potential was determined.

Second, the algorithm was run for the combinations of flight plans and BMPs. The impact of the algorithm on capacity and the delays induced was obtained from the resulting rescheduled flight plans. Third, the rescheduled flight plans were simulated alongside the BMPs in BlueSky to test for the number of strikes remaining after bird-strike avoidance and to analyse false alerts. These were identified by comparing the strikes prevented with the strikes that took place prior to the intervention of the algorithm.

It was hypothesised that the algorithm reduces the number of bird strikes with crossing birds. Since lingering birds are disregarded, the average number of strikes involving these birds should stay constant.

The thresholds for intervention are set conservatively. Hence, also birds with a small risk of collision can cause delays. Still, due to focusing on crossing birds, the delays should remain within tolerable limits.

Table 5.2: Shares of birds (n = 1,906,240) and caused strikes (n = 69,463) in the different altitude bands.

	0 m - 200 m	**200 m - 1,000 m**	**200 m - 400 m**	**400m - 1,000 m**
share of birds	7 %	93 %	59 %	34 %
share of strikes	79 %	21 %	13 %	8 %

INPUT DATA AND SPECIFICATIONS

To obtain representative results, the flight plans randomised for the validation experiment (cf. section 4.2.4) were used. They contain 1,000 randomisations for the four departure shares of 25 %, 50 %, 75 % and 100 % of a high and a medium air traffic scenarios, resulting in a total of 8,000 air traffic scenarios.

To evaluate the reproducibility of the algorithm, the flight plans were split into a baseline and a validation data set. 80 % of all flight plans per departure share were used in the baseline, the remaining 20 % of flight plans in the validation. They each were combined with BMPs for high, medium and low bird strike risk. This led to 9,600 scenarios for the baseline and to 2,400 scenarios for the validation per air traffic intensity.

The BMPs used for the validation experiment of the collision avoidance algorithm (cf section 3.2.2) were used for the baseline scenarios. For the validation scenarios, BMPs were generated from the same calendar weeks as the BMPs of the baseline.

When assuming perfect predictability of bird movement, birds recorded by the weather radar were assumed to fly straight through the considered airspace (cf section 3.2.2). To reflect unpredictability in bird behaviour, the following uncertainty elements were included here. The weather radar data is updated in five minute-intervals and average bird directions and velocities can be retrieved [44]. For each provided update, the birds present were assigned a new velocity and direction. To allow for uncertainties in bird behaviour, the actual update time of each bird was varied. A normal random distribution was used for all variations. The possible range of velocities lay within the observed standard deviations of $6m/s$, or $1m/s$, should the randomly picked value fall below. The heading change was distributed $\pm 15°$ around the average heading change observed by the radar. The appointed update times lay in a range of $90s$ around the actual update time. The assignment of flight altitudes, bird mass and number of birds in flocks was performed by following the procedure described in section 3.2.2.

In the initial studies described in chapters 3 and 4, tracks up to 1,000 m were integrated. However, the validity of the bird tracks incorporated from the weather radar data is limited since they are artificial. In addition, while there are many birds present in that airspace layer, only few of them cause collisions, as Table 5.2 displays. While the vast majority of birds included in the simulations fly above 200 m, it is the birds below that altitude that most often cause collisions. Consequently, to include weather radar birds with a representative share without challenging memory-requirements too much, weather radar birds are considered from 200 to 400 m.

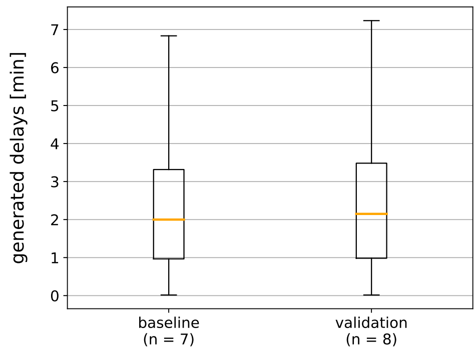


Figure 5.5: Duration of Delays imposed by the algorithm focusing on crossing birds (n: average number of delays per day).

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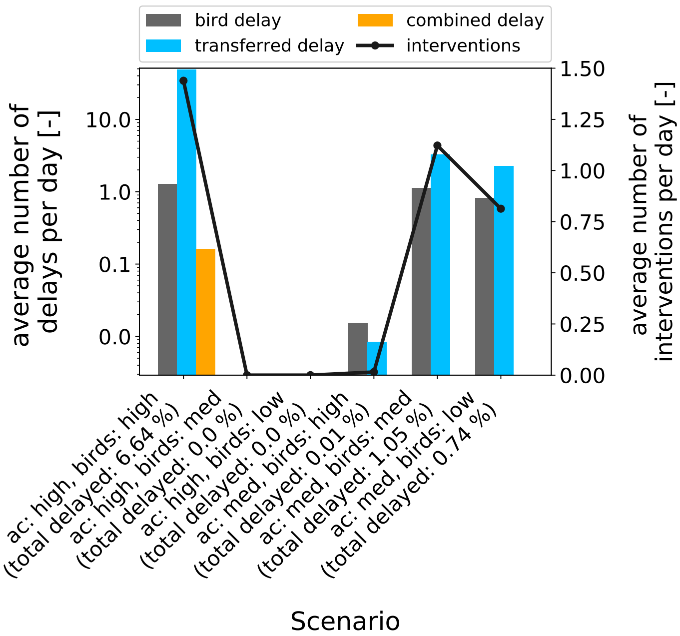
5.3. RESULTS

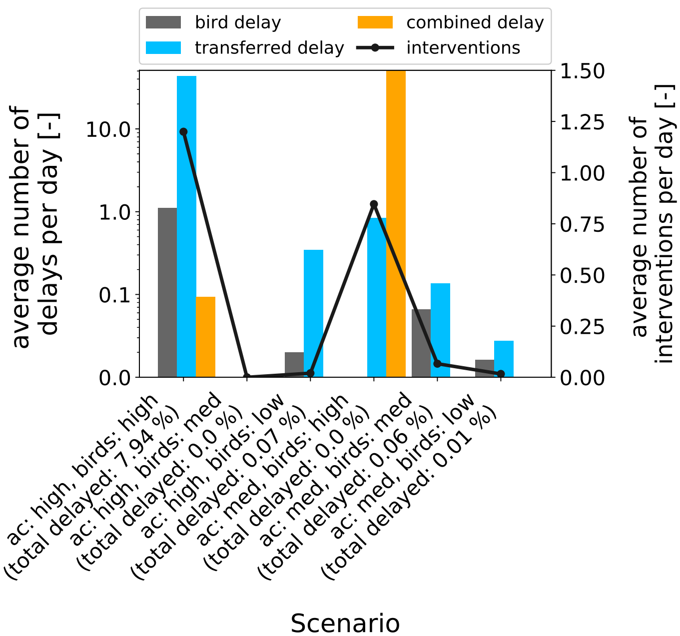
The bird strike risk algorithm presented in this chapter focuses on preventing strikes with birds crossing the flight path of departing aircraft and which are expected to cause damage to the aircraft. Birds lingering on or close to the runway are excluded. The limitation to prevent potentially damaging strikes was performed to find a balance between safety and capacity, limiting the induced delays to a reasonable level.

Within the evaluation, the number of interventions and the resulting delays were considered first. Figure 5.5 provides an overview of the imposed delays. Their distribution is similar between the baseline and the validation with the vast majority lying around seven minutes. Delays above ten minutes and as such above a tolerable level were outliers. Their share amounted to 0.8 % of delays in the baseline and 0.5 % in the validation. The average number of daily delays amounts to seven in the baseline and to eight in the validation. All aircraft of all scenarios were able to depart within the designated airport opening hours. Hence, the capacity was never impaired.

To gain more insight into the origin of delays, Figure 5.6 depicts the average number of interventions per day and scenario as well as the average number of generated delays. The average number of interventions per day and scenario is very low. In some scenarios, even no intervention at all took place. One intervention by the algorithm results in up to six delays in total. As in the evaluation of the collision avoidance algorithm, delays are grouped into *bird delays*, *transferred delays* and combined delays. The delays additional to the ones caused to prevent a bird strike (*bird delay*) are delays inherited from a previous departure (*transferred delay*). If an aircraft with a *transferred delay* receives a *bird delay*, it is called *combined delay*. *Transferred* and *combined delays* appear mostly in the high air traffic scenarios. There the flight plans are denser and a rescheduling of a departure is more likely to cause domino effects for subsequent departures. More *transferred delays* than *bird delays* take place in all scenarios except for the combination of medium air traffic intensity with high bird strike risk in the baseline.



(a) baseline



(b) validation

Figure 5.6: Number of interventions and generated delays by type for the different combinations of air traffic intensities and bird strike risk within the baseline and the validation (note logarithmic scale for delays; ac: aircraft, med: medium).

Table 5.3: Bird strike rates (number of collisions per 10,000 flights).

Case	Original flight plans	Revised flight plans	Difference
baseline	57.80	58.02	0.8 %
validation	43.14	43.05	0.2 %

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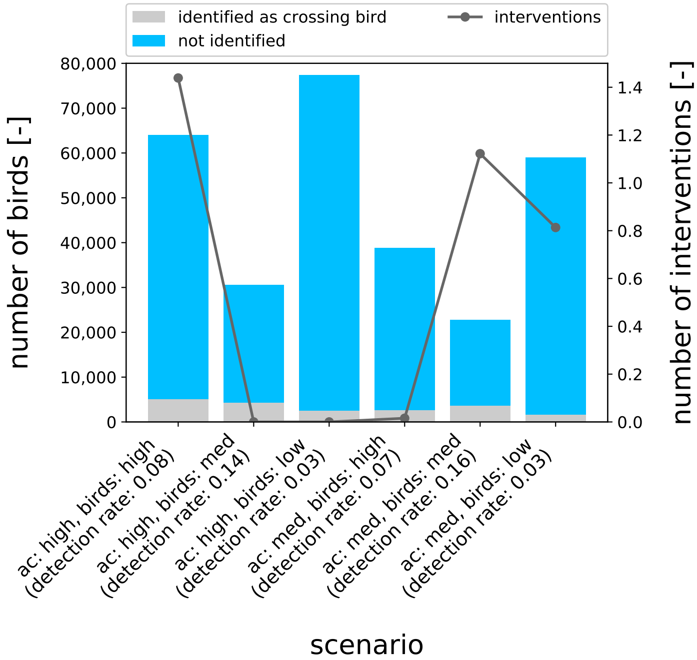
To evaluate whether an intervention by the algorithm was successful, aircraft with a *bird delay* and without any *transferred delay* from a previous departure were considered. Thus, they experienced the identical bird situation, which made them comparable. Testing whether these aircraft experienced a bird strike after having received a bird delay in the revised flight plan served as measure for successful interventions. For both the baseline and the validation, the share of comparable flights amounted to 95 %. The algorithm prevented 139 collisions with crossing birds in the baseline and 9 in the validation. In the baseline, three of these flights experienced a strike with another bird than the targeted one. All other departures delayed due to bird strike risk departed collision-free. All comparable correct interventions were successful with respect to the target birds.

