Value analysis of Integral bird control at an airport

A decision making support tool

N. (Nitant) Shinde

MSc thesis report

Delft University of Technology

Faculty of Aerospace Engineering

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THESIS REPORT

For the degree of Master of Science in Aerospace Engineering at Delft University of Technology

N. (Nitant) Shinde

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Faculty of Aerospace Engineering
(Control and Operations)

The undersigned hereby certify that they have read, and recommended the acceptance of this MSc thesis report entitled "Value analysis of Integral bird control at an airport" by N. (Nitant) Shinde in partial fulfillment of the requirements for the degree of Master of Science (MSc) at the Faculty of Aerospace Engineering, Delft University of Technology.

Dated: July 25, 2017

Exam committee chair: ______________________

Prof. Dr. R. (Ricky) Curran

Supervisor: ______________________

Ir. P.C. (Paul) Roling

External examiner: ______________________

Ir. J.A. (Joris) Melkert

Reader: ______________________

Prof.dr. W.E. (Warren) Walker

Reader: ______________________

Hans Van Gasteren (Royal Netherlands Air Force)

To Marlies...

Preface

Background

My journey with this research project has been a life-transforming experience. The curiosity of research problem itself (unpleasant interaction of birds and aircraft), the anecdotal reference of the famous water landing of US Airways A-320 in Hudson river also known as "Miracle on Hudson", triggered my enthusiasm to use my skill set to find a research solution that had a "real world" relevance. I stumbled upon several hurdles to obtain clarity, derive something meaningful out of information overload of content on the bird-strike problem-solution. All the knowledge (researches, industrial solutions, unclear efforts) had to be implemented in a MSc graduation framework to do something that can bring scientific and personal value of my work. I introduced the idea of pursuing then a broadly-defined MSc assignment to my supervisor Paul Roling, and together we formulated an achievable research proposal. I spent several days reviewing literature and gathering relevant information useful to answer the research objectives, and had a good understanding of the model requirements. Through elaborate discussions with my unofficial mentor Mr. Hans van Gasteren, friends and professional in the aerospace industry, and supervisors I could drive my efforts to realize the design of the stochastic model presented in this report. I was also able to present my research approach and expected results at the World bird-strike conference in December 2016 held in Amsterdam. Overall, the immense learning curve, improvement in scientific skill set, satisfying results are the biggest take-away from this experience. It will be an understatement to say how much I grew as a "Scientist" turned "Engineer" (also graduating as one) in different phases of my MSc journey.

Acknowledgements

I experienced the power of learning, collaboration, and engagement in this research work like never before. A MSc work is an individually driven, self-managed project management excersise but I was very fortunate to be supported in critical-thinking, mentorship, and appreciation by some powerful individuals, and this section is dedicated to them.

To facilitate the opportunity to learn, and thrive in this part of the world, my deepest gratitude goes to my parents Shilpanjali and Dr. Kiran Shinde, sister Shravanti, and brother-in-law or "The pillar of support" Amit Yadav. Next to them is "the" friend, philosopher and guide Frederik Mohrmann who did everything he could to be there for me. My Dutch family of Marlies, Peter, Hector, Troela (my furry love) and Dolfie for giving me a "home away from home", for making me realize how true love and care goes beyond cultural differences! Natascha at the library for real-world teaching, motivation, and free coffee, Jeroen and Paul for their support. The contribution of these individuals to see me graduate is priceless.

For the majority of learning, and iterative development of my research work, I would like to acknowledge the unconditional support of Mr. Hans van Gasteren (Head of Nature Bureau at Royal Netherlands Air Force). Thank you Hans for the endless calls, meetings, and the database you supplied for this research, all to support academic researches and grow forward with cooperation. I was also very happy to learn that my results will be used for further discussions at the RNLAF.

I would also like to acknowledge the support, advice, and constant encouragement from Prof. Warren Walker, my supervisors Paul Roling, Mihaela Mitici, and Prof. Ricky Curran. Your vision for a MSc graduate and TU Delft ambassador pushed me to work harder, and I am thankful for the lessons before I start my professional career.

To friends, lovers and haters - thank you.

Abstract

Motivation and problem statement

Bird strikes are not uncommon to aviation; they have been a severe threat to safety ever since manned flight and over the years have lead to human fatalities and economic setbacks. The obvious reason is the close proximity of airports with wildlife. Birds travel across the flight corridor to and from the roosting/feeding areas in the airport vicinity, causing a high bird-strike potential. To prevent this, bird control management of an airport engages bird control measures that target long-term (habitat management) reduction in bird population coming to the airport, and short-term on-airfield bird dispersal measures. While bird-strikes still continue to increase with increasing aircraft movements, the value evaluation of the bird control measures play an important role in exploring solutions to strengthen and further deepen bird-strike mitigation strategy. The stakeholder ecosystem consisting of airside operations, legislative authorities, and airport planners need a common framework to coordinate, cooperate, and support local/global bird-strike risk mitigation programs. The combination of these needs, sparked the interest, and motivation to conduct this research.

From an academic point of view, the aim was to set to explore the bird-strike problem further, use statistical knowledge to build a model that realizes an analytical solution, and ultimately assess the value addition of cost-effective on-airfield (reactive) bird control that minimizes the bird-strike damages.

Research objectives and methodology

The research objective is to present value analysis of integral bird control measures using the proposed methodology of a probabilistic bird-strike risk model. Several sub-objectives were set to realize the aim of the research. Firstly, the bird-strike problem was explored further by identifying the elements that could be worked on to leverage the scope of the proposed methodology. Secondly, the model itself was designed, and executed for Eindhoven airport as a case study; the results of which served as an input for a Monte Carlo Simulation. Thirdly, the forecasted results of the Monte Carlo Simulations were analyzed in the context of a cost-benefit analysis and risk analysis to ascertain meaningful conclusions that strengthen the research hypothesis.

Results

The results of the Monte Carlo Simulation model presented a clear overview, and a decent representation of the bird-strike problem for Eindhoven airport. The cost-benefit analysis indicated the optimum of potential saving from damages of a bird-strike with/without bird control to the investment in bird control measures; for all the six bird species chosen. This helps define the trade-offs, and relevance for building strategies to achieve higher cost-benefit ratios and reducing risk.

The risk analysis concluded in justifying the risk assessment of bird species in an improved bird-strike risk matrix suggested in this research. The basis was the potential, and extent of bird-strike damages due to bird species with a known risk level.

Limitations and conclusions

A few limitations deterred the complete realization of the scope defined for this research. These were mainly in the assumptions, and data analysis part of the research process. The limitations also reflect the demerits of realizing a simple but implementable model that on hand addresses the novelty of the solution proposed, but on the other trades-off the complexity that provides in-depth scientific credibility. However in spite of the limitations, the analytical approach quantified in a statistical model proves to strengthen the research hypothesis and partially answered the research question. The recommendations for future-work are proposed to explore research opportunities and further collaboration between stakeholders.

Table of Contents

List of Figures

List of Tables

List of Acronyms

CONOPS	Concept of Operations
NOTAM	Notice to Airmen
ACARS	Aircraft Communications and addressing reporting system
RPAS	Remotely Piloted Aircraft System
ATIS	Automatic Terminal Information Service
EHAM	Airport code for Amsterdam Airport Schiphol
ICAO	International Civil Aviation Organization
BSAS	Bird-strike Risk Alerting System
RNLAF	Royal Netherlands Air Force
ATCo	Air Traffic Controller
ATC	Air Traffic Control
AAS	Amsterdam Airport Schiphol
EIN	Eindhoven Airport
RWY	Runway
AGL	Above ground level
ASL	Above sea level
AIP	Aeronautical Information Publication
FAA	Federal Aviation Administration
FOD	Foreign object damage
HMI	Human Machine Interface
NLR	National Aerospace Laboratory
FOB	Flock of birds
A/C	Aircraft
SMS	Safety Management Systems
ALARP	As Low As Reasonably Possible
MCS	Monte Carlo Simulations
NASA	National Aeronautics and Space Administration
LCD	Liquid-crystal-display
MRO	Maintenance Repair Overhaul
AOG	Aircraft On Ground
POW	Aircraft Engine (s)
WIN	Aircraft Windshield
NOS	Aircraft Nose
RAD	Aircraft Radome
FUS	Aircraft Fuselage
WING	Aircraft Wing
LIG	Aircraft Lights
CBA	Cost Benefit Analysis
IATA	International Air Transport Association
CDF	Cumulative Distribution Function
KPI	Key Performance Indicator
R&D	Research & Development
KLM	Koninklijke Luchtvaart Maatschappij
SARPS	Standard and Recommended Practices

Chapter 1

Introduction

A bird-strike with an aircraft has reported in thousands of major/ minor accidents over the years in civil aviation. Royal Air Maroc AT-685 (Operated by Atlas Blue) in 2010, US Airways Flight 1549 popularly known as "The Miracle on Hudson" in 2009, American Airlines Fokker F100 in 2003 - These high-profile incidents are prominent aviation accidents in recent years that highlight the problem being described in this paper. Regardless, they have one thing in common - bird ingestion in the engines during take-off resulting in engine failure. Emergency landings in these three cases saved the lives of passengers on-board, but it created a stir in the aviation community to address the cause of it - bird-strike.

A bird-strike is defined as the collision between an airborne animal and a man-made vehicle (aircraft) that results in minor or significant damage to the vehicle and in some cases complete loss of the vehicle [4]. However, the problem of birds striking the aircraft is not new. Since 1912, the available data shows that 223 people have been killed worldwide in 37 civil aircraft accidents, and a minimum of 63 aircraft written off as a result [10]. Military aviation (exercises involve flying at higher speed and low altitude, hence higher risk) reports more than 353 incidences involving 165 fatalities since 1950 [15]. These statistics are only a fraction of the total bird-strike being reported, experts say many go unreported [14]. The number of bird-strikes in recent times continues to grow as air traffic and bird population around airports increase rapidly. Birds near the airport pose a serious threat to the aircraft, as 90% of wildlife strikes occur in the airport environment [6]. Amsterdam Airport Schiphol recorded 8.4 bird-strike per 10,000 air transport movements in 2015 compared to 5.8 in 2014 [8]. In general, statistical analyses show that about 91% of departure collisions and 83% of arrival collisions occur within 5 nautical miles (9260 meters) of the airport and 92% of all bird-strike happen below 3000 feet (914.4 meters) AGL. [6] [7] [2]. Globally, airports set an altitude restriction for exercising bird control measures. At Amsterdam Airport Schiphol this is set to upper limit of 200 ft for landing aircraft, and of 500 feet for departing aircraft. A tentative and probably conservative estimate of bird-strike cost is US$1.2 billion per year in damage; not taking into account the cost in operational delays, a big part of the estimate. [12]

ICAO defines bird-strike risk index (based on a coefficient derived from bird-strike rate per 10000 aircraft movements) that indicates the severity of the bird-strike problem for a certain airport, and a common measure to compare different airports globally:

Bird-strike rate	0 - 0.2	0.3 - 0.9	1 - 2.9	3 - 10	10 <
Severity	Very low	Low	Medium	High	Very high

Table 1-1: ICAO bird-strike risk index [26]

ICAO mandates airside operators to report bird activity, and strike counts to the airport indirectly collecting the global database of bird species, damage to aircraft, and other contributing factors like weather, flight phase at impact, etc. The Bird-strike Reporting Form (BSRF) is designed for direct reproduction by ICAO member states, but can be extended with additional information [1]. Amsterdam airport Schiphol (AAS) depends on KLM for the bird-strike count, and in turn on the KLM pilots that report [2]. Since there is no defined bird-strike count regarded as the most acceptable or ideal, or a standard tool in place for quantitative risk assessment, most airports adopt the "As low as reasonably practicable" or ALARP approach for bird-strike management [4]. Additional to BSRF reporting, Standard and Recommended Practices (SARPS) introduce a guideline for airports globally to follow a certain standard to construct , and exercise effective bird control.