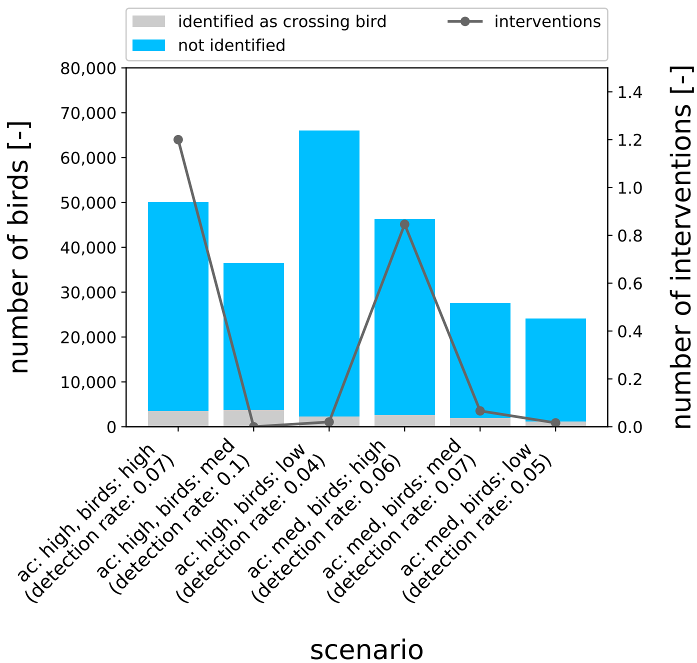
The bird strike rates, corresponding to the number of strikes per 10,000 flights, for the original as well as the revised flight plans can be found in Table 5.3. In the baseline, the strike rates slightly increases by 0.8 %. In the validation, it decreases by 0.2 %. When normalizing the number of prevented strikes by 10,000 flights, similar to the bird strike rate, the baseline has a prevention rate of 70 and the validation of 20. Still, the bird strike rates in the baseline are higher than in the validation.

To analyse these opposing trends, the number of interventions were compared against the number of birds present in the airspace as well as the ones identified as crossing birds. When analysing the results which are presented in Figure 5.7, it has to be kept in mind that the bird scenarios were selected based on the strike risk they hold rather than number of birds (see section 5.2.3). The number of interventions and the number of birds present do not correspond well. For example, most birds occur in the combination of high air traffic intensity and low bird density in the baseline and the validation, but (almost) no interventions take place. Also between the number of identified birds and number of interventions, there is limited consistency. Moreover, even though the corresponding bird densities in the baseline and the validation originate from the same calendar weeks, numbers of birds as well as the detection rates vary.

The decision to delay an aircraft depends on the determined values for risk as well as its factors probability and severity. If the three of them exceed the selected thresholds, an algorithm intervention is triggered. To evaluate the resulting interventions in detail, the analysis is performed individually for probability and severity. Their distribution for strikes where the algorithm intervened correctly or falsely are shown in Figure 5.8. Moreover, the distributions where the algorithm did not intervene and the aircraft then collided with birds are presented. Figure 5.8a depicts the distribution of probabilities. They all are above the threshold of 0.3 for correct and false interventions, as required for the triggering of the algorithm. The spreads are larger for false alerts, reaching higher

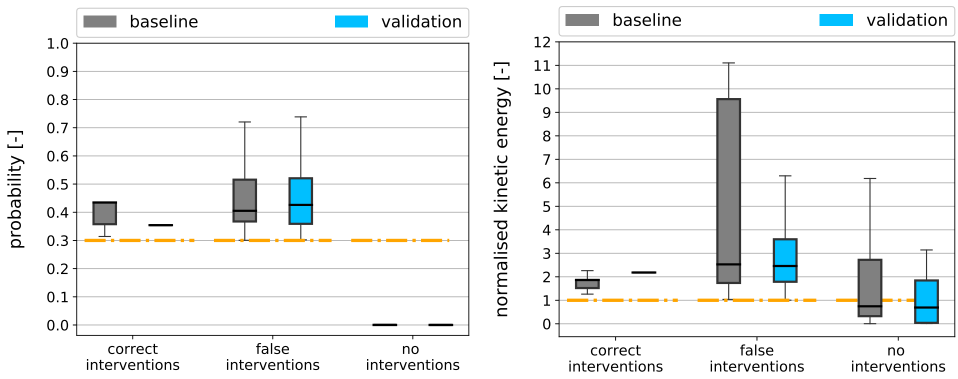


(a) baseline



(b) validation

Figure 5.7: Number of birds and number of interventions for the different combinations of air traffic intensities and bird strike risk within the baseline and the validation (ac: aircraft, med: medium).



(a) probability

(b) kinetic energy

Figure 5.8: Distributions of probability and kinetic energy normalised by the certification specification requirements for impact resistance. Dashed lines represent the thresholds for triggering an algorithm intervention. This is only triggered when the thresholds of probability as well as kinetic energy are exceeded.

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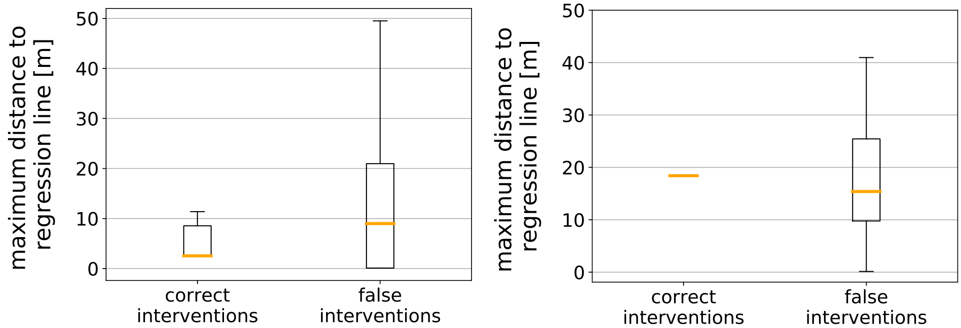
probabilities than in the case of correct alerts. They are comparable between baseline and validation in case of false alerts. In case of correct alerts, the spread is much smaller for the validation than for the baseline. For missed strikes, the probabilities were just slightly higher than zero and as such way below the threshold to trigger an intervention.

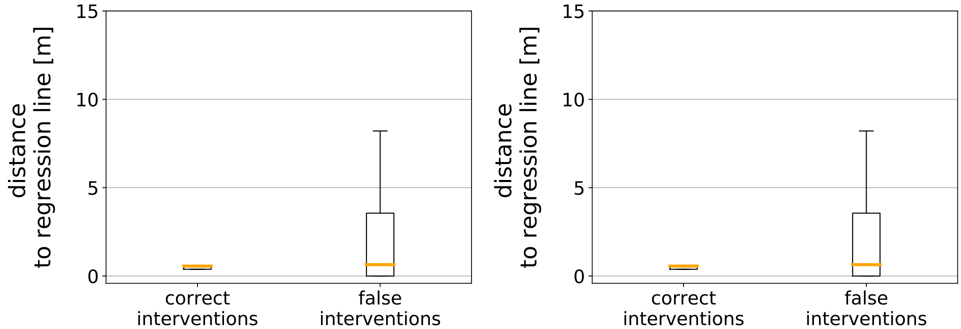
Figure 5.8b illustrates the second risk element, the severity of strikes. The predicted kinetic energy was normalised by the kinetic energy required to tigger an algorithm intervention. Hence, the threshold lies at one. The spreads of the baseline is higher than for the validation for all three alert types. The lower boundary of the predicted kinetic energies lies higher than for false alerts for correct alerts. The majority of strikes which were missed by the algorithm exceeded the threshold of kinetic energy. However, due to the small predicted probabilities as seen in Figure 5.8a, no intervention took place.

The last part of the analysis focused on the bird movement prediction which underlies the determined probability of a strike. Its quality was evaluated by considering correct and false alerts. As introduced in Equation 5.6, the probability of collision depends on the maximum distance from the regression line d_{max} and the variation in bird speed along the trajectory. The latter is expressed as time interval in which the bird is expected to cross the aircraft trajectory. To analyze the precision of predicted bird location, the maximum perpendicular distances between the bird positions known at the time when the future trajectory was predicted and the regression line, d_{max}, were analysed. Their distributions for correct and false alerts are illustrated in Figure 5.9. For both alert types, there is a wider spread at a lower level in the baseline than in the validation. While the distributions of false alerts are to some extent comparable between the baseline and the validation, the distribution for correct alerts is much wider in the baseline, with a relatively high median of about 20 m in the validation. Figure 5.10 shows, how far from the regression line the bird was at the time of the CPA. In the baseline, the birds causing correct alerts are much closer to the regression line, with a small spread of values only. Also in the validation, the spread is smaller than for the validation. However, the majority of



(a) baseline (b) validation

Figure 5.9: Variation of maximum distance from the regression line at the time of prediction.



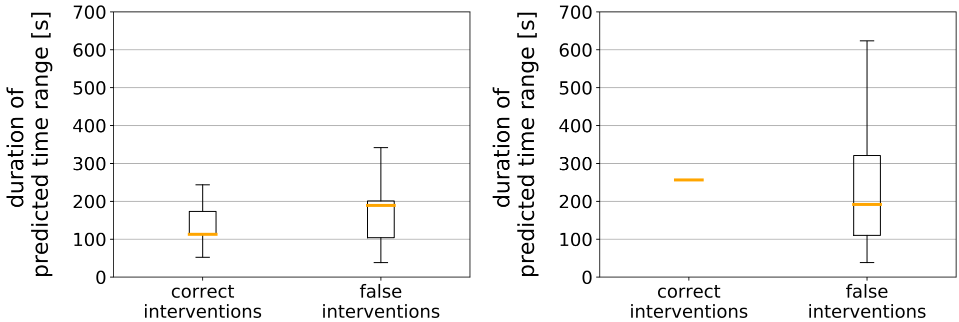
(a) baseline (b) validation

Figure 5.10: Distance from the regression line at the time of CPA.

birds triggering false alerts are closer to the regression line. The majority of offsets for false and correct alerts lay well below ten metres. All offsets were smaller than d_{max}.

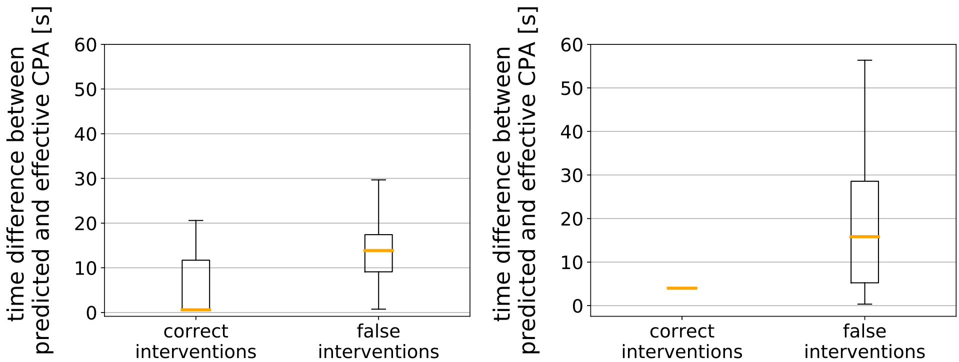
To evaluate the precision of predicting the time of arrival at the CPA, the period between the earliest and latest expected arrival time is shown in Figure 5.11. In the baseline, the spreads for the false alerts are slightly higher than for the correct interventions. In the validation, it is much higher for the false interventions. However, there are also smaller time intervals than observed for the correct alerts. The predicted time ranges span up to 300 s for correct alerts and up to 650 s for false alerts. This indicates a high variability in bird velocities, especially for birds causing false alerts.

When considering the difference between predicted and effective time of the CPA depicted in Figure 5.12, the much higher precision for the correct alerts becomes visible for both, the baseline and the validation. While birds which were correctly predicted to collide arrived with a maximum time offset of 20 s at the CPA, the difference amounts up to almost 60 s for false alerts. The birds always arrived either earlier than or within the predicted time range. When considering correct alerts, 33 % of birds arrived earlier, 67 % within the predicted time range in the baseline. In the validation, all of these birds



(a) baseline (b) validation

Figure 5.11: Duration of time intervals in which the bird was expected to cross the aircraft trajectory.



(a) baseline (b) validation

Figure 5.12: Time difference between the birds' predicted and effective time of arrival at the CPA.

arrived within the predicted time range. Regarding the false alerts, 16 % of birds arrived earlier and 84 % within the predicted time range in the baseline. In the validation, 13 % of birds arrived earlier than and 87 % within the predicted time range.

5.4. DISCUSSION

In this chapter, the effects of a bird strike advisory system which delays departing aircraft in case of a bird strike predicted with high likelihood and the potential of damaging the aircraft were evaluated. The previous chapter had demonstrated the strong safety potential of a collision avoidance algorithm assuming perfect predictability of bird movement. In this chapter, the algorithm was enhanced with a module to predict bird movement and to calculate the risk of bird strikes.

In the optimised settings of the initial study presented in chapter 4, where the algorithm aimed at preventing strikes with all birds in the airport environment, imposed delays could exceed acceptable levels for tight flight plans. This indicates the need for prioritising alerts for highly likely and potentially damaging strikes to keep delays and impact on runway capacity reasonable.

Since birds lingering on and close to the runway were identified as being over-represented in the input bird data and, in addition, are already in the scope of currently implemented prevention measures implemented by WCUs, they were excluded for the bird strike risk algorithm developed in this chapter. Hence, the algorithm focuses on strikes with birds predicted to cross the runway centre line and its extension. Moreover, only those of them, which were expected to cause damage to the departing aircraft, caused an intervention of the algorithm.

The consequent reduction of interventions resulted in acceptable delays imposed on departures. Only 0.8 % of delays exceeded the acceptable threshold of ten minutes in the baseline, 0.5 % in the validation. The maximum observed delay amounted to 21 minutes, representing an outlier. All aircraft were able to depart within the airport opening hours. Hence, the airport capacity could be maintained. This was true even though the thresholds to trigger an intervention were set relatively low to obtain a sufficient number of interventions for the analysis. The threshold values amounted to 0.3 for probability and severity, respectively, and to 0.09 for their product.

in real operations, especially the severity-criterion could be adjusted if interventions impair traffic flows too strongly. However, it should be kept in mind that the severity of a strike can also be increased due to e.g. hits of multiple birds into different aircraft components. This was not considered in this study. Hence, additional research might be required to refine the definition of the severity criterion itself.

The algorithm succeeded in preventing bird strikes. Still, the overall bird strike rates did not significantly change for the revised flight plans. This resulted from strikes experienced by aircraft inheriting *transferred delays* from departures which were delayed due to bird strike risk. As such, the missing positive safety effect is connected to one-sided effects of changing the take-off time of an aircraft. When an aircraft, which originally would have departed collision-free, is rescheduled due to a false alert, either departs collision-free as well or experiences a collision. Collisions can therefore only be added but not removed for aircraft that initially took off without a bird strike. Hence, in case of birds whose flight path is hard to predict, the additional strikes happening to aircraft that experienced a *transferred delay* can compromise the safety benefits by correctly prevented strikes. These additional strikes were either caused by birds that could not be seen by the algorithm due to taking off after the aircraft or due to an insufficient number of known positions to predict their track. Consequently, the hypothesis of a reduction in bird strike rates could not be confirmed for this implementation.

The majority of bird strikes where the algorithm decided against intervention, exceeded the damage criterion. The reason is that their probability stayed below the respective criterion. Hence, the algorithm did not intervene. Since the probability threshold was set to a relatively low value of 0.3, the inability to meet that threshold implies an insufficient precision in the prediction of bird movements. The prediction logic builds on linear regression of the bird track known at the time of intended aircraft take-off, including uncertainty buffers to allow for lateral deviations and speed variation along the track. In the parallel direction, the distance between the bird and the predicted track in form of a regression line is relevant. For both correct and false alerts, the offsets at the time of CPA were low with a maximum of 15 m for false alerts. Since the sum of the radii of the protected volumes of the involved aircraft and birds amounts to ca 20 m, the offset lies still within the protected volume. However, there were also offsets in the perpendicular direction, where the predicted time interval at the CPA is relevant. The prediction in that direction was more imprecise as the results show. Even for correct alerts, the predicted intervals lasted up to 300 s. For false alerts, they spread up to 650 s. Since the time intervals are calculated based on the minimum and maximum bird speeds along the known part of the trajectories, this indicates high variability in bird velocity, resulting in a high uncertainty, when the bird will cross the flight path of the aircraft. This is indicated by the offset between the predicted and effective arrival of the birds at the CPA. Their maximum ranges to 20 s for correct interventions and to 60 s, which is still large, but smaller than the wide spread of time ranges suggest. The comparison of the results in the parallel and perpendicular directions reveals that the predictability of flight direction is higher than the one of bird velocity.

Adjusting the calculations by basing the probability in the perpendicular direction on the expected time of arrival at CPA rather than the predicted time interval could slightly improve the results. However, due to the relatively large offsets of up to 60 s considering the false alerts, the success of that measure might be limited. To achieve more realistic predictions, a more sophisticated approach is recommended. As such, deep learning on multi-year data of bird movement could be performed to develop site-specific bird movement models. Since radar is limited in the ability to distinguish between individual bird species, the inclusion of data from different sensors such as video- or infrared-based technology or even observations performed by humans or drones should be considered.

The avian radar data used in the entire PhD study was limited in its range. Hence, tracks of birds flying in higher altitudes were modelled from bird densities obtained from weather radar. Due to the small update rate of this radar type of five minutes, a small change in heading can quickly lead to an increasing deviation from the predicted direction of flight and thus contribute to the imprecision of the selected prediction approach. Recently, the range of avian radar technology has increased to cover more of the critical areas outside the airport boundaries. Incorporating these data is expected to increase the prediction results when using the method presented in this chapter. In addition to the range increase, modern avian radar provide height information. As such, avian radar data currently available allows the thorough study of bird movement supporting the development of more sophisticated methods to predict bird movement as described above.

The number of interventions varies among the combinations of air traffic and bird movement intensities. A higher abundance of birds or even a higher number of crossing birds does not necessarily imply a higher number of interventions by the algorithm. The variation of flight plans is, especially in the high air traffic intensity scenarios, limited by the large number of flights that have to be performed within the airport opening hours. Hence, the main variation is achieved by the different bird movement flight plans. This is demonstrated by the difference of factor 1.3 between the bird strike rates in the baseline and the validation. This difference occurs even though the bird movement information for the same bird densities in the baseline and the validation originate from the same calendar weeks. Hence, the bird abundance and the behaviour of birds leading to risks for air traffic can differ strongly between consecutive days.

The variability between baseline and validation is also observed in the other metrics. The differences of prediction precision (Figures 5.9 to 5.12) are larger for the validation. In contrast, the calculated probabilities and damaging potentials spread wider for the baseline in all cases. The latter could result from the larger data set used in the baseline. However, since the predictions themselves spread wider for the validation, this rather indicates the high variability in bird movement even within one calendar week.

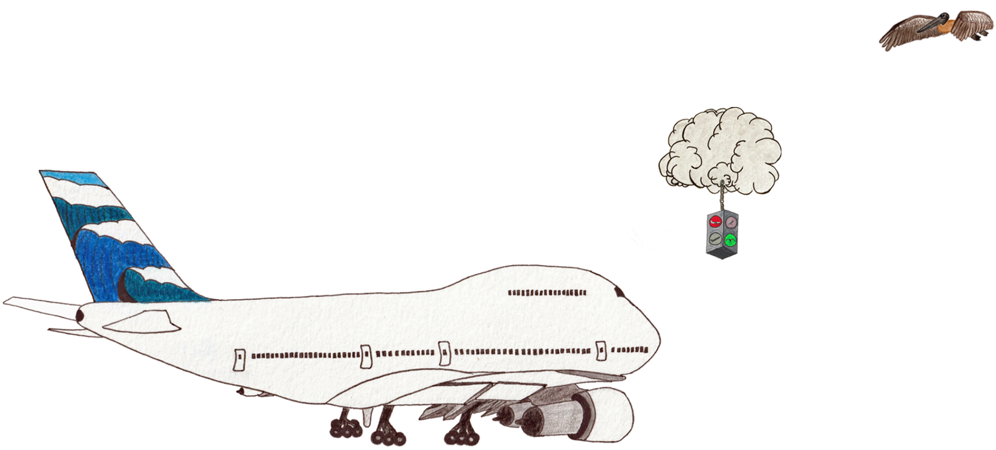
Factors influencing the bird strike risk from the bird perspective might include different weather conditions. Since bird movement information was selected from days with little or no precipitation to get maximum detection rates by the radar (see section 3.2.2), other factors such as wind, temperature, cloudiness or humidity might play a role. To achieve a prediction, when the bird strike risk is highest even within the same season and when algorithm interventions are most appropriate, a more in-depth study of the dependencies of bird strike rates of weather conditions is needed. This knowledge could be useful for refining the algorithm and for implementing relative thresholds to trigger interventions depending on the current situation.

5.5. CONCLUSIONS

This chapter evaluated the impacts on the safety and capacity of an airport when implementing a bird strike advisory system, which calculates the risk of bird strikes by predicting tracks of birds and estimating the impact of a collision. Simple linear regression was applied on the known parts of the tracks to extrapolate their future path. The algorithm focuses on birds expected to cross flight path of aircraft and generate aircraft damage upon collision. The study has demonstrated that a precise prediction of bird movement is essential to enhance aviation and avian safety with a bird strike advisory system. The selected approach based on linear regression does not suffice this purpose even when probabilistic aspects are taken into account. However, it has been shown that with a reasonable number of interventions, airport capacity can be kept even at high air traffic intensities. To find and implement suitable models to more precisely predict bird movement and as such to strongly enhance the number of correct alerts, deep-learning on multi-year data of bird movement and a shift from risk of individual bird strikes to cumulative bird strike risk is recommended to develop a feasible implementation of a bird strike advisory system.

6

Discussion and Conclusions



SUMMARY

To evaluate the feasibility of a bird strike advisory system for the prevention of bird strikes, a modular approach was pursued within this PhD research. This chapter revisits the individual steps described in the previous sections. By connecting and discussing the results obtained throughout the dissertation, overall conclusions are drawn. The chapter closes by presenting the contribution of the thesis to the research field of bird strike prevention and recommendations for future work.

6.1. MAIN FINDINGS

Involving pilots and air traffic controllers in the bird strike prevention process has been discussed as a vital next step to lower the risk of collisions between birds and aircraft. In this thesis, the focus was on the concept of a bird strike advisory system for air traffic control. The primary research question to be answered was

> **Main Research Question**
>
> How feasible is the implementation of an air traffic control advisory system for the prevention of bird strikes?