Experts describe the three most important components to address bird-strike hazard management as: "Awareness", "Bird avoidance, and control" and "Aircraft and airport operation". Awareness is the study of the ecology, and behaviour of the birds species present on, and around the airport, the problems they cause and potential danger they present [39].

On-airfield bird-strike prevention is based on the assumption that birds that stay in the runway environment will sooner or later fly and then may interfere with starting or landing aircraft. Bird avoidance, and control on airfields therefore focus on how bird attractants (birds feed on insects/small animals) can be minimized using Habitat management considering the design and lay-out of the airport; and for birds still preset, use reactive measures to disperse, capture or even kill if necessary [9][39]. Schiphol airport employs 17 bird controllers to patrol the entire runway area and chase away the birds using flare guns, audio equipment generating alarm (distress) calls, mobile green lasers, gas canons, and using falcons (a bird of prey). A radio-operated robot bird of prey (ROBIRD - A type of Ornithopter) was tested at Schiphol to chase away the birds in a particular direction, in an attempt for a better bird control [5] . But the ROBIRD was unable to patrol the entire area and could not fly across the ditches. Furthermore an integration of a RPAS (Remotely Piloted Aircraft System) into complex airport operations was investigated by National Aerospace Laboratory of the Netherlands, and the results of validation are company confidential [1]. For any reported bird-strike, the aircraft's operator faces significant damage. Hence the role of air operators, airports, and aircraft manufacturers becomes important in the overall bird-strike mitigation strategy.

Bird control measures are not used to their best potential, they are sometimes not even suitable to be used, and/or themselves become hazardous for airside operations. Another bottleneck is the lack of qualitative, and quantitative impact of bird control measures beyond airside operations, such as: ecosystem, public perception, etc. on the overall bird-strike costs. This steers a need for a value analysis in terms of a cost-benefit study that further helps in collaboration, and coordination among stakeholders, an essential step for achieving bird control standards through a systematic management mechanism [3]. The risk analysis helps profile the damage costs due to bird species, and together with CB analysis gives a good basis for bird-strike mitigation strategy.

This research presents a value analysis (in terms of cost-benefit analysis and risk analysis) of integral bird control measures at an airport, and discusses whether the results can support a short-term and long-term strategy planning for airports, and airlines in managing resources in order to reduce potential damaging bird-strikes.

1-1 Research aim, objectives, and research questions

The objective of this research is to support the bird-strike mitigation strategy for an airport based on known bird-strike prone species and their potential damage. It is realized by presenting a value analysis (in terms of cost-benefit and risk analysis) for bird control measures. The insights of the value analysis can be used by several stakeholders to reduce the overall risk of bird-strike problem itself.

The aim of this research is a two-step study: To simulate a bird strike risk potential with, and without bird control measures in place. Second step, to evaluate the potential savings using bird control measures in form of a cost-benefit analysis, and risk potential per bird specie for a damaging bird-strike. The research gives inputs to improve overall airside operational efficiency, safety, minimal environmental damage, etc. The study will address the core research question, and the sub questions as described below. The order of the sub questions is most likely the order in which they are answered.

Question: Can the value analysis of integral bird control measures improve the bird-strike mitigation at an airport?

1. What are the current bird control measures used in an airport environment? What is the present day involvement of different stakeholders?
2. Are the current bird control measures the most effective in the conventional sense? What is the impact on damages?
3. What inference can be drawn from a value analysis of bird control measures?
4. Would a value analysis based decision support tool bring noticeable changes to the improve the strategic planning for bird-strike reduction at a major airport like Eindhoven?

To be able to provide answers to the above questions, and define the scope of the project, some project goals (objectives) have been set out in a semi-chronological order.

The objectives set for this research are:

1. Identify, and create an inventory of the bird control measures currently used; study the present day operations of the stakeholders (bird controllers, airport wildlife management team, aircraft operators, Government) involved.
2. Design and develop a probabilistic bird-strike risk model to evaluate the expected damage costs for a certain bird-strike probability which is based on birds counted
3. Create a Monte Carlo Simulation model to forecast the uncertainty in the costs with/without bird control measures for a specific airport
4. Use the Monte Carlo simulation results to ascertain a cost-benefit analysis of singular or integral bird control. Use the same results to evaluate risk potential of bird-strike damage per specie using risk analysis.

1-2 Document structure

Chapter 2 summarizes the literature review on various aspects of the assignment, and uses it as a background necessary for answering the sub-questions. Chapter 3 introduces the methodology used to design and develop a probabilistic bird-strike risk model, followed by Chapter 4 that applies the model in a case study for Eindhoven airport. This chapter concludes with presenting a value analysis in terms of risk and cost-benefit analysis. Chapter 5 summarizes the results, interpretation of the value analysis for different stakeholders, and concludes with recommendation for future work. References are listed in the Bibliography section towards the end of the report.

Chapter 2

Literature review

The literature review is a summary of the background knowledge useful to develop the research methodology, and to answer the research objectives. The first section introduces the problem of bird and aircraft interaction, bird behaviour and characteristics. This is followed by the explanation of airport operations, and concludes with a detailed account on different bird control measures.

2-1 Bird behavior and flight characteristics

Tracking the daily flight activity of birds helps us determine the probability and severity of the hazard they cause in an aircraft-bird collision. It is thus important to know how their physical, and flight characteristics, behavioural pattern, etc help in our understanding of the situation and using the information to assess effectiveness of bird control measures.

2-1-1 Physical characteristics and behaviour

Birds are the natural inhabitants of the sky, their physical features like wings (forelimbs), absence of a urinary bladder (to reduce weight), and a four-chambered heart pumping warm blood for the high-metabolic energy demands of flight [15], help to soar, and sustain natural flight.

Most of the birds are diurnal like humans, i.e. active during the days, and rest/sleep during nights. They begin flying in the early morning hours before sunrise until 11:00 a.m. Midday, the activity drops to resting, loafing, preening, and avoiding predators. There is often a second activity peak in the late afternoon and early evening when birds again move back to the feeding and roosting sites. During nights, the birds prefer to rest alone in sheltered areas such as dense foliage, cavities or tangled undergrowth. Depending on latitude and time of year, the period spent sleeping can vary from four to eight hours. 71,9% of bird strikes are recorded during day time, and out of these 84,4% of strikes occur below 500ft. During the day, almost 81,8% of the total air traffic is civil, and combining these statistics reveals that the chance of a bird strike at night is 1,76 times higher than that during the day, hence the conclusion that bird activity is high round the clock. [11][15]

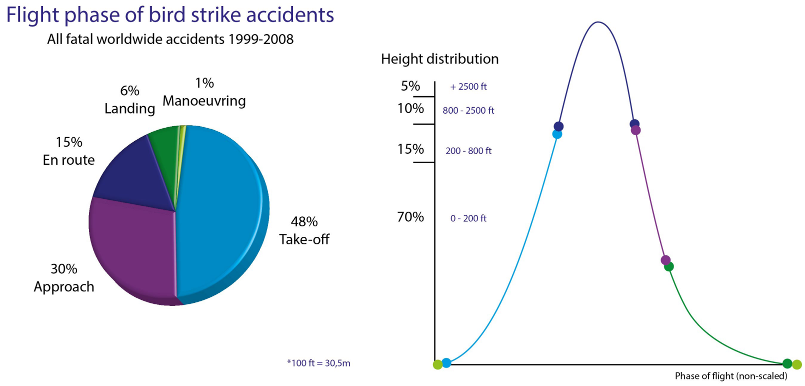


Figure 2-1: Bird-strike problem explained [11]

Another important factor is the local weather; birds are generally less active during extreme heat or cold, rain or snow, mist or fog. In these conditions, birds significantly limit time spent feeding and moving about. In contrast, bird activity can show a marked increase immediately before and following rain showers. The rain drives insects out of the trees, and brings worms and other invertebrates above the ground surface. A burst of feeding activity follows. After a summer rain at many airfields, runways must be cleaned-they become slick with worms and attract hundreds of birds that flock to the sudden surfeit of food. Pools that develop after rainfall also provide much needed water for drinking and bathing.[15]

Through natural evolution, birds have learned to respond quickly to animals that prey upon them – avoid, and escape them. But when they find new or unfamiliar objects in their environment as long as these objects do not cause harm, birds quickly habituate to them. Evidence suggests that airport birds have adapted to their surroundings, learning that aircraft are not a threat. The sight of birds feeding and loafing along busy runways-apparently oblivious to noise and movement-is a familiar one.

For this research, bird behaviour towards aircraft is also considered. It varies with different species, but is based on the maturity of the bird (young/adult) and any threat the bird may be under at that time (calm/panic state of mind). Birds near a runway have an unpredictable behaviour to approaching, and departing aircraft. The flight corridor is perceived as a path with hurdles, and is thus avoided by some species, whereas others confidently cross the runway leading to a potential collision scenario.

Young and migrating birds unfamiliar with the airport environment seem more prone to panic flight. Adults of the same species may completely ignore aircraft. In panic flight, starlings and shorebirds form dense flocks, and then undertake extremely hazardous and erratic movements over the airfield, resulting in thick congregations of birds crossing the path of arriving and departing aircraft.

The response of birds in flight is also highly unpredictable. Typically, birds undertake simple manoeuvres to escape the path of aircraft. Bird escape-flight behaviour also varies by species. Typically, gulls attempt to out-fly an aircraft rather than move away at right angles to the aircraft's path. Hawks and eagles will occasionally attack aircraft rather than avoid them.

2-1-2 Flight characteristics

Most birds flap their wings to move forward and attain lift. Smaller species fly at moderate speeds between 16 and 32 km/hr. Larger birds such as waterfowl can maintain flight speeds of more than

64 km/hr, although high speeds make significant energy demands and are generally avoided. During migration, birds take advantage of tail winds at various altitudes to significantly increase their speeds, sometimes achieving radar-detected ground speeds of more than 96 km/hr.

2-1-3 Bird-flight altitudes

The majority of day-to-day movements occur between 30 to 300 feet above ground level (AGL). Little regular activity occurs above 1,000 ft AGL, so it's not surprising that over 80% of reported bird strikes occur when aircraft are below that level; the vast majority of strikes are suffered below 300 ft AGL. [15]

One of the highest altitude bird strikes on record involved a Boeing 747 that struck a large bird flying over the West African coast at 37,000 ft above sea level (ASL), but high-altitude bird activity generally occurs only during migration. At that time, birds attain greater heights either to take advantage of winds aloft or to pass over obstacles such as mountain ranges. Migrating Bar-headed Geese have been reported above the summit of Mount Everest, and typically cross the Himalayas at altitudes up to 30,000 ft ASL. A flock of swans migrating from Iceland to Western Europe was reported by a pilot at just over 27,000 ft ASL. Mallards have been reported at 21,000 ft, and Snow Geese have been reported at 20,000 ft. While the altitudes of most migrating birds tend to be much lower, documented average migration altitudes are impressive. Radar observations during peak migration movements in Europe have shown that the majority of migrants flew between 5,000 and 7,000 ft AGL, with a lower limit of 1,600 ft and an upper limit of 11,500 ft.