To answer this question, a modular approach was followed throughout this thesis. The results of each section are combined here and discussed within the context of the dissertation leading to the final conclusions and the answer to the research question.

6.1.1. MODELLING OF BIRD STRIKE RISK

The aim of the dissertation was to evaluate the feasibility of a bird strike advisory system on an airport level, examining its effects on safety and capacity. To enable a research set-up for large-scale experiments involving different combinations of aircraft flight plans and bird movement data, BlueSky Open Air Traffic Simulator was extended in a first step, as presented in chapter 3. Modules to represent bird movements and to detect collisions as well as near miss occurrences between birds and aircraft were developed and integrated into the simulator. Data from avian and weather radar was used to include bird movement information in the entire critical area from ground up to 1,000 m.

Based on historic observations, species distributions and flock formation models were created for diurnal and nocturnal flight. Moreover, a method to derive individual bird tracks from the information provided by weather radar was developed. Finally, protected volumes for individual birds and flocks as well as for aircraft were defined. These models also served as inputs for the collision avoidance and bird strike risk algorithms.

Monte Carlo simulations combining different air traffic flight plans and BMPs showed that the bird strike risk is over-represented threefold within the simulation environment. Next to limitations in the modelling of birds, their high presence within the input data and missing reactions to nearing aircraft contribute to that result. In addition, not all bird strikes are reported in reality, leading to an underestimate of the real risk and an increase in the offset of the simulation results. However, since these are reproducible, they can serve as baseline to represent the bird strike related safety-potential of an airport.

The risk of bird strikes can only partially be related to the season. The simulations showed that especially the data of the month of June, where there is a peak in bird strikes due to first flights of newborn and thus inexperienced birds, biases the correlation between bird abundance and collision risk. Even when excluding June, the correlations remain weak. However, when including the near miss occurrences – aircraft and birds getting closer to each other than 50 m – and thus strongly increase the number of events, the correlations become moderate. Hence, to some extent, bird abundance does influence the risk of collisions after all.

The simulation platform in its extended state is based entirely on open sources and is freely available [122]. Bird strike-related investigation can make use of the tool, including individual air traffic and bird movement data sets. For example, effects of mitigation measures on bird presence or impacts of bird strikes such as described in Appendix A can be analysed by including own data. Due to the open character of the simulation platform, it can be tailored to satisfy the specific requirements of any study.

6.1.2. COLLISION AVOIDANCE ALGORITHM

6

To represent a bird strike advisory system delaying departing air traffic in case of high predicted risk, a bird strike risk algorithm was developed in two stages and the output tested with Monte Carlo Simulations in the BlueSky Open Air Traffic Simulator. Chapter 4 introduced the collision avoidance algorithm which represents the core of the bird strike risk algorithm. The general structure of the algorithm is established in a modular way. This allows the implementation of additional elements such as the prediction of bird movements. Furthermore, it facilitates the enhancement of the collision avoidance algorithm to the bird strike risk algorithm by extending it with the different elements of the risk calculations while ensuring comparability of results.

With its division in a filtering and a collision resolution phase, the collision avoidance algorithm is tailored to facilitate quick conflict-resolution between individual aircraft and large numbers of birds, as can be present in the extended airport environment. On the one hand, this is important to achieve reasonable run times when running high numbers of scenarios as performed throughout this thesis. On the other hand and in the long term, when considering the actual implementation at an airport, this property is vital to facilitate real-time warnings for controllers.

The collision avoidance algorithm assumes birds to be perfectly predictable. It aims at preventing all predicted strikes, imposing delays sufficient to just miss the respective birds. With over 99 % of prevented strikes, the strong safety potential of that setting and the bird strike advisory system in general, was demonstrated in Monte Carlo simulations involving different bird and air traffic flight patterns. However, the number and duration of delays could get high for tight air traffic schedules on days with high bird abundances. Hence, it was recommended that the algorithm should focus on birds that cannot be targeted by the bird deterrent measures that are currently implemented on the airport grounds. This was pursued when implementing the bird strike risk algorithm which prevents bird strikes based on the risk of collision.

6.1.3. BIRD STRIKE RISK ALGORITHM

In chapter 5, the collision avoidance algorithm was extended with a module to predict bird movement and to calculate the risk of bird strikes. The resulting bird strike risk algorithm targets at the predicted damaging bird strikes involving birds who are expected to cross the flight path of departing aircraft. Birds present on or close to the runway were shown to strongly increase the number of delays while in reality they would be taken care of by WCUs (cf. Appendix B). Therefore, these lingering birds were disregarded by the algorithm. To predict bird tracks of birds expected to cross the flight path of a departing aircraft, a simple linear regression model was implemented based on the bird positions known at the intended take-off time of the aircraft. The probability of a strike was determined by the expected distance between bird and aircraft at the CPA, including uncertainties to account for lateral deviations from the regression line as well as variations in bird velocity. To evaluate the damaging potential of strikes, the kinetic energy of the impact was determined by including the aircraft speed at the expected CPA and the bird mass known from the radar data. Departure delays were imposed when the risk – the compound of the probability and expected severity – exceeded a predefined threshold. It was found that this approach did prevent bird strikes. However, the algorithm was not able to significantly change the bird strike rates since the number of prevented strikes could not always compensate for newly occurring strikes which did not exceed the threshold for algorithm intervention to aircraft with *transferred delays*. Hence, the chosen approach of predicting bird movement based on simple linear regression did not meet the goal of enhancing safety. Regarding traffic flows, the capacity could be maintained and the number of interventions led to reasonable delays even for high air traffic intensities. This demonstrates that delaying of aircraft within reasonable limits can be applied even at busy airports. Considering the safety potential demonstrated by the collision avoidance algorithm assuming perfect predictability of bird movement presented in chapter 4, the research question can be answered as follows.

6

Main Conclusions

The implementation of a bird strike advisory system is feasible given that bird movement can be predicted in a sufficient quality to reliably warn of highly likely and damaging strikes while issuing a strongly limited number of false alerts.

To achieve this sufficient quality of prediction, more research is required. A proposal for an approach based on this thesis work as well as a recommendation for the elements to be considered are provided below.

6.2. LIMITATIONS AND FUTURE WORK

All studies performed within this dissertation relied on data from two radar sources, namely avian and weather radar. Since the avian radar data available was limited in its range at the time the dissertation started, it was complemented with weather radar data to cover the entire extended airport environment. As no tracks but only bird densities can be obtained from weather radar, trajectories within its range had to be manually modelled. In the mean time, technology has improved and avian radars with full coverage of the extended airport environment have become available. Moreover, these radars provide altitude information, which was added manually within the thesis. Including data of these radars into the studies is expected to increase the accuracy of modelling the bird strike risk within simulations, especially for encounters with individual birds. As flocks of birds are still tagged without information of the number or size of flock members, the need to assume the expansion of their protected volumes remains. Whereas they were modelled as static and disc-shaped within this thesis, more variable shapes are expected to lead to more realistic estimates of bird strike risks within the simulation. In addition, a collision with a flock of birds does not lead to a single impact at one specific point but to multiple impacts across the aircraft surface. The consequences on the potential of damage have yet to be studied.

This dissertation demonstrated how vital a precise prediction of bird movement is to exploit the full safety potential of a bird strike advisory system. For this purpose, more sophisticated models have to be developed. Since bird behaviour is highly individual and depending on environmental factors such as weather and site-specific conditions, deep learning on multi-year data is recommended. This should be performed in the context of ornithological as well as ecological aspects. Moreover, the reactions of birds to nearing aircraft should be studied and incorporated in the resulting prediction model.

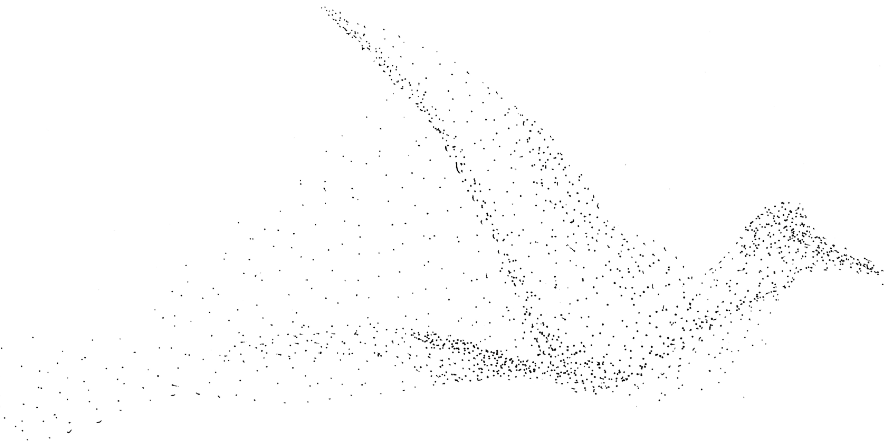
The ability of radar to identify bird species is strongly limited. To establish species-specific models, the incorporation of additional sensor types should be evaluated. In addition, the decision whether to delay an aircraft could include the cumulative risk of collisions with birds along the entire departure trajectory.

In the long term, when considering the actual implementation of a bird strike advisory system, operational aspects have to be addressed. Next to situational awareness and changes in workload for pilots and controllers, on which initial studies have been performed [88], additional uncertainties arising from real-time operations should be considered. These involve reaction times to alerts by the controllers, transmission time to the pilots as well as their reaction times. Suitable buffers as well as reasonable thresholds for triggering departure delays should therefore be addressed.

6.3. Main Contributions and Final Conclusions

Within this thesis, an open-source air traffic simulator was enhanced to provide a platform for bird-strike related studies. The underlying bird model is applicable for multiple purposes such as for collision detection within the bird strike risk algorithm developed within this thesis. The modular structure of the algorithm facilitates adjustments and extensions for future research. Within the thesis, a methodology using Monte Carlo Simulations to validate and analyse measures to prevent bird strikes was introduced and the maximum potential of the concept of a bird strike advisory system was demonstrated. The importance of focusing interventions to receive a feasible implementation with regard to airport capacity has been substantiated. It has been shown that there is room for adding departure delays to prevent bird strikes even at airports operating close to their capacity limits. Hence, when finding bird movement prediction models to increase the success rate of the given number of the interventions imposed in these studies, the implementation of a bird strike advisory system will become feasible, both in terms of airport capacity as well as safety.

Appendices



A

Potential of Damage

This chapter is based on the publication

I.C. Metz, T. Mühlhausen, J. Ellerbroek, D. Kügler, J.M. Hoekstra, *Analysing Bird Strikes in Fast-Time*, Proceedings of the North American Bird Strike Conference, Halifax, Canada, 2019 [128].

SUMMARY

The study presented in this chapter analysed the bird strikes observed within the Monte Carlo simulations performed in chapter 3 regarding their potential for aircraft damage. For this purpose, the kinetic energy of about 8,000 observed strikes was compared to the certification requirements by the aviation authorities regarding impact-resistance of the structure, the windshields and the engines of aircraft. The analysis showed that 3.2 % of all bird strikes caused damage in the simulation. In comparison, US bird strike statistics showed 0.6 % damage over a 26-year period. The analysis of the simulation outcome revealed that the share of damaging strikes is strongly increased by the strikes caused by flocks. By enhancing the model with flock compositions from the US or a comparison to European strike reporting data, more accurate results are expected.