2-1-4 Bird soaring and gliding

Other bird-flight behaviours such as gliding, soaring and towering also pose a threat to aircraft. Towering is the slow circling flight that birds engage in as they harness rising parcels of warm air. Towering, soaring and gliding are often used in combination; the bird takes advantage of rising thermals of air-towering to effortlessly gain altitude- and then uses the gained altitude to soar aloft and then glide down. Soaring and gliding flight are energy-efficient behaviours typical of larger bird species-such as condors, vultures, eagles, hawks, storks, gulls and pelicans-that travel long distances as they hunt and migrate. In bird-hazard assessment, soaring flight is important for a number of reasons:

- Towering conditions are often found at or near airports. Open and flat, airfields contain large expanses of concrete and asphalt which re-radiate stored heat, creating ideal conditions for the development of local thermals. As a result, towering birds- particularly hawks and vultures-often concentrate and circle above airfields.
- Soaring birds tend to make their daily movements at greater altitudes than other birds. During ideal thermal conditions, hunting hawks and vultures can maintain altitudes greater than 1,000 ft AGL. The high altitude soaring flight of raptors such as eagles and vultures puts them out of reach of most wildlife management techniques.
- During the migration period, large concentrations of hawks and vultures congregate in areas such as mountain ranges and coastlines-areas that offer dependable thermals and updrafts. In the late morning-along North American migration corridors- boil of hawks and kettles of vultures each containing hundreds and thousands of birds are not uncommon. Under ideal conditions, these birds can ride thermals to altitudes at which they can no longer be seen from the ground.

Bird sizes cover a considerable range. A tiny hummingbird weighs no more than an ounce, while a large flightless ostrich weighs up to 300 lbs. The vast majority of birds, however, weigh less than a pound.

2-2 Airports - Safe havens for bird presence

There are about 9000 species worldwide, mostly near the equator [15]. At Schiphol airport alone, around 70 species inhabit a large area of 1600 acres [21].

The population density of birds or number of birds per unit of area varies considerably among regions and habitats. In general, greater numbers of bird species are attracted to areas offering abundant food, thus increasing their numbers. From the sleeping or resting grounds (indicated as red stars in the figure below), bird species like the geese travel a minimum of 1-3 km to the nearest grassland to forage. Drinking, and resting areas (marked as blue triangles), and foraging grounds (marked in yellow) lie very close to Polderbaan runway making it highly susceptible for bird crossing [18].

Research on the inner circle of 10 km suggests that these foraging flights occur from Spaarnwoude, Vinkeveensche plassen and Kagerplassen [22]. This implies that aircraft landing, or taking off from the Northern side of Polderbaan have high possibility to encounter a bird crossing, and potential bird collision. AIP of Netherlands (EHAM - SID of RWY 36L) corroborate with north-bound operations (straight climb at heading 52degN and up to 4nm).

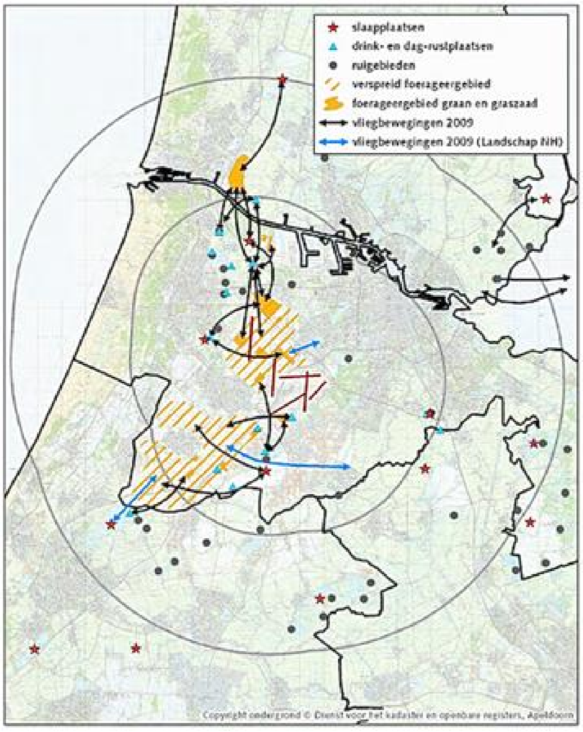


Figure 2-2: Birds around Schiphol [18]

To describe the bird-strike problem at airports for known bird species, it is a common practice to build a **bird-strike risk index** for airports that represent:

1. Probability represented by **bird-strike rate** ie. number of bird-strikes per 10,000 aircraft movements

2. Severity represented by **Biomass** of the bird species

The risk matrices for Schiphol, and Eindhoven [40] are indicated in the figures AAS-risk and EIN-risk. The risk matrices indicate the position of similar or different bird species in the context of threat they present to a main-port like Schiphol, and a regional airport like Eindhoven. The thresholds for Probabilities BSRI-1 and severity BSRI-2 can be found in the Appendix (A-3).

This representation has proven to be inaccurate, rather be represented by damaging bird species present at an airport, and their bird-strike impact force (measure of severity). Such a matrix will help identify the high/low risk species (including their behavior, and flight characteristics), and decide on the bird strike mitigation strategy for the concerned airport.

(a) Amsterdam Airport Schiphol **(b)** Eindhoven

Figure 2-3: Bird-strike risk matrix [40]

2-3 Current day working of airside operations, and other stakeholders

In a typical airport operational environment, there are multiple stakeholders involved in managing hazards, including bird strikes. The information sharing is restricted to only two – Bird Control (or Bird Watch), and Runway controller (Air Traffic Control). Together, they spearhead tactical risk management activities linked with bird strike hazard, and prevention.

An airport operational environment pyramid [16] is shown in the figure 2-4. It indicates the major actors involved in overall bird strike prevention. At the base are technology developers, and system vendors like research organizations/universities, and Radar companies. They are responsible to develop concepts, and systems to be used by others. Regulators (ICAO, FAA, etc), and certification organizations assess, and validate the systems. They are also responsible for ensuring safety compliance, and thus play a very important role in the pyramid. Airport operations work on the regulations approved, and ensure the airport delivers enhanced awareness to the aircraft under its control. This includes the Tower, and ATC. They are ultimately responsible for managing the aircraft on ground and in the air, and to coordinate the detection, deterrence, and avoidance of a bird strike as the final line of defence.

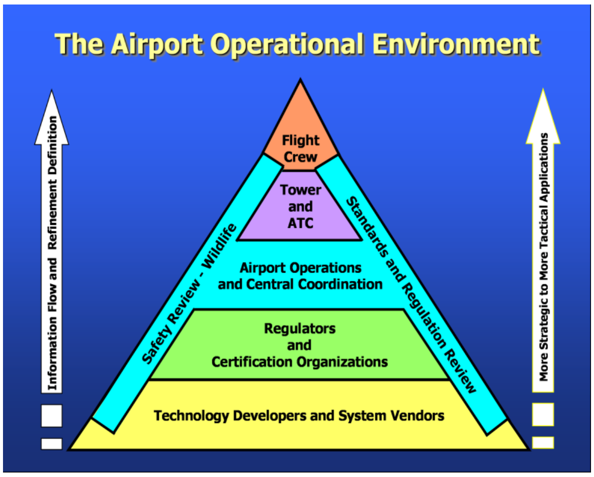


Figure 2-4: Airport operational environment

A bird control team at an airport is responsible to visually scan the aerodrome, and execute a dispersal of bird flocks to ensure smooth operations. At Schiphol, bird scaring and runway inspection are done by two or more bird controllers at any given time. Their responsibilities include reporting bird presence in the area, scare them with light bullets (depending on category of bullet, necessary to execute with permission of TWR), sound or with the help of dogs, ensure a clear runway free of bird remainders (if any) or other unwanted FODs. They regularly communicate, and report the situation to the runway controllers. In an event of a bird strike reported by a pilot, the bird control is delegated to check the runway, and report the runway condition (free of FOD). The tower controller informs the pilots of the next departure before the takeoff clearance is issued. [19]

There are special procedures, and guidelines laid out in the Voorschriften Dienst Verkeersleiding or VDV for bird controller at Polderbaan (RWY 18R/36L) during 2230 and 0630 hrs. The important thing to notice is the guidelines set for a 90m zone around the runway. The bird control can request permission to check, report, and scare bird flocks in the 90m zone that circumvents the area stretching from both sides of the runway until 92,5m from centerline and 60m from runway end. [19]

The ideal or desired situation is when the information flows through the top of the pyramid. Whereas airport operations can receive and filter large data streams in airport-specific formats to provide actionable information to its trained ground personnel, pilots are limited by their need to manage multiple information sources and manage multiple risks.

Literature also suggests that the NOTAMs, AIRAC, ATIS, and ACARS are regularly updated, and give out information like “Bird activity in the area”, but do not characterize the threat, and severity of the situation, hence at tactical level, prove to be inadequate. They continue to be a conventional practice at the airports around the world. [16]

EUROCONTROL facilitates a general checklist for the ATCo to handle unusual situations for dealing with bird strikes. The principle is termed as “ASSIST” or A: Acknowledge (Acknowledge the bird strike, and check if the pilot can control the aircraft); S: Separate (Separate the aircraft in trouble with other traffic, and keep the active runway clear); S: Silence (Non-urgent communication is avoided);

I: Inform (Inform the emergency services at the airport); S: Support (Support the pilot with information, or any other assistance); T: Time (Provide the time for the crew to assess, and don't press with non-urgent intervention). There is not a off-the-shelf procedure to deal with tactical interventions, but experience, and better situation awareness of the stakeholders tackle the reactive measures. (EUROCONTROL)

2-3-1 Bird-strike risk management

For an airport, the efforts to manage the risk for a potential bird-strike depends on the preparedness (tools) in three categories [27]:

1. Airport Habitat Management
2. Airport Locality Habitat Review
3. Active on-airport bird control systems

Airport Habitat Management

The availability of food, water, shelter, places to nest, rest and roost make airports an attractive landscape for birds. Airport habitat management is designed to eliminate or minimize local population of birds by modifying vegetation heights (adjusting the height of grass, and bushes) and landscape (ecological architecture of airport, and surrounding area) with an aim to make it less attractive for some bird species. It is an expensive, and long-term deterrent method and effective only for target species. [28][25]

Airport Locality Habitat Review

The area beyond airport perimeters have the potential to attract, and host bird activity. Birds are attracted to open farmlands, recreational parks or still-water bodies like lakes, indirectly a threat to operational safety of aircraft during landing/take-off. ICAO defines the radius of 13kms circle around the airport to be considered before a wildlife management plan is drafted.[34]

Active bird control measures

Bird control is managing the prevention of bird strike by using people, and tools to control the bird population in an airport environment.[25] A detailed inventory of bird control measures with specifics of the parameters they are most effective is laid out in this MSc thesis report (case study). A summary of the commonly existing bird control methods at major airports are:

- **Audio Repellents**: Birds are repelled or chased away by sounds producing equipment. The biological basis for the birds to leave is the startling reaction to sound, and the fear of potential predator. Most commonly used sound deterrents are pyrotechnics (cartridges, flares, electronic alarms), propane gas cannons or bioacoustics (pre-recorded distress calls).

- **Visual Deterrents**: Visual deterrents are human, and animal-friendly methods to repel birds mostly in daylight. Traditional methods include placing Scarecrows or Hawk kites and balloons which birds perceive as fear for potential predation, and avoidance of unfamiliar objects. Reflecting tapes (based on reflection of light put on them) are cheapest deterrents but have a similar low-level impact as Scarecrows. Carcasses or models of dead birds widely used in agriculture attract the birds of prey.[28] At Schiphol, many experiment with both mounted or model gulls have been conducted to test the effectiveness of this method, and the results testified that posture and placing of the models was very important. [28] Also more realistic the models (more expensive), the longer the deterrence will last.

  Falconry is one of the most effective, and moderately expensive visual repellent methods for birds. Species of falcons also known as birds of prey like Peregrine, Gyr, Lanner or Saker Falcon or Merlin can be trained effectively for bird dispersal at airports both at low, and high altitudes. Birds avoid an immediate confrontation with a predator. However, there are several limitations: extensive training, food and housing for the bird of prey (maintenance), an operationally available full-time team, and the birds can only be flown during daylight and good weather and flying is not possible just after feeding or during moult. [28][35][36] In many cases, falconry was abandoned because of these limitations. Using Falconry at an airport should include the local situation, environmental and animal laws governing use of bird of prey, and the limitations should be taken into account.

  Remotely Piloted aircraft system (RPAS) or Ornithopter shaped in the silhouette of a bird of prey, have been tested with success on gulls at Schiphol, and on dunlin in Canada. The RPAS is flown across or towards the target birds by remote control, in such a way that a raptor is imitated.[5] The major limitations were the inability of the ROBIRD to patrol the entire area, fly across the ditches, and expensive (training, and cost of drones). Furthermore an integration of a RPAS into complex airport operations was investigated by National Aerospace Laboratory of the Netherlands, and the results of validation are company confidential.[1]

  Lights create a sudden flash, blind/disorient, and hence scare away birds. They are generally placed around the airfield or on bird patrol vehicles, act as short term deterrents but unfortunately birds get strongly habituated to them. Some migrating species are even attracted by lights at night. Especially during falls, increased numbers of "Passerines" have been recorded at or around lighthouses, lightships or illuminated large industrial areas along the coast. [28] Lasers prove to be one of the most effective visual repellents, but literature suggests the usage to be limited due to the negative effects like phisiological damage it can bring to the pilot crew if laser is not operated safely.

- **Chemical Repellents**: Chemical methods are very effective short term deterrents. Examples: Tactile agitation, Grass posioning, Water, Reta, Polybutene, Methyl anthranilate, and other toxic repellents are sprinkled on the surface or near the roosting places of birds.[28] In the Netherlands, chemical repellents are not used nor are experiments conducted. This is due to moderate climate with a lot of rain where the chemicals do not stay effective. [37] The use of potentially toxic chemicals may also have legal (and ethical) complications.[28]

- **Exclusion methods**: Creating physical barriers like walling, netting and placing wires exclude or restricted areas for birds to nest, feed or roost. This long term deterrent is expensive (heavy investments), and need detailed feasibility studies. Gulls appear to use several feeding sites spread out over a large area. It is therefore important to use large horizontal nets at all potential feeding grounds in wider surroundings than just the close vicinity. Such nets make maintenance of the terrain difficult.[37][28] Experiments have been conducted with heated surfaces, based on the assumption that gulls prefer warm surfaces for roosting or loafing. No positive results were obtained. [35]

- **Removal methods**: Two removal methods are explained - Traps and shooting or ammunition killing (shotgun or rifle). This means that the bird species of potentially high bird-strike risk die at a rate faster than their natural death rate. Traps are inexpensive, but needs a dedicated personnel to frequently reset the traps or empty the cages. [25] Killing great numbers of birds is, apart from difficult and expensive, generally not an acceptable control method. Moreover, it may have an adverse effect not only on the birds, but also humans. Decreasing numbers result in less competition between the surviving birds for resources, so the remaining population may well be "healthier". [7][28] Killing or shooting the birds is considered the "last resort" in bird control, this is due to the environmental, and socio-political-emotional aspect of the problem.

- **Other methods**: There are several methods locally designed, and implemented depending on the bird species, and local conditions. The major ones are listed:

  1. Avian radars: Since 2003, Bird radars or avian radars, traditionally off-the-shelf marine radars have been deployed for use as a real-time tactical bird strike avoidance system. They were earlier used by biologist to study bat, bird, and insect activity [23]. With the advances in digital processing, and computing potential in the last decade, radar data extrapolated as plots (flock/individual birds) and later as tracks has made it user-friendly with multiple stakeholders. The challenge is however not to simplify the data, but make it possible to make operational risk management decisions, and to integrate the display (and an intelligent algorithm) in the existing workstation of the stakeholders like ATCo (ground controller).[23]

     The literature suggests two different views on the usability of avian radar to be integrated into the aviation operating environment. One view is what the radar vendors have (in the light of a sales pitch), and the other is of the regulators (FAA/USDA/Research Organizations in other parts of the world). Radar detection capabilities have been proven for military and space application. The US Air Force, and Royal Netherlands Air Force (RNLAF) use the radar system for low flying exercises, NASA used it during the launch of the space shuttle. [3]. But the complexity lies in commercial aviation setting. Operational risk decisions based on the radar data require additional data.

  2. Microwaving, and Magnets: Products using magnetic fields can disorient birds, and hence considered a repellent. [25]

2-3-2 Aircraft based bird-strike prevention

The introduction of ‘glass cockpit’ in the aircraft cockpit are the replacement of the Flight Management System (FMS) on LCD, and that opens another concern. In the year 1989, an Airbus 320 aircraft, operating at flight level 25 and 250 knots (IAS), collided with a vulture (weighing approx 4,5 kg) just above the windshield. Although the windows were not penetrated, bird-impact force was strong enough to destroy 4 of the 6 cockpit display units (CRTs) and triggering a fire warning, causing the shutdown of one of the two engines.[41]

Literature suggests that the aircraft design may contribute to a reduction of the damage of a bird strike event. Special attention to the design of vulnerable aircraft components (engines, windshield, leading edges) with respect to collisions, makes the aircraft more resistant to impact by birds. [41]

Chapter 3

Methodology

The need of a cost-effective bird control toolbox is realized by designing a **Probabilistic bird-strike risk model** to represent the bird-strike problem at an airport. The model design is approached analytically based on the literature resources, consultation and know-how from the industry experts, and rationalizing the bottlenecks of existing bird-strike mitigation strategies into potential solutions.

This chapter describes the modeling framework of the Probabilistic bird-strike risk model based on the research question (s) defined. The research objectives are represented as requirements for the model, and using known methodologies, translated into model design. The overview of this process is explained in a flow diagram connecting requirements to model using methodologies. The methodologies provide a guideline to analyze the input and output (process diagram) of the model:

- Probabilistic modeling for building the model
- Monte Carlo Simulation for performing risk, and cost-benefit analysis

The risk model is represented as an Event sequence diagram indicating relevant probabilities and severity (in damage cost headings) together as *Risk value*. The choice, and interaction of model parameters are defined with splitting up the model in three causal modules. An overview of the input - output of modules can be seen in figure 3-3. The working is explained through a mathematical formulation followed by the output (risk value). The output serves as the input for Monte Carlo Simulations, and the results are further analyzed in terms of risk analysis and cost-benefit analysis towards the conclusion of this chapter.

The process overview (3-1) illustrates how requirements are used by methodology to obtain a model, which is further analyzed to answer the research question.

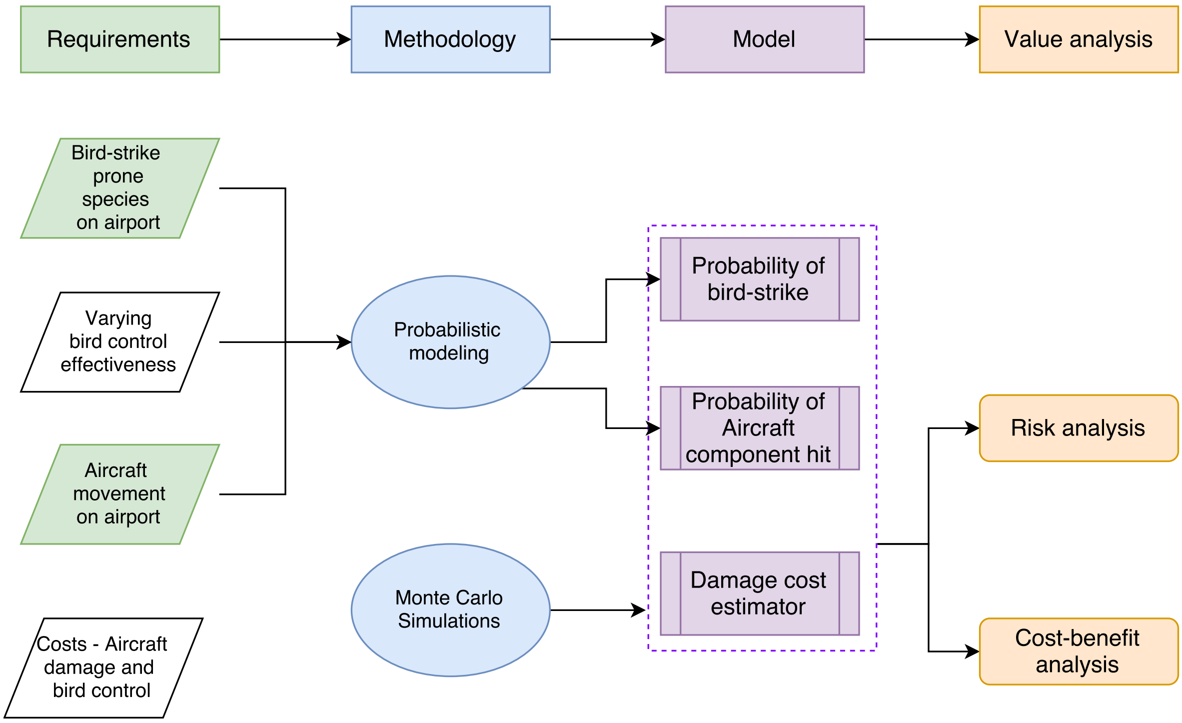


Figure 3-1: Process overview

3-1 Methodology

The following section is dedicated to understand a systematic analytical approach that uses underlying statistical concepts and theories to realize a model. In this research, a Probabilistic bird-strike risk model is built that is detailed enough to be replicated and used for other combination of bird-strike problem scenarios (for different birds on different airports).

3-1-1 Probabilistic modeling

Probability models are quantitative models that incorporate random variables and their probability distribution based on past (historical) data. The use of probabilistic models for risk analysis explores the inherent uncertainty and variability of the variables that result in estimating risk. [48] Instead of a single risk value, a probability risk model gives a range of outcomes (values) that are suitable for better insights in risk estimation.

Normal distribution

In probability theory, the normal (or Gaussian) distribution, is a continuous probability distribution that is often used as a first approximation to describe real valued random variables that tend to cluster around a single mean value μ. [44]

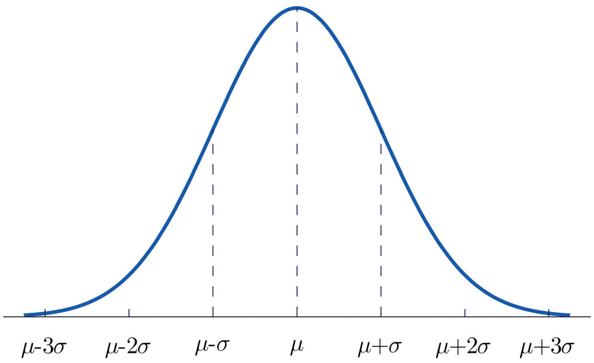


Figure 3-2: Normal distribution [43]

A random variable **x** is said to be normally distributed with mean μ and standard deviation σ if its probability distribution is given by

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \tag{3-1}$$

In modeling, a normal distribution ensures that a database structure is suitable for general-purpose querying and free of certain undesirable characteristics—insertion, update, and deletion anomalies—that could lead to a loss of data integrity. [45] Two parameters used in the modules were normalized, their mean and standard deviation is based on the input data. The parameters and their rationale:

Parameter	Rationale
Bird count (B_Count)	Yearly distribution of bird inspections
AC component hit	AC component hit during a bird-strike

Table 3-1: Parameters normalized in the model

3-1-2 Assumptions

The parameters chosen in the model are either standard parameters used in a probability-based mode, or sufficient addition of assumptions that help describe the analytical process of the model. To keep the scope of the model more realizable, the following assumptions were used:

- For every bird inspection, only 1 unit per bird control measure was used.
- A fitting parameter is used in the asymptotic function to calculate the probability of bird-strike P(BS). The basis of this parameter α is to have a realistic bird-strike probability that corresponds to historical data.
- The dispersed birds that return back to area where they were dispersed from, are called *Returning birds*. The model does not consider the influence of these birds on P(BS)
- The aircraft flight phase is not treated separately in the model.