A.1. INTRODUCTION

At and around airports, surveillance technology to track bird movement is increasingly available. Up to date, the generated information is mainly used by local WCUs to localize hot spots of bird activity [121]. If stored and accumulated, the data can be used to analyse patterns of bird movement trends and to evaluate the effect of novel measures to reduce the risk of bird strikes. In the context of this study, the data was incorporated in the simulation environment described in chapter 3. Within the there performed Monte Carlo simulations, the impacts in form of kinetic energy of all collisions were recorded. For the here presented study, the recorded kinetic energies were compared to the certification requirements defined by the European and US-American aviation authorities. This allowed to analyse the observed collisions regarding their potential to cause damage. Finally, the results were compared to multi-year reports of the FAA.

A.2. METHOD

The here performed analysis used the collision logs obtained from the Monte Carlo simulations performed in chapter 3. These contained information about the aircraft velocity at the time of collision as well as the mass of the bird(s) involved. This data was used to calculate the kinetic energy which was defined as determining criterion to evaluate the potential impact of the strike. The following sections describe the individual steps performed to achieve an estimate of the damage resulting from simulated bird strikes.

A.2.1. DAMAGE IDENTIFICATION

Kinetic energy builds the foundation for the calculations performed in this analysis. It is defined as

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

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

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Table A.1: 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 8,618 kg (19,000 lb) or less [64]	*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 8,618 kg or less [77]
CS-25 Large Aeroplanes turbine-powered aeroplanes of more than 5,700 kg (12,500 lb) maximum certified take-off weight, excluding commuter airplanes which are covered by the category Normal Aeroplanes [62, 65]	*14 CFR Part 25 Transport Category Aircraft* multi-engine airplanes with more than 19 seats or a maximum take-off weight greater than 8,618 kg [79]

To calculate the impact of a bird strike on the involved aircraft, the bird's mass as well as the total velocity of bird and aircraft are relevant. The records of the simulations do not include the flight path angle between bird and aircraft. Hence, only the predominating aircraft velocity is used to calculate the kinetic energy at the time of impact.

CERTIFICATION CRITERIA

To evaluate whether simulated bird strikes are damaging, their kinetic impact is compared to the certification requirements for aircraft by the European and US-American aviation authorities. Depending on the aircraft size, different certification requirements are in place. In the context of commercial aviation, which is in focus of this study, the categories Normal (EASA) / Normal Category Airplanes (FAA) respective Large Aeroplanes (EASA) / Transport Category Aircraft (FAA) are relevant. Their definitions, which are mostly corresponding to each other, are provided in Table A.1.

Within the simulations, only aircraft of the category Normal Aeroplanes / Normal Category Airplanes were represented [64, 77]. The requirements concerning the impact resistance of airframes towards bird strikes are mostly corresponding in European and US-American regulations. They cover the following aspects.

- Windshield: Withstand without penetration an impact of a 1.8 kg (4 lb) bird such as a great black-backed gull at cruise speed.
- Structure: Successfully completing a flight after an impact with a 1.8 kg bird when the aircraft velocity relative to the bird along the aircraft flight path equals cruise speed at sea level or 0.85·cruise speed at 2,438 m (8,000 ft), whichever is more critical.
- Empennage: Successfully completing a flight after an impact with a 3.6 kg (8 lb) bird such as a greylag goose at cruise speed (FAA only).
- Pitot tubes: sufficient separation to prevent an impact damaging all of them.

Table A.2: Kinetic energy criteria as defined by CS 25 / 14 CFR part 25 [65, 78]. 8,000 ft correspond to 2,438 m, 200 kts equal 103 m/s.

Component	**Kinetic energy criterion**
Windshield	$E_{kin} = \frac{1}{2} \cdot 4lb \cdot (v_{reference})^2$
Structure	$E_{kin} = \frac{1}{2} \cdot 4lb \cdot (0.85 \cdot v_{reference_{8000ft}})^2$ $E_{kin} = \frac{1}{2} \cdot 4lb \cdot (v_{reference_{sealevel}})^2$
Engine	$E_{kin} = \frac{1}{2} \cdot m_b \cdot (200kts)^2$

Engine ingestion tests have to be passed to prove the impact resistance of engines. No *Hazardous Engine Effect* may occur [63]. *Hazardous Engine Effects* include

- 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.*

Depending on the engine's diameter and the tested bird size, different thrust settings have to be applied. EASA requires tests involving single and flocking large birds. The FAA adds tests regarding small and medium single as well as flocking birds [63, 74].

For this study, the criteria regarding windshield, structure and engines were analysed. As the empennage section is excluded from the protected volume in the simulation (cf. 3.8 in chapter 3), the corresponding criterion was not regarded. The criterion considering the pitot tubes was neither considered, as it is not related to impact resistance. The references for kinetic energy are visualized in Table A.2. As this study only considers bird strikes up to 1,000 m (3,281 ft), the structure criterion including $v_{reference_{sealevel}}$ was selected. Consequently, the criteria for windshield and structure are identical.

The bird masses within the criteria for windshield and structure resistance are fixed. In the engine criterion, the bird mass to be included depends on the specific test conditions – size and individual or flocking birds – and the surface area of the engine inlet throat. For this study, the highest and thus most critical bird mass of 2.7 kg (6 lb) was selected. It can be found in the set-up for large single birds and engines with engine inlet

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Table A.3: Bird size categories as defined by the aviation authorities.

Size category	Weight range (kg)	Weight selected for simulations (kg)	Example bird
small	< 0.085	0.0425	house sparrow
medium	0.085 - 1.15	0.6175	rook
large	> 1.15 - 3.65	2.4	mallard

throat surface area between 1.35 m^2 and 3.90 m^2 (14.53 square feet to 41.98 square feet), as mainly represented in the simulation. The test conditions for the impact resistance of structure and windshield include aircraft reference velocities. These were obtained by aircraft type from the BADA 3.12 data base.

Simulated Data

To determine the kinetic energy of strikes in the simulation, the following input parameters were included. Birds of the mass categories as defined by the FAA [74] were assigned to the average mass of that category. To determine a mass for the category large, the additional category very large as defined by the ATSB, was used as upper limit [16]. Table A.3 provides an overview of the respective categories.

The simulated aircraft represent turbofan aircraft of the wake categories medium, heavy and super as defined by ICAO [103]. The study analysed damage caused by strikes with all kinds of birds represented in the simulation. Furthermore, the damage resulting from collisions with individual birds and flocks of birds were evaluated individually.

Reference Data

To validate the study outcomes, the calculated damage rates were compared to bird strike reports gathered over 26 years in the US [54]. Reports classifying the experienced damage as *substantial* or *destroyed*, which are expected to exceed the certification requirements, were included while the categories *none*, *minor*, *uncertain* and *unknown* were excluded. To evaluate the effect on the aircraft's structure, reports containing information about strikes on the nose, the wings and the fuselage were included. Table A.4 provides an overview of the share of bird strikes experienced and causing damage for the relevant categories structure, windshield and engines. The shares, when excluding the remaining components, can be found in Table A.5. Out of these, 2.1 % were reported to have experienced serious damage or led to destruction of an aircraft. Hence, the shares of damaging strikes to be considered have to be multiplied by this figure. This was performed in the last column of Table A.5.

Table A.4: Damaging bird strikes in the US between 1990 and 2016 (n = 141,538). Source: [54].

Component	Hits (%)	Damaged per category (%)	Damaged in relation to all strikes of all categories (%)
structure	40.6	10.8	3.9
windshield	16.6	4.3	0.7
engines	12.4	25.8	3.2
other components	30.4	11.0	3.5
sum	**100.0**	**-**	**11.3**

Table A.5: Share of damaging strikes for the relevant aircraft components. Source: [54].

Component	Percentage damaged in relation to all damaging strikes of all categories	Percentage of damaging strikes in the categories *substantial* and *destroyed*	percentage damaged in relation to all strikes of all categories when only considering *substantial* and *destroyed*
structure	35.2		0.75
windshield		2.1	0.1
engines	28.5		0.6

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Table A.6: Share of damaging strikes when considering all birds, flocks of birds and individual birds as well as the reference.

Component	**Damaging strikes all birds** [%]	**Damaging strikes flocks** [%]	**Damaging strikes individual birds** [%]	**Damaging strikes reference** [%]
structure	2.8	18.1	0.1	0.75
windshield	2.8	18.1	0.1	0.1
engines	4.4	26.1	0.6	0.6

Table A.7: Share of damaging strikes when considering all birds, flocks of birds and individual birds as well as the reference.

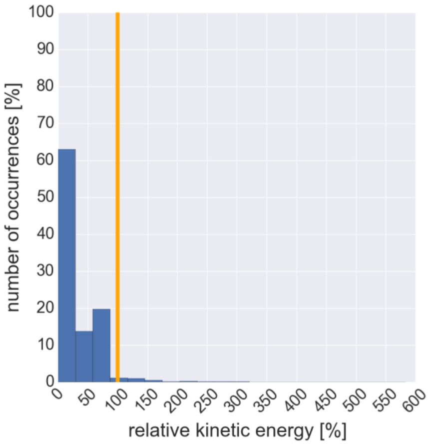
Bird category	**Damaging strikes simulation** [%]	**Damaging strikes reference** [%]
all birds	3.2	
individual birds	0.3	0.6
flocks	20.0	

A.3. RESULTS

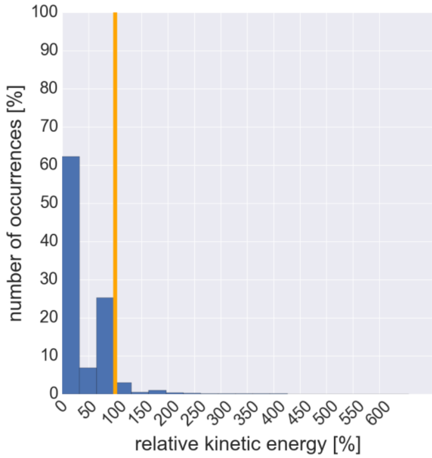
To analyse the potential impact of the simulated bird strikes, their kinetic impact was compared to the certification requirements by the aviation authorities. Strikes exceeding the requirements were defined as damaging. The total number of recorded strikes was 7,879. The rate of damaging strikes was calculated for flocking birds, individual birds and all birds. Of all strikes, 15 % involved flocks of birds. These caused 93.5 % of all damaging strikes. The 65 % of strikes, where individual birds were concerned, caused 6.5 % of all damages. Table A.6 summarizes the share of damaging strikes per relevant component and per bird category.

The total damage rate results from standardising the shares of damaging strikes per categories with the number of total occurrences. It is visualized for the three bird groups as well as for the reference in Table A.7.

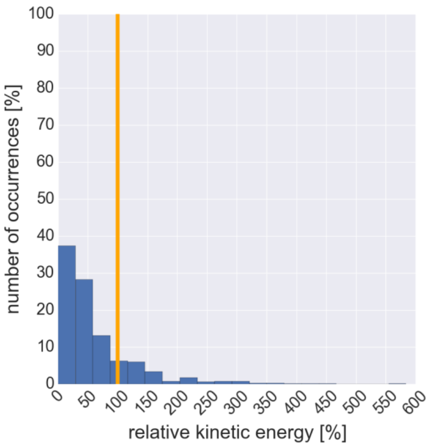
Figure A.1 provides an overview of the distribution of kinetic energy in relation to the certification criteria covering structure, windshield and engines as well as bird groups.