- The aircraft is always present during/just after a bird inspection, i.e. probability of aircraft presence, P(AC) = 1. The assumption infers that an aircraft is always bird-strike prone.
- A bird-strike hit on aircraft critical component has a significant operational effect. For example: Aircraft hit on departure/climb is assumed to return to the same/nearest base, and immediate access to Maintenance Repair Overhaul (MRO) is available. This influences the Aircraft-On-Ground (AOG) costs.
- A replacement aircraft for the affected bird-strike hit aircraft is always available at the departing airport. This does not allow network loss to propagate.
- Ancillary costs (Runway closure, Accident investigation) are not taken into account
- The usage and effectiveness of bird control measures is considered for "average days" in a year. Hence factors that influence on a non-typical day are not taken into account.
- The bird control action is planned and implemented by trained professionals. It does not deviate with different bird controllers. In practice, experience of bird controllers play a big role in choice of a bird control measure for dispersing an observed bird(s) based on local conditions.

3-2 Probabilistic bird-strike risk model

Based on the modeling framework, a Probabilistic bird-strike risk model is designed and discussed in this section. The goal of the model is to output the total costs (in terms of a risk value) incurred during a bird inspection. The total cost comprises of - Expected damage cost for a probability of bird-strike, and bird control cost(s). The model uses several defined methodologies to meet the goal. The output of the model is further forecasted using Monte Carlo Simulation to achieve a greater understanding and awareness of future uncertainty, which ultimately helps in supporting the bird-strike risk mitigation plan.

The complete functionality of the model is realized in three modules linked with causality, and the sections below elaborate on their design, working, and mathematical formulation. The first two modules compute the **bird-strike probability** using basic probabilistic modeling technique, and the third module estimates the extent of damage or **severity of the bird-strike**.

The methodology formulates the use of the following parameters to construct the model, the interaction of the parameters is further illustrated in the input-output flow diagram.

Parameter	Explanation
B_Count	Number of birds counted during bird inspection
B_Undsp	Number of birds undispersed during bird inspection
B_Return	Number of returning birds during bird inspection
P (BS)	Probability of bird-strike during/just after bird inspection
P (AC)	Probability of aircraft presence during/just after bird inspection
P (Cr_comp)	Probability of aircraft critical component hit at bird-strike
P (NCr_comp)	Probability of aircraft non-critical component hit at bird-strike
V_AC	Velocity of aircraft at bird-strike

Table 3-2: Parameters used in the methodology

3-2-1 Working of the model

The working of the model demonstrates the analytical process followed to compute a risk value (expressed in damage cost) per bird inspection cycle - ie. number of the birds counted. The detailed working of the model is explained by splitting it in modules, each explaining the input-output (fig 3-3), and working using mathematical formulation.

The broader functionality of the risk model can be seen in the schematic (fig 3-4).

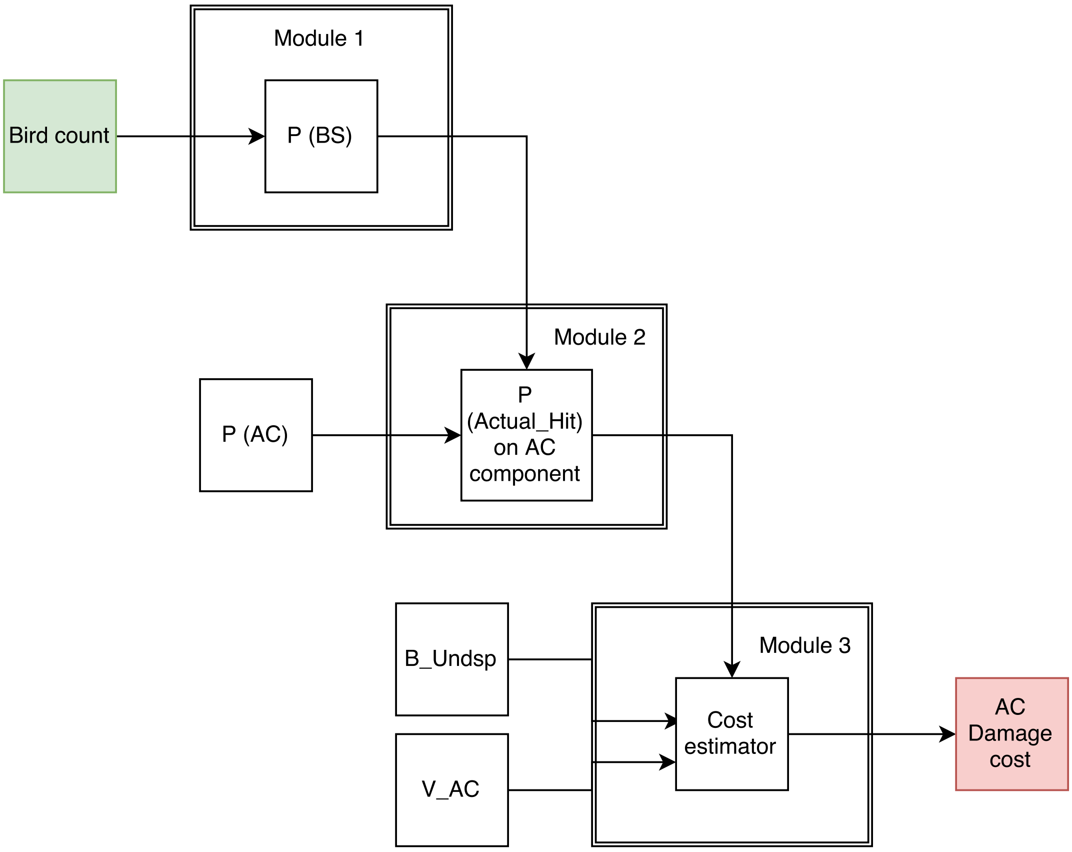


Figure 3-3: Schematic: Input-output for modules

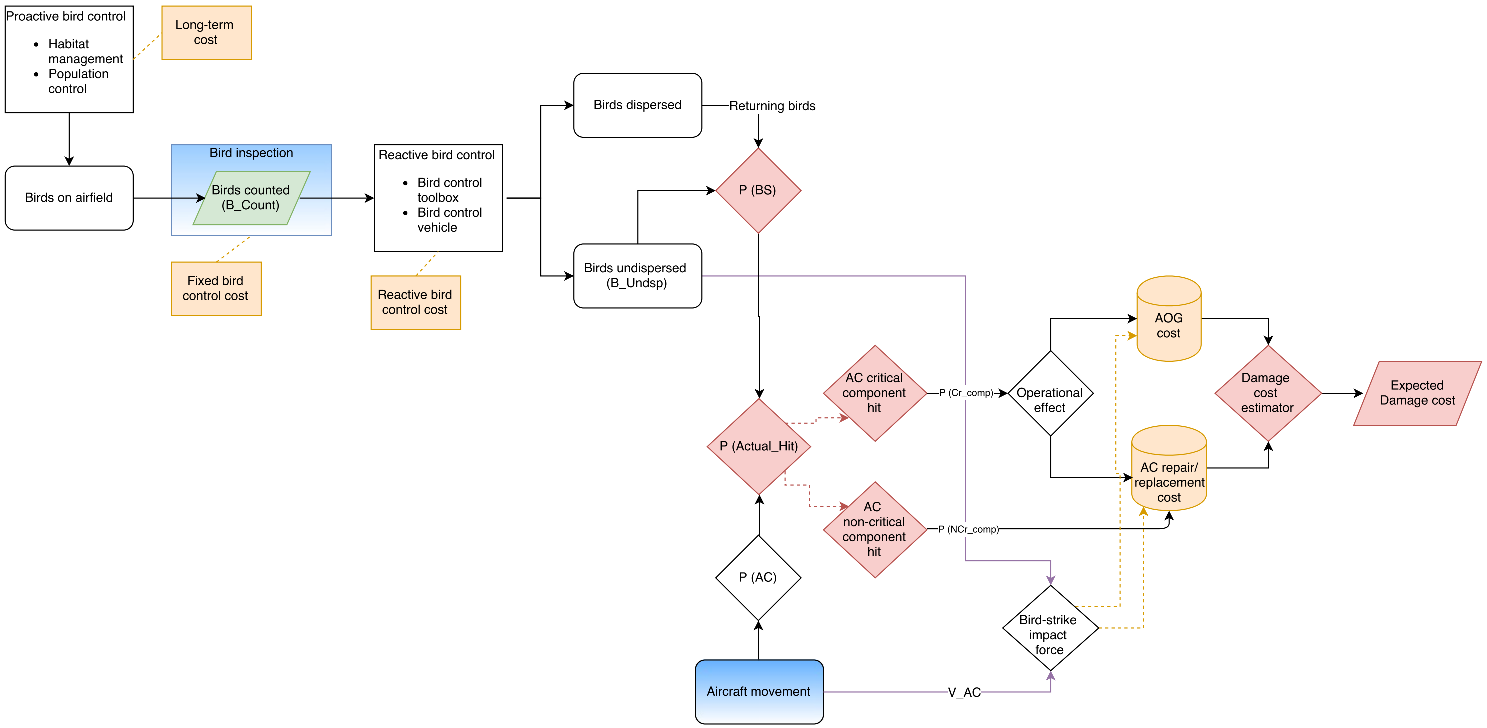


Figure 3-4: Probabilistic bird-strike risk model

3-3 Module: Probability of a bird-strike

This section details the first part of the model. The goal of this module is to calculate the probability of a bird-strike or P(BS) per bird inspection for an observed bird count, based on bird control measures used. Primarily two bird control measures are used:

1. Proactive bird control
2. Reactive or on-airfield bird control

Proactive bird control (described in the literature review) or the long-term bird control measures like habitat management and population control influence the number of birds on airfield at any given time. The effectiveness of these measures are dependent on the following factors:

1. Topography of the airport or surrounding ecosystem - Natural (mountains, lakes, etc) and artificial (built-up areas like buildings) influence the on-airfield bird population.
2. Climatic conditions - Airport sites prone to higher rainfall, day temperatures, visibility, and strong winds contribute to higher bird presence. Rainfall and higher day temperatures increase the availability of worm, or other soil living invertebrates, thus making the site attractive for the bird species to feed.
3. Migration peaks - During the migration period, bird population on the airfield increase significantly, not only in number but also severity of bird-strike. This is also detailed in the literature review in this report.
4. Proactive bird control like a Habitat management plan (for a set period of time) which on an average reduces the bird population present at the airport.

Reactive or on-airfield bird control is the focus of this research. The reactive bird control toolbox consists of several bird control measures depending on the bird species, their historic effectiveness. The **module figure** places the objective of this module in context. Following sections are dedicated to the working, and mathematical formulation of P(BS).