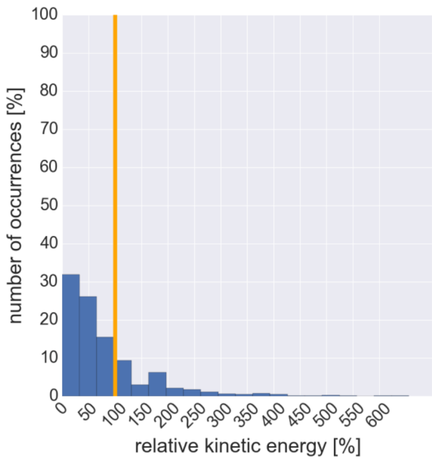
(a) WS and structure, all birds



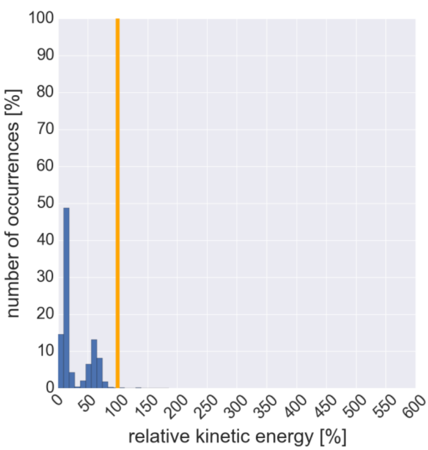
(b) Engines, all birds



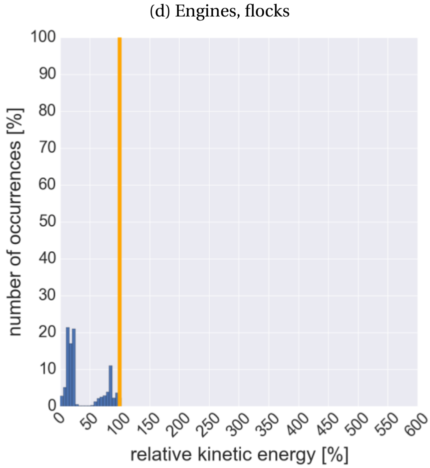
(c) WS and structure, flocks



(d) Engines, flocks



(e) WS and structure, ind. birds



(f) Engines, ind. birds

Figure A.1: Distribution of kinetic energy for all birds, flocks and individual birds for the categories windshields (WS) and structure as well as engines. The orange lines correspond to the level of kinetic energy of the respective certification requirements.

A.4. DISCUSSION AND CONCLUSIONS

This analysis focused on the damage caused by simulated strikes. For this purpose, the kinetic energy at the time of the impact was calculated for all simulated strikes. Subsequently, it was compared to the kinetic energy aircraft have to withstand to comply with the certification criteria of the aviation authorities. The analysis was performed regarding the impact resistance of structure, windshields and engines. It was found that the damage rate is higher for engines than for structure and windshields. This can be traced down to the certification requirements. Even though the applied bird mass is higher in the engine criterion (see Table A.5), the reference velocities in the other criteria exceed the 103 $\frac{m}{s}$ (200 kts) as applied for the engine criterion. Hence, the kinetic energy, at which a damage results, is higher for windshields and structure and thus the number of occurrences lower.

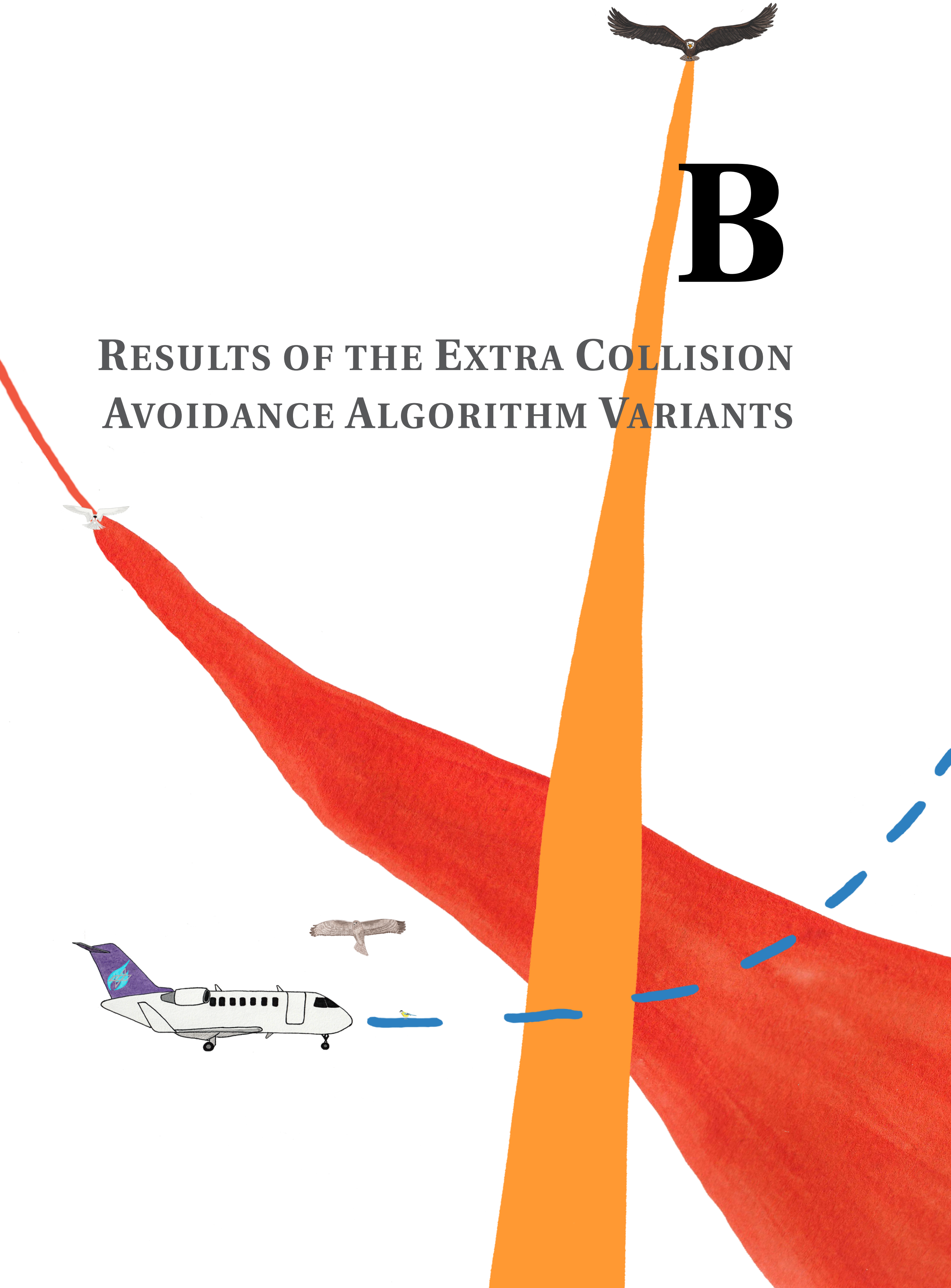
With regard to structure, two certification requirements including different reference velocities are available (see Table A.2). The aircraft has to be able to withstand the impact of the more critical case. Within the simulations, the criterion referring to the reference speed at sea level was more critical for all observed strikes. Hence, this criterion became identical to the one regarding structure and the results for structure and windshield correspond to each other.

The damage rates calculated in this study are higher than the ones reported to the FAA. The caused damage is strongly influenced by the biomass involved in the bird strike. Within the simulation, the 15 % strikes involving flocks of birds caused 93.5 % of all damaging strikes. Hence, the overall damage rate of 3.2 % is strongly influenced by the strikes caused by flocks. With the exception of the reference value for engine damage, all references lie between the values for individual birds and all birds. This indicates an overestimate of the damaging strikes caused by collisions with flocks of birds. This is created by a strong right shift in kinetic energy experienced by the individual components as can be seen in Figures A.1c and A.1d. One reason might be that the flock model underlying the here presented simulation environment originates from European data, while the reference values are obtained from the US. For further validation, either data to generate a flock model for birds flying in the US or comprehensive bird strike data from Europe in general and the Netherlands in particular would be required. The definition of protected volumes might be another contributing factor for the overestimate. In the model, birds in flock fly in dense formation. To calculate the kinetic energy of the impact, the mass of all birds in the flock is used. However, flocks fly in varying constellations in reality. In case of a strike, not necessarily all birds are hit and not all of them strike the aircraft at the same location. Furthermore, due to the curved shapes of the aircraft's front surfaces, the impact force is reduced.

The calculations for the kinetic energy of simulated strikes do not include the relative velocity of the bird towards the aircraft's flight path. It is expected that due to the dominance of aircraft speed, the influence of the bird velocity is relatively small. Hence, only a small improvement of the model is expected when including relative bird velocity. The simulation output can be used for initial damage calculations. Further enhancements of the model could be achieved by refining the calculation of kinetic energy for flocks of birds. Moreover, a validation with European bird strike reports would be beneficial.

B

Results of the Extra Collision Avoidance Algorithm Variants



SUMMARY

The bird strike risk algorithm presented in chapter 5 was developed based on the insights gained from two preceding versions of the algorithm, the probability-based and the risk-based versions. Their set-up as well as their outcome is provided in this appendix. This is followed by the discussion, leading to the justification why the final version of the algorithm focuses on potentially damaging strikes with crossing birds.

B

B.1. INTRODUCTION

The bird strike risk algorithm was developed in three iterations. At first and as for the collision avoidance algorithm, aircraft were delayed if the probability of collision with any bird exceeded a threshold in the *probability-based* version. Thereafter, the damaging criterion and thus the consideration of risk was introduced in the *risk-based* version of the algorithm. The insights gained from these two versions led to the final bird strike risk algorithm which is presented in chapter 5. This appendix describes its two predecessors as well as their impact on safety and capacity.

B.2. METHOD

B.2.1. COLLISION DETECTION AND RESOLUTION

The general structure of the three bird strike risk algorithms is comparable. The difference lies in the birds considered by the collision detection logic and, in case of the *probability-based* version, the missing of the severity criterion. In contrast to the final version of the bird strike risk algorithm as described in chapter 5, birds lingering on or close to the runway are included in the *probability-based* and the *risk-based* versions. In the *probability-based* version, the algorithm delays departures if the probability of the predicted strike exceeds a set threshold. In the *risk-based* version, the algorithm intervenes, if also the expected kinetic energy tops a threshold, indicating a damaging potential of the collision.

Figure B.1 depicts the steps to detect and resolve collisions within the two variants. In the *broad phase*, it is determined which tiles the aircraft will cross along its flight path. All birds stored in these or in adjacent tiles are forwarded to the *narrow phase* for the actual collision resolution. Initial studies of historic radar data have shown that birds which cause collisions are either crossing the extended runway center line (crossing birds) or showing erratic flight behaviour on and around the runway (lingering birds). The categorization is performed as described in chapter 5. Up to this point, the process corresponds to the one within the final version of the algorithm. After categorizing the birds present into these two groups and in contrast to the final version, the algorithm first addresses the lingering birds. Due to their erratic behaviour, their future flight path is hardly predictable. Hence, their presence on the runway is sufficient to delay an aircraft in the *probability-based* version. In the *risk-based* version, only lingering birds expected to cause damage are considered.