3-3-1 Working of the module

During a typical bird inspection, bird species and their count (visually seen, or with an avian radar) is logged, and depending on the presence of aircraft movement, a bird control action is planned and executed. The decision of a bird control measure is taken based on:

1. Bird control toolbox available
2. Historically-proven dispersal success for a particular bird species. The table summarizes the **average** usage, and effectiveness of bird control measures for Buzzard at Eindhoven airport. Similar tables for other bird species can be found in Appendix

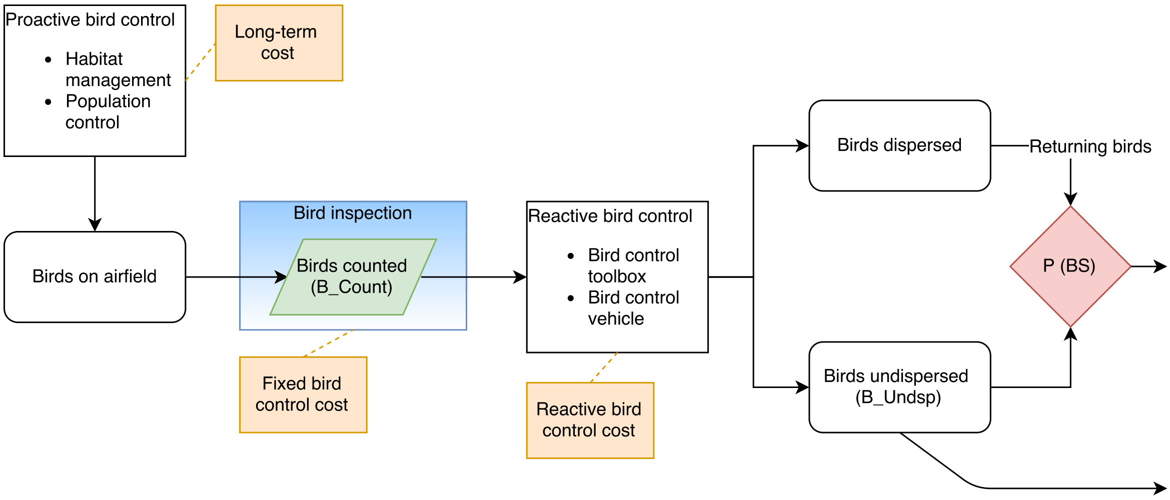


Figure 3-5: Schematic: Probability of bird-strike module

	Sound dispersal	Pyrotechnics	Shooting	Lights	Bird control vehicle
Usage	42%	47%	6%	1%	5%
Effectiveness	90%	89%	100%	50%	100%

Table 3-3: Bird control measures for Buzzard at Eindhoven (data from 2000-2016) [40]

3. Bird controller's experience based on external factors like weather, proximity to the bird specie flock(s).

In this model, the number of birds counted (**B_Count**) during an inspection is considered as input, and after a bird control action, the birds undispersed (**B_Undsp**) as bird-strike prone, hence sub-input for calculating the P (BS). The probability of dispersed birds with a potential return to be bird-strike prone is not considered in the module.

3-3-2 Mathematical formulation

The output of this module is probability of bird-strike P(BS) per bird inspection is derived, and represented by the following equation:

$$P(BS) = 1 - \left[\frac{1}{1 + \alpha\,(B\_Undsp)}\right] \tag{3-2}$$

where B_Undsp are the number of undispersed birds after a bird control action is executed, and α is a fitting parameter of the horizontal asymptotic function. The values of α should lie between 0 and 10^{-5} to have a realistic bird-strike probability. For this model, α is fixed to **0.0005**.

Additionally, the P(BS) is influenced by *Returning birds*. As mentioned in the assumptions,

$$B\_Return = 0 \tag{3-3}$$

Bird control costs

The components of bird control costs incurred for ***n*** bird inspections, can be summarized as:

$$Total\ Bird\ control\ cost = \sum_{i=1}^{n} [Proactive\ bird\ control\ + Fixed\ bird\ control\ + Reactive\ bird\ control] \quad (3\text{-}4)$$

Since the effectiveness of proactive bird control measures is difficult to quantify per bird inspection, a yearly cost component is used and simply divided by the number of scheduled inspections. Fixed bird control costs are incurred irrespective of whether reactive bird control measures are used or not, and can be given by:

$$Fixed\ bird\ control = \sum_{i=1}^{n} [BC\_sal + BC\_vehicle + Fuel\ cost + Field\_Admin\_cost] \quad (3\text{-}5)$$

where,

Parameter	Explanation
BC_sal	Salary of bird controller. This is the most expensive component of the cost function. The remuneration of bird controllers depends on experience, training, and labour laws
BC_vehicle	The cost of transporting the bird controller, and the toolbox
Fuel cost	Bird control vehicle fuel cost
Field_Admin_cost	Administrative costs with logging, and other hardware/software costs to ensure records are kept intact in Bird-strike reporting forms (BSRF)

Table 3-4: Parameters in the fixed bird control cost function [40]

These parameters are based on information acquired from broader literature review and interviews with industry experts.[40]

Reactive bird control costs for ***n*** bird inspections are based on historic probability of use. For this model, a random number generator was used to select a bird control measure, and correspondingly return the cost from a look-up table with estimated bird control measure cost [40].

$$Reactive\ bird\ control = \sum_{i=1}^{n} [(Probability\ of\ use) * \ Unit\ cost\ of\ use] \quad (3\text{-}6)$$

The unit cost of use per bird control measure, and the calculation per bird inspection is given in the Appendix for further reference.

3-4 Module: Probability of Aircraft component hit

This section describes the intermediate module of the model, and the goal is to calculate the number of instances an actual bird-strike occurred at a critical or non-critical component of the aircraft. The schematic below explains the working of the module:

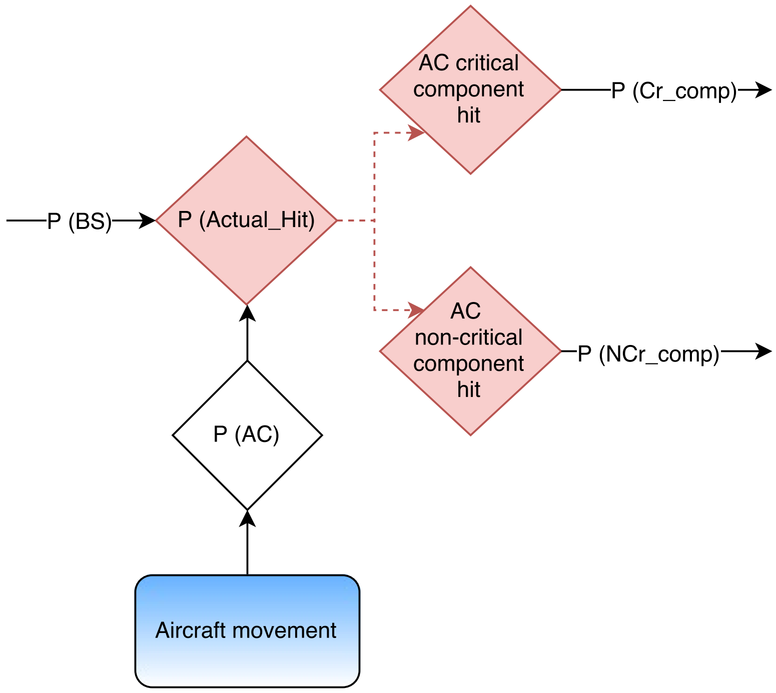


Figure 3-6: Schematic: Probability of Aircraft component hit

Input

This module has two inputs:

1. Probability of bird-strike or P (BS) during/just after a bird inspection
2. Probability of moving aircraft or P (AC) during/just after a bird inspection

3-4-1 Mathematical formulation

A bird-strike by definition is the interaction of a flying bird(s) with an aircraft. Based on the inputs for this module, the probability of an actual hit per bird inspection is given by:

$$P(Actual\_Hit) = P(BS) * P(AC) \tag{3-7}$$

Furthermore, a bird-strike on an aircraft can result in hitting a critical or a non-critical component. The aircraft components are categorized as critical or non-critical based on **effect of a bird-strike on the operational safety/airworthiness of the aircraft**. The following table categorizes the components:

Critical component (Cr_comp)	Non-critical component (NCr_comp)
Engine (POW)	Fuselage or Landing gear (FUS/LAN)
Windshield (WIN)	Wing (WING)
Nose or Radome (NOS/RAD)	Lights or Other similar size component (LIG/Others)

Table 3-5: Aircraft components - Critical and non-critical

The probabilities for the aircraft component hit can also be classified in two:

1. **AC critical component(s) hit**:

   Probability of a critical component hit is given by:

$$P(Cr\_comp) = \{P(POW) + P(WIN) + P(NOS/RAD)\} * P(Actual\_Hit) \tag{3-8}$$

where,

Aircraft component	Definition
P (POW)	Normalized probability of bird-strike on Engine(s)
P (WIN)	Normalized probability of bird-strike on windshield
P (NOS/RAD)	Normalized probability of bird-strike on Nose or Radome
P (FUS/LAN)	Normalized probability of bird-strike on Fuselage or Landing gear
P (WING)	Normalized probability of bird-strike on Wing
P (LIG/others)	Normalized probability of bird-strike on Lights or other components

Table 3-6: Aircraft component probabilities

The normalized probabilities are derived using random number generator and historical average probabilities of aircraft component hits from Transport Canada. [10]

Operational effect

A significant operational effect is considered when a bird-strike hits aircraft's critical component. The result of an operational effect could be a disruption of flight phase (Ex: Returning back to departing airport, or abort take-off) decided by the flight crew. An operational effect results in higher damage cost, an additional component of Aircraft-on-ground (AOG) costs above the direct aircraft repair/replacement costs.

$$P(Cr\_comp\_SOE) = \{0.5\} * P(Cr\_comp) \tag{3-9}$$

2. **AC non-critical component(s) hit:**

   Probability of a non-critical component hit is given by:

$$P(NCr\_comp) = \{P(FUS/LAN) + P(WING) + P(LIG/Others)\} * P(Actual\_Hit) \quad (3\text{-}10)$$

   It is assumed that a non-critical component hit does not result in a significant operational effect, and hence:

$$P(NCr\_comp\_SOE) = 0 \quad (3\text{-}11)$$

3-5 Module: Damage cost estimator

The goal of this module is to estimate the severity of a bird-strike on an aircraft's critical or non-critical component. The output of this module calculates the total expected damage cost based on probabilities and pre-defined cost headings obtained through literature sources, MRO log of airlines, and expert interviews. Damages are classified based on the bird-impact force, and corresponding cost headings are inputted in the estimator to give the output.

Damage category	Bird-impact force (minimum)	Bird-strike impact force (maximum)
Low	0	30KJ
Medium	30KJ	60KJ
High	60KJ	1GJ

Table 3-7: Damage categories based on Bird-impact force [49]

where,
KJ = Kilo (10^3) Joules
GJ = Giga (10^9) Joules

Damage categories do not consider a particular or different aircraft type, this assumption is based on EASA report. [49] Regardless of the aircraft type, the flocking tendency plays a big role in setting the threshold of the damage categories. For example, a small size bird like Buzzard with a single bird or flock of 2, hence low bird density, will result in lower damage. This when compared to Canada Goose with higher bird density (high biomass per bird, and larger flocking tendency) will result in medium or higher damage.

Bird-impact force

The extent of damage indicates the severity of a bird-strike, and is measured by a **Bird-impact force equation** [10] indicated below. The bird-impact force equation gives a better account of the strike severity over a simple bird kinetic energy equation since it uses the Bird density (a parameter that includes flock size of bird-strike prone birds).

$$Bird - impact\ force\ (in\ Joules) = \frac{2\pi r^2 \rho V^2}{3} \tag{3-12}$$

where,
r = Distance over which bird-impact is delivered in meters
ρ = Bird density (derived from biomass of the undispersed bird or B_Undsp_Biomass)
V = Aircraft velocity at the instant of bird impact (V_AC) in kmph

The schematic highlights the multiple inputs needed for a damage estimator.