Bird reactions to nearing aircraft are not considered in this study. Therefore, lingering birds can stay for an unlimited time on or close to the runway. To limit this, a maximum time, when WCU could be expected to interfere and harass the birds in reality, was set.

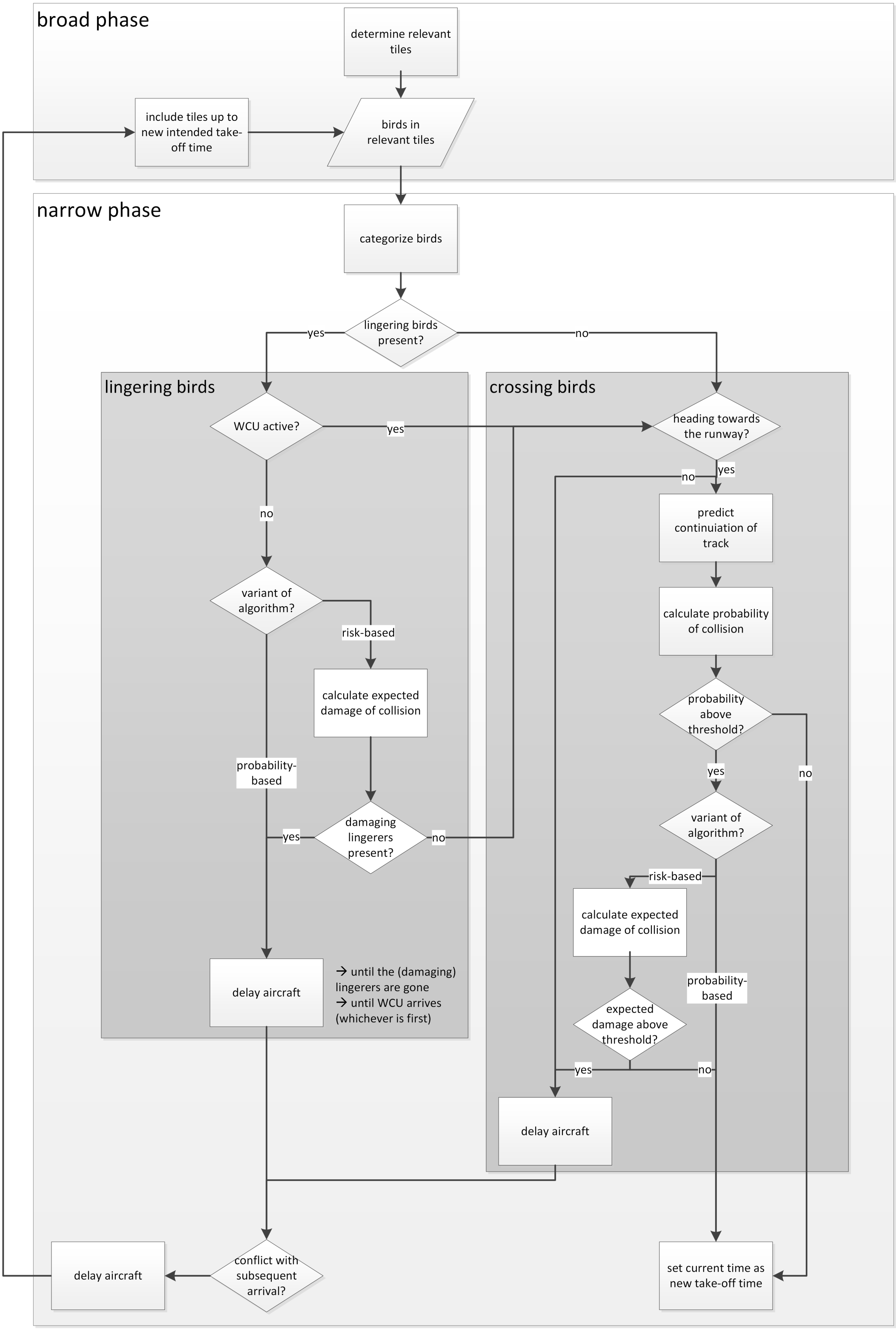


Figure B.1: Steps of the collision detection and resolution when including lingering birds.

Lingering birds arriving after that time are considered to be taken care of by WCU and no further delays of lingering birds are added. As soon as all lingering birds have left or the intervention time of WCU is reached, the trajectory of the aircraft at the now valid departure time is tested for potential conflicts with crossing birds.

Here, the expected continuation of flight paths of crossing birds is calculated first. As in the final version, simple linear regression is used for that purpose. Second, the probability respective risk of a strike is determined. If the accepted limit is exceeded, the aircraft is delayed until the critical crossing bird passed the runway or turned away.

As in the final version, the algorithm tests whether separation minima with subsequent arrivals are still reached after every delay added due to birds. If required, a departure is shifted behind the arrival and tested again for potential collisions until there are no lingering birds and the probability/risk of collision with a crossing bird stays below the acceptable limit. Subsequent departures inherit delays from their predecessors, should their departure times come below the separation minimum.

B.2.2. PROBABILITY AND SEVERITY OF PREDICTED STRIKES

To evaluate whether a departure should be delayed due to the presence of crossing birds, the probability of a collision with each relevant crossing bird was calculated. In the *risk-based* version, the expected kinetic impact was calculated in addition to serve as severity criterion. The probability as well as severity of strikes with crossing birds was calculated as in the final version. The probability of lingering birds present at the time of intended take-off always equaled one. To determine the severity of all potential bird strikes with lingering birds in the *risk-based* version, the aircraft speed at the predicted intersection point was used, as for crossing birds.

The threshold for probability amounted to 0.3 for crossing birds and to one for lingering birds. The severity threshold was set at 0.3 for all birds. These settings correspond to the ones selected for the final version. All remaining specifications of the algorithm are identical and the combinations of air traffic and bird movement information were divided into a baseline (19,200 scenarios) and a validation (4,800 scenarios) as well.

B.3. RESULTS

This section presents the outcomes of the *probability-based* and *risk-based* versions of the bird strike risk algorithm.

The number of delays generated per traffic day by the two algorithm versions as well as the spread of delay duration is depicted in Figure B.2. The spreads are larger and at a higher level for the *probability-based* version. This also applies for the number of delays. They are similar between the baseline and the validation for both algorithm variants. In both cases, the maximum delay duration is slightly smaller for the validation.

The shares of delayed departures resulting from the two algorithm variants are shown in Table B.1 for the baseline and in Table B.2 for the validation. Moreover, the share of delays that lasted for longer than ten minutes and therefore are labelled as unacceptable are presented. Finally, the share of delays shifted past the opening hours are illustrated. The results for the baseline and validation scenarios are similar. The weighted averages of all figures are strongly influenced by the high air traffic intensity.

Table B.1: Share of delayed departures as well as unacceptably delayed departures and departures outside the opening hours for the baseline (average number of departures per day: 562 at high air traffic intensity, 312 at medium air traffic intensity and 437 on average).

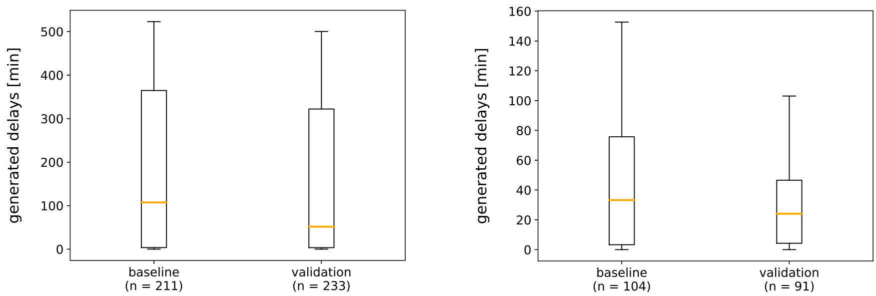
algorithm version	**air traffic intensity**	**delayed departures [%]**	**unacceptably delayed departures [%]**	**departures past opening hours [%]**
probability-based	high	53	34	10
	medium	42	27	0
	weighted average	**49**	**32**	**7**
risk-based	high	30	22	< 1
	medium	12	1	0
	weighted average	**23**	**14**	**< 1**

Table B.2: Share of delayed departures as well as unacceptably delayed departures and departures outside the opening hours for the validation (average number of departures per day: 562 in high at intensity, 312 in medium at intensity, 437 on average).

algorithm version	**air traffic intensity**	**delayed departures [%]**	**unacceptably delayed departures [%]**	**departures past opening hours [%]**
probability-based	high	59	35	11
	medium	43	28	< 1
	weighted average	**53**	**33**	**7**
risk-based	high	27	21	< 1
	medium	9	< 1	0
	weighted average	**21**	**14**	**< 1**

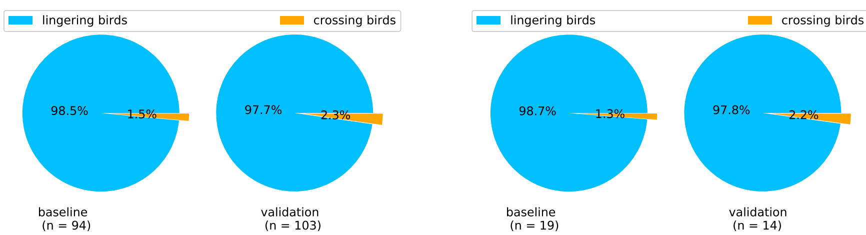
Table B.3: Bird strike rates for unimpeded air traffic flows as well as after the intervention of the *probability-* and *risk-based* versions of the algorithm.

algorithm version	**baseline**	**validation**
unimpeded air traffic	58	43
probability-based	25	20
risk-based	52	40



(a) *Probability-based* version (b) *Risk-based* version

Figure B.2: Duration of delays for the two algorithm variants (n: average number of delays per day).



(a) *Probability-based* version (b) *Risk-based* version

Figure B.3: Share of interventions targeting at crossing and lingering birds (n: average number of interventions per day).

The impact of the *risk-based* version is much smaller than the one of the *probability-based* version. This is also reflected in the difference in bird strike rates prior and after the algorithm intervention as shown in Table B.3. The *probability-based* version reduces the strike rates much stronger than the *risk-based* version.

The vast majority of algorithm interventions addresses lingering birds as Figure B.3 presents. The distribution between interventions on lingering and crossing birds are highly similar for the two versions of the algorithm. In both cases, the share of crossing birds is slightly higher in the validation.

B.4. DISCUSSION

The impact of the *probability-based* and *risk-based* versions of the bird strike risk algorithm on the air traffic flows is large. Thereby, the effect of the *risk-based* version is much lower in all aspects. This is connected to the additional severity criterion required to trigger an algorithm intervention. The delay duration as well as the share of delayed traffic strongly decrease when neglecting strikes expected to be harmless for the aircraft involved. Still, to delay more than 20 % of all departures on average, leading to 14 % of departures delayed by more than 10 minutes is way beyond feasible in operations.