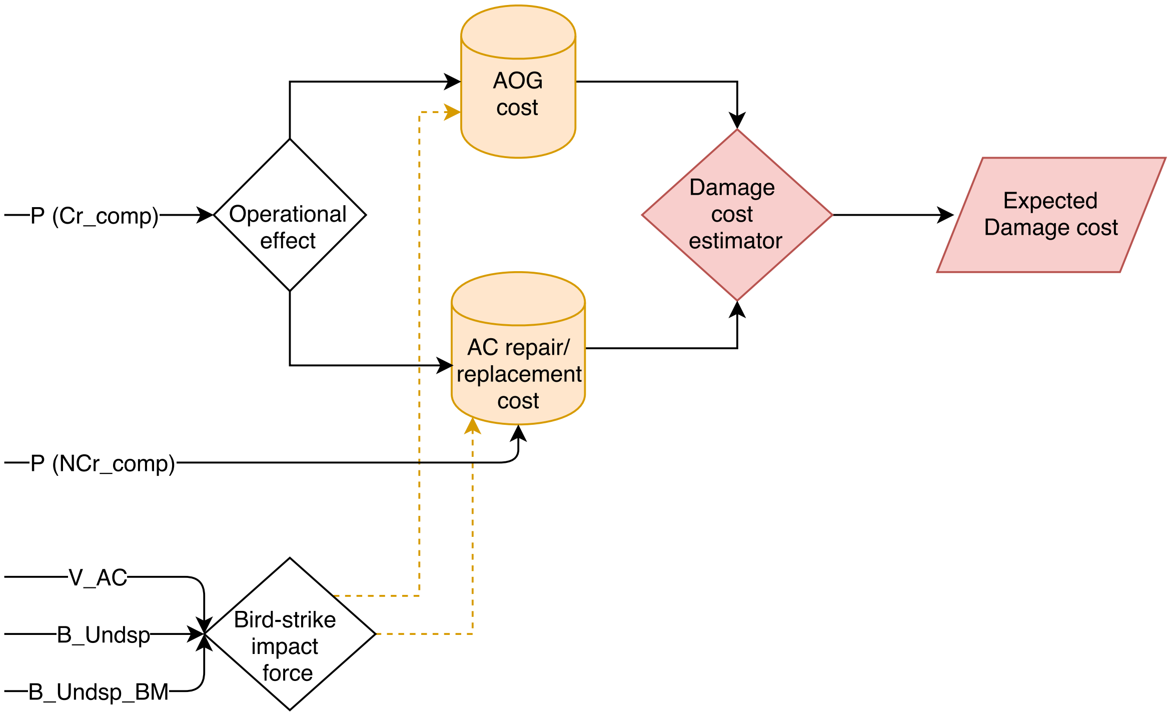


Figure 3-7: Schematic: Damage cost estimator module

3-5-1 Mathematical formulation

The damage cost functions are defined based on the probability of critical/non-critical components, and the cost parameters (using damage categories). The cost parameters are summarized as,

Cost parameter	Explanation
Avg_C(component)	Average repair/replacement cost of the aircraft component hit
AOG(component)	Average Aircraft-On-Ground costs or the downtime costs after bird-strike incident and before resuming normal operations

Table 3-8: Cost parameters for damage estimator

The average repair/replacement, and AOG costs [46] are based on damage categories, and the cost headings can be referred from the table in Appendix.

The following expected damage cost functions are based on the aircraft component hit:

1. Expected damage cost of a critical aircraft component including a significant operational effect (AOG costs):

$$Damage\,cost\,(Cr\_comp) = P(Cr\_comp) * \left\{ \sum_{i=1}^{a} P(POW) * Avg\_C(POW) + \sum_{j=1}^{b} P(WIN) * Avg\_C(WIN) + \sum_{k=1}^{c} P(NOS/RAD) * Avg\_C(NOS/RAD) \right\} + P(Cr\_comp\_SOE) * \left\{ \sum_{i=1}^{a} AOG(POW) + \sum_{j=1}^{b} AOG(WIN) + \sum_{k=1}^{c} AOG(NOS/RAD) \right\} \quad (3\text{-}13)$$

where,

i = 1 –>a	Number of bird-strikes in a year on aircraft Engine(s)
j = 1 –>b	Number of bird-strikes in a year on aircraft Windshield
k = 1 –>c	Number of bird-strikes in a year on aircraft Nose/Radome

Table 3-9: Aircraft critical component incidences

2. Expected damage cost of a non-critical aircraft component:

$$Damage\,cost(NCr\_comp) = P(NCr\_comp) * \left\{ \sum_{l=1}^{d} P(FUS/LAN) * Avg\_C(FUS/LAN) + \sum_{m=1}^{e} P(WING) * Avg\_C(WING) + \sum_{n=1}^{f} P(LIG/others) * Avg\_C(LIG/others) \right\} \quad (3\text{-}14)$$

where,

l = 1 –>d	Number of bird-strikes in a year on aircraft Fuselage/Landing gear
m = 1 –>e	Number of bird-strikes in a year on aircraft Wing
n = 1 –>f	Number of bird-strikes in a year on aircraft Lights/other components

Table 3-10: Aircraft non-critical component incidences

Output

The output of the damage estimator indicates one-single cost per realization of the model execution, hence one risk value cost. The summation of output damage costs from all the days of the year when bird control was actively conducted (number of bird inspections per year) is then used as an **input** for the Monte Carlo Simulation, that estimates the uncertainty of damage costs for any variation in the model parameter(s).

3-6 Value analysis

Value Analysis (VA) is a systematic, formal and organized process of analysis and evaluation. It is not haphazard or informal and it is a management activity that requires planning, control and co-ordination to achieve a specified goal. [52]

In the context of this research, the key focus of value analysis is to give a broader perspective of the acceptability of a bird control toolbox (combination of the bird control measures) by defining the redundant cost of damaging bird-strikes in comparison with cost for bird control. To build up the analysis, two types of techniques (also called as analysis) are used - *Cost-benefit analysis* and *Risk analysis*.

Risk analysis and CB analysis are performed on the results obtained by realizing the output of probabilistic bird-strike risk model in Monte Carlo Simulations. This section introduces the need and importance of Monte Carlo Simulation.

3-6-1 Monte Carlo Simulation

The traditional approach to addressing uncertainty in bird-strike events (strike, and the damage) forecasting is to supplement the base-case forecasts with high and low forecasts based on the measures in place. These do convey that there is uncertainty in the forecast and provide a rough, although typically narrow, range of likely outcomes. This approach provides the airport management team, and other decision making stakeholders only a cursory understanding of the risk profile facing the airport and offer limited information on the various factors that may influence bird-strike events. Furthermore, due to the limited insight they provide, the findings from this approach is rarely incorporated into the strategy planning process in any meaningful way.

Monte Carlo method is realized in terms of a statistical simulation technique used to understand the impact of risk, and uncertainty in probabilistic risk modeling. To find the uncertainty in forecasting models, some assumptions are made for parameters in the model, and MCS is used to estimate the expected value of them. The actual value cannot be determined with certainty, but based on historical data (previous estimates) or expertise in the field, or past experience, concrete estimates can be drawn. While this estimate is useful for developing a model, it contains some inherent uncertainty and risk, because it's an estimate of an unknown value.

When a model is based on ranges of estimates, the output of the model will also be a range. Based on the range, MCS indicates the likelihood of the resulting outcomes. [30] A random value is selected for each of the parameter, based on the range of estimates and the model is calculated based on this random value. The result of the model is recorded, and the process is repeated. A typical MCS calculates the model hundreds or thousands of times, each time using different randomly-selected values. When the simulation is complete, a distribution is achieved, each data point based on random input values. [30].

MCS does not necessarily intend to produce more accurate forecasts; it is are designed to provide a greater understanding and awareness of future uncertainty. This understanding can then be used in supporting bird-strike mitigation plan of an airport, and provide input to strategic analysis and financial analysis of the same. [47]

The outcome will be determined by the evaluation of the MCS model in full functionality, and inferring the results in terms of value analysis - Cost benefit analysis and Risk analysis. Whether the outcome indicates an improvement, degradation or no change in bird-strike mitigation plan, it does not alleviate the usefulness of the research. The expectation is a positive outcome that will give an account of the acceptability of the value analysis, and its potential scope for future research, and implementation in decision making. Conversely, negative results would allow future research to develop alternative methods of assessing value of bird control measures, and effect it has on the factors identified in this research. Either way, the study delivers a framework for integrated bird control, and can be adapted to accommodate other future iterations or new methods.

3-6-2 Cost-benefit analysis

The cost-benefit analysis is expressed as a ratio of the potential savings in damages with/without bird control (due to the effectiveness/ ineffectiveness) to the bird control costs. For the selected bird species, higher CB ratio determine lower risk, and acceptable bird control measures.

The mathematical formulation is given by:

$$Cost - benefit\ ratio\ (CBR) = \frac{Potential\ saving\ [(Expected\ -\ Actual)\ damage\ costs]}{Bird\ control\ costs} \tag{3-15}$$

Chapter 4

Case study - Eindhoven airport

4-1 Context

The probabilistic bird-strike risk model is applied in a case study - Eindhoven airport (IATA: EIN, ICAO: EHEH) in the south of the Netherlands. It is among the fastest growing (in aircraft movements) regional airports in Europe, and implements an integrated policy for growth, the local environment and sustainability. Eindhoven airport is however surrounded by agricultural fields, and water bodies that attract different species of local and migratory birds, hence bird-strikes become an important consideration to address. The motivation for choosing **EIN** as the case study was due to:

1. The presence of a diverse bird species (low to high risk) in the airport environment.
2. The average bird-strike rate of **8.0** per 10.000 aircraft movements, which classifies the airport as a 'High risk' airport. [26]
3. Bird control at the airport is planned, and executed by the Royal Netherlands Air Force. There is an active willingness of RNLAF to collect, and share bird data and expertise to support academic researches.
4. A growing regional airport to test the proof of concept

	Data used in risk model
159	Bird inspections for 2015
6	High risk bird species
6	Reactive (on airport) bird control measures used

Table 4-1: Summary: bird-strike risk analysis at Eindhoven

4-2 Monte Carlo Simulation results

The probabilistic bird-strike risk model was run using the database for selected bird species at Eindhoven airport in the year 2015. For calculating the expected damage cost, two separate scenarios were considered - with or without using bird control measures. The output of the scenarios were:

1. Expected damage cost without bird control
2. Expected damage cost with bird control
3. Bird control cost

These outputs served as an input for three separate Monte Carlo simulators in Excel, each generating future estimates of the costs. This section presents the MCS results (CDF plots) for two bird species -**Buzzard** and **Starling** and the summary of simulation parameters.

The rationale for choosing the pair is based on:

1. Difference in biomass per bird - A Buzzard weighs around 800gm, while Starling around 80gms
2. Difference in flocking behavior - Buzzard flies alone, while Starling fly in a flock of 60 birds on average.
3. Similar bird control measures used - Historically, both Buzzard and Starling react to similar bird control measures, hence it is easy to compare effectiveness of measures for them individually.

The distribution chosen for result analysis is an empirical cumulative distribution function (**CDF**) with an assumption that dataset (used for MCS) was continuous in costs.

4-2-1 Expected damage without bird control

The P (BS) was calculated with the condition:

$$B\_Undsp = B\_Count \tag{4-1}$$

i.e. all the birds counted during an inspection were left undispersed. The results from the MCS conclude:

- The expected damage costs due to a bird-strike involving a Buzzard lie below €270K, and less than 10% lie under €200K.
- Whereas, for Starling the costs go up to €1,3million. The least damaging bird-strike caused by a Starling is 27% costlier compared to Buzzard.

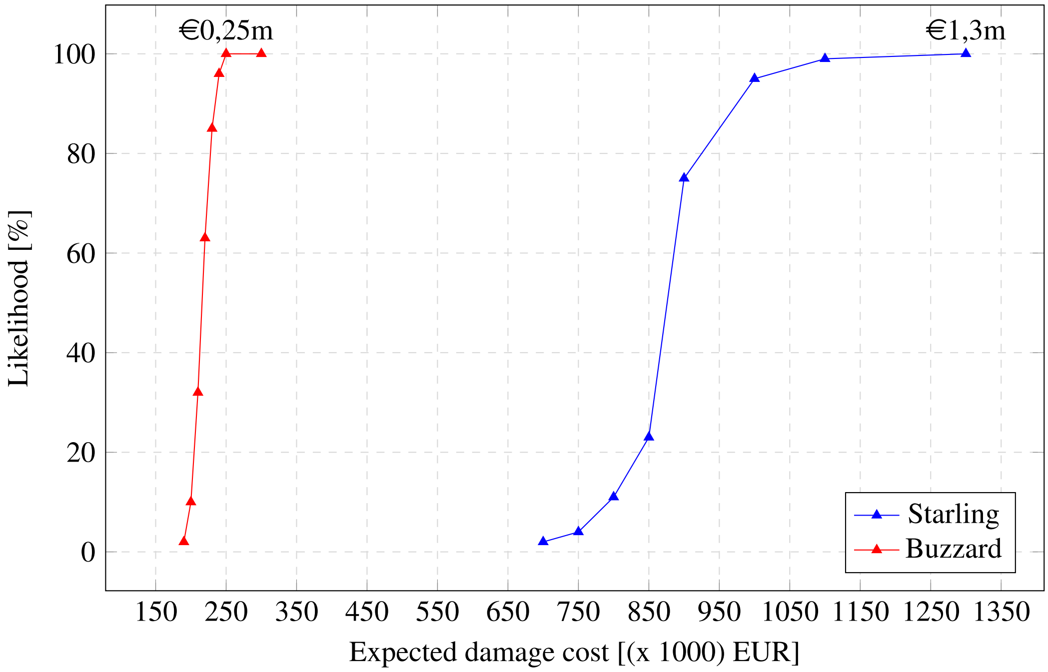


Figure 4-1: Expected damage cost **without** bird control

Simulation parameters	Costs
Average damage	€226.798
Median	€226.664
Lowest	€185.305
Highest	€269.025
Standard deviation	€13.070

Table 4-2: MCS summary for Buzzard - Damage costs **without** bird control

Simulation parameters	Costs
Average damage	€934.891
Median	€925.796
Lowest	€685.020
Highest	€1.310.382
Standard deviation	€105.299

Table 4-3: MCS summary for Starling - Damage costs **without** bird control

Inference on comparing species

The difference in bird specie biomass and flocking tendency justifies the enormous difference in the expected damage costs. A single Starling bird has a 1/10th biomass and flocking tendency of 30 times as compared to Buzzard. The latter is due to **murmuration** or swarm behavior that the flock of Starling exhibit by aggregating and flying together in large numbers.[50] In an event of bird-strike, multiple aircraft components are hit, thus causing higher damage.

The results also justifies the placement of Starling as a higher bird-strike risk specie than Buzzard in the Bird-strike risk matrix used for bird control planning at Eindhoven.

4-2-2 Expected damage with bird control

Applying bird control measures to disperse Buzzard and Starling can still leave some of them undispersed *B_Undsp*. The historic effectiveness of bird control measures for EIN can be found in the Appendix. The results show:

- The expected damage costs due to a bird-strike involving either a Buzzard or Starling lie below €7500.
- The average damage cost involving Buzzard was 6,5 times more than that of Starling

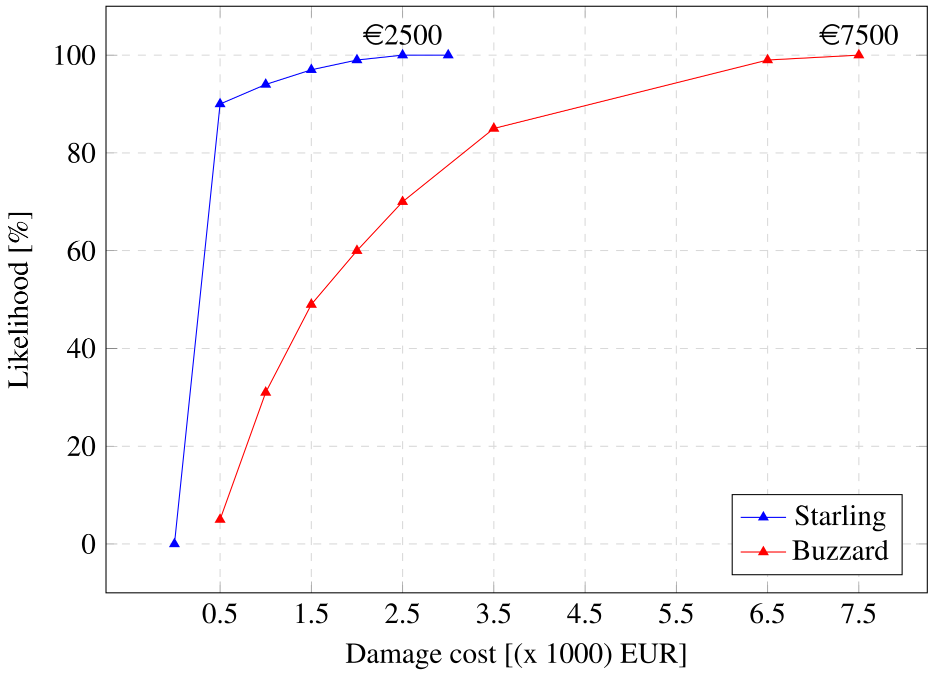


Figure 4-2: Expected damage cost **with** bird control

Simulation parameters	Costs
Average damage	€1.863
Median	€1.515
Lowest	€239
Highest	€7.899
Standard deviation	€1.345

Table 4-4: MCS summary for Buzzard - Damage costs **with** bird control

Simulation parameters	Costs
Average damage	€283
Median	€178
Lowest	€148
Highest	€3.021
Standard deviation	€355

Table 4-5: MCS summary for Starling - Damage costs **with** bird control

Inference on comparing species

The results justify that using the same bird control measures for both species result in the drastic reduction in damage cost compared to the previous scenario of no bird control. However, these results should be understood and interpreted with bird control costs incurred in order to compare the extent of effectiveness of the measures on both species.

4-2-3 Bird control costs

The methodology chapter describes the cost components of bird control:

1. Reactive bird control costs that emerge from the Probabilistic bird-strike risk model. Hence these are variable costs
2. Fixed cost (Ex: bird control vehicle during bird inspection) and proactive costs are constant regardless of usage of reactive bird control measures

The MCS results for total bird control costs is plotted below:

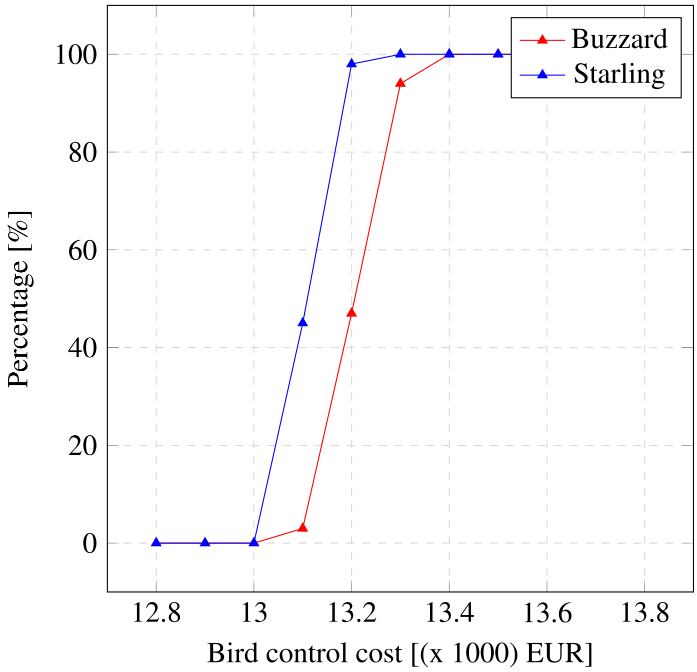


Figure 4-3: Bird control costs

Simulation parameters	Costs
Average bird control	€13.305
Median	€13.305
Lowest	€13.121
Highest	€13.475
Standard deviation	€56

Table 4-6: MCS summary for Buzzard - Bird control costs

Simulation parameters	Costs
Average bird control	€13.207
Median	€13.207
Lowest	€13.069
Highest	€13.346
Standard deviation	€46

Table 4-7: MCS summary for Starling - Bird control costs

Inference on comparing species

Using bird control significantly reduces the expected damage costs (under €7500) for both the species using similar bird control measures. Yet the rationale for the difference between higher damage by Buzzard compared to Starling is:

1. Undispersed Buzzard (s) cause more damaging strike (due to higher biomass per bird), hence higher damage cost.
2. The flock of Starling is easily dispersed by Pyrotechnics or/and Sound dispersal (effectiveness of 96%).

The cost distribution of bird control costs (per bird control measure, per unit use) can be referred in the Appendix (Table A-4)

4-3 Value analysis

Value analysis for the research methodology is expressed in terms of Risk analysis and Cost-benefit analysis, in the sections below. The combination of the two analyses support a comprehensive decision-making process by:

1. Determining the risk level of a bird specie
2. The most cost-effective bird control toolbox to lower the risk

4-3-1 Risk analysis

The output of a single realization of the probabilistic bird-strike risk model is an estimated risk value(computed from the probability of a bird-strike and its severity) using bird control. This risk value expressed in terms of **expected damage cost** serves as the basis of risk analysis of a specific bird specie. The ultimate goal is to construct a forecasted risk matrix featuring bird species present at an airport, based on:

- Probability of a bird-strike damage (controllable)
- Severity index of the bird-strike damage (not-controllable)

The goal of the risk analysis is to ascertain the risk level of a damaging bird-strike of a bird specie. To reach the goal, the following steps were taken per bird specie, and ultimately expanded to represent risk potential of all bird species for an airport:

1. The damage cost distribution from the Monte Carlo Simulations was categorized as Low, Medium, and High risk based on assumed thresholds (Appendix Table A-30). Probability of a damage cost, and corresponding risk level is found by:

$$P(DC) = \frac{No.\ of\ data\ points}{MCS\ iterations} \tag{4-2}$$

2. The severity of the risk matrix are the damage categories.

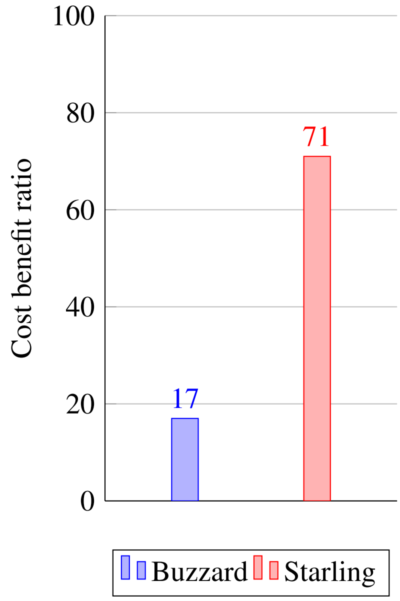
Categorizing the damage costs is relative to different airport, aircraft operator and other stakeholders. The author recommends a thorough research further followed by comparing the resulting risk analysis with established bird-strike risk