It was found that more than 97 % of algorithm interventions are targeted at birds lingering close or on the extended runway center line for both algorithm versions. Hence, the majority of delays is referred to lingering birds as well. As explained in chapter 5, lingering birds are already taken care of by WCU in reality, which is not reflected in the simulation. Therefore, it was decided to disregard these birds in the final version of the bird strike risk algorithm.

The additional criterion of kinetic energy in the *risk-based* algorithm version does clearly reduce the impact on runway capacity and the number of delays is smaller than in the *probability-based* version. However, also the number of prevented strikes is smaller as the observed changes in bird strike rates indicate. Still, since the remaining strikes are expected to be uncritical for the aircraft involved, it was decided to keep this criterion for the final version of the algorithm to ensure tolerable delays for all air traffic scenarios.

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Nomenclature

Greek Letters

k	shape parameter of the Weibull distribution
λ	scale parameter of the Weibull distribution

Latin Letters

b	wing span, m
E	energy, J
f_s	sampling rate, Hz
d	distance, m
h	height, m
m	mass, kg
n	sample size
r	radius, m
t	time, s
u	uncertainty, -
v	velocity, m/s

Subscripts

ac	aircraft
$bird$	bird
CPA	closest point of approach
kin	kinetic
max	maximal possible value
min	minimal possible value
nom	nominal value
$parallel$	parallel direction
$perp$	perpendicular direction
PV	protected volume

CONVERSIONS

1 kg	2.2046 lb
1 m	3.2808 ft
1 m/s	1.9438 kts
1 lb	0.4536 kg
1 ft	0.3048 m
1 kt	0.5144 m/s

ACRONYMS

ABP	Actual Bird Position
ACAS	Airborne Collision Avoidance System
ACI	Airports Council International
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATSB	Australian Transport Safety Bureau
BADA	Base of Aircraft Data
BMP	Bird Movement Plan
CAA	Civil Aviation Authority
CPA	Closest Point of Approach
EASA	European Aviation Safety Agency
EU	European Union
EUROCONTROL	European Organization for the Safety of Air Navigation
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
HMI	Human-Machine-Interface
IAF	Initial Approach Fix
KIAS	Knots-Indicated Airspeed
ICAO	International Civil Aviation Organization
NOTAM	Notices to Airmen
PBP	Predicted Bird Position
RNLAF	Royal Netherlands Air Force
SID	Standard Instrument Departure
SSR	Secondary Surveillance Radar
UAL	United Airlines
UK	United Kingdom
US	United States of America
UTC	Coordinated Universal Time
WCU	Wildlife Control Unit

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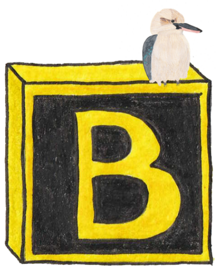

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[2]with fond memories of that very particular all-ladies one: Sophie A., Dyah and Ye
[3]Jerom

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Brunswick, April 2021

Curriculum Vitæ

Isabel Carole Metz

30-05-1989	Born in Bern, Switzerland

Education

2015 – 2021	PhD in Aerospace Engineering Delft University of Technology, Delft, The Netherlands German Aerospace Center DLR, Brunswick, Germany *Thesis:* Air Traffic Control Advisory System for the Prevention of Bird Strikes
2013 – 2015	Master of Science in Mobility and Transportation Technische Universität Braunschweig, Brunswick, Germany *Thesis:* Aircraft Performance for Open Air Traffic Simulations performed at Delft University of Technology, Delft, The Netherlands
2009 – 2013	Bachelor of Science in Mobility and Transportation Technische Universität Braunschweig, Brunswick, Germany *Thesis:* Evaluate the Feasibility of a 4D-Flight Management System for Air Traffic Simulations performed at the German Aerospace Center DLR, Brunswick, Germany
2000 – 2008	Swiss Baccalaureate Diploma Freies Gymnasium Bern, Bern, Switzerland

Experience

2021 – present	Research associate German Aerospace Center DLR, Brunswick, Germany *Research focus:* safety and security in air traffic management
2017 – 2018	Project manager, part-time FCS Flight Calibration Services GmbH, Brunswick, Germany *Project focus:* bird strike risk reduction for the FCS fleet

2013 – 2014	Research assistant German Aerospace Center DLR, Brunswick, Germany *Research focus:* air traffic management simulations
2008 – 2009	Intern Swiss Post, Bern, Switzerland *Focus:* project management assistance & parcel delivery

SCIENTIFIC CONTRIBUTIONS

2020 – present	Reviewer for *The Aeronautical Journal*, *Ecography* and *Transportation Research Part D: Transport and Environment*
2019	Interviewed for B. I. Koerner. "It's a Bird! It's a Plane! The Midair Collisions Menacing Air Travel", *Wired*, 24-01-2020

AWARDS

2020	2nd place in the DLR Contest of Visions *Preventing Bird Strikes with Artificial Intelligence* German Aerospace Center DLR
2015	Karl Doetsch Young Scientist Award *for an outstanding master thesis* Aeronautics Research Centre Niedersachsen
2015	Matthäi Award *for excellent master studies* Technische Universität Braunschweig, Department of Architecture, Civil Engineering and Environmental Sciences
2013	World Record Student team, Technische Universität Braunschweig, *for the world's largest flying paper plane* Guinness World Records

List of Publications

Journal Articles

5. **I.C. Metz**, J. Ellerbroek, T. Mühlhausen, D. Kügler and J.M. Hoekstra, *Analysis of Risk-Based Operational Bird Strike Prevention*, Aerospace **8**, 32 (2021)

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5. **I.C. Metz**, M. Freese, T. Pett and S. Schier, *Integrating Bird Strike Risk Information into the Airport Management System*, Proceedings of the German Aerospace Congress DLRK, Brunswick, Germany, 2016.

4. **I.C. Metz**, T. Mühlhausen, J. Ellerbroek and J.M. Hoekstra, *Evaluating the Effects of a Bird Strike Advisory System*, Proceedings of the World Bird Strike Conference, Amsterdam, the Netherlands, 2016.
3. **I.C. Metz**, J.M. Hoekstra, J. Ellerbroek and D. Kügler, *Aircraft Performance for Open Air Traffic Simulations*, Proceedings of the AIAA Modelling and Simulation Technologies Conference, Washington D.C., USA, 2016.
2. N. Carstengerdes, M. Schaper, S. Schier, **I.C. Metz**, A. Hasselberg and I. Gerdes, *Controller Support for Time-Based Surface Management. First Results from a Feasibility Workshop*, Proceedings of the 3rd SESAR Innovation Days, Stockholm, Sweden, 2013.
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4. **I.C. Metz**, T. Mühlhausen, J. Ellerbroek, D. Kügler and J.M. Hoekstra, *Estimating the Impact of Bird Strikes*, 6th International Eurasian Ornithological Congress IEOC, Heidelberg, Germany, 2018.
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2. **I.C. Metz**, T. Mühlhausen, J. Ellerbroek, D. Kügler and J.M. Hoestra, *Detect to Avoid: Supporting Aviation Safety with Bird Movement Information*, ENRAM Radar Aeroecology Conference, Rome, 2017.
1. **I.C. Metz**, J. Ellerbroek, T. Mühlhausen, D. Kügler and J.M. Hoekstra, *ATC Advisory System for the Prevention of Bird Strikes*, 6th SESAR Innovation Days, Delft, the Netherlands, 2016.

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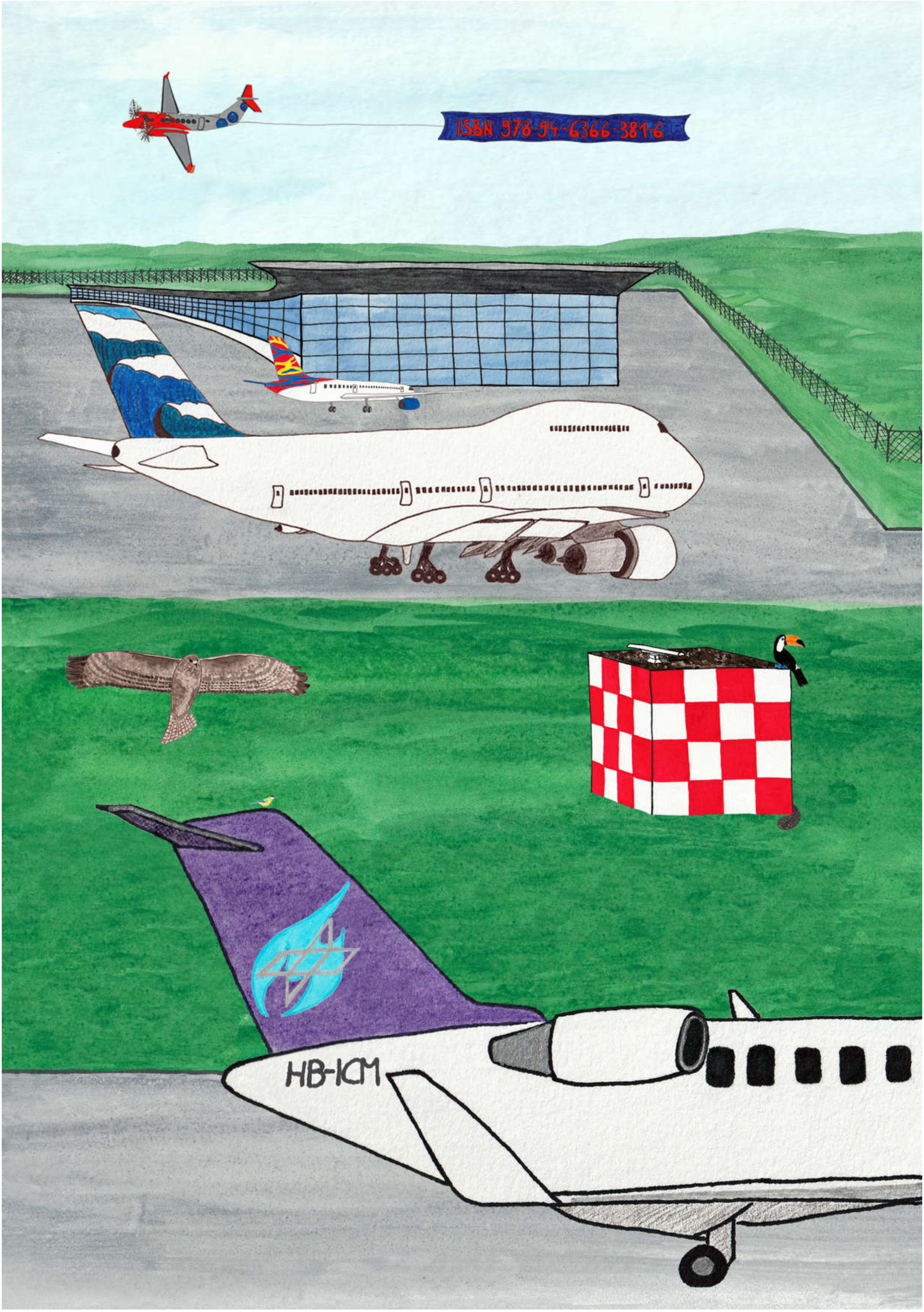
1. International Transport Forum, *Ready for Take Off? Integrating Drones into the Transport System*, ITF Research Reports, OECD Publishing, Paris, France, 2021 (contributing author).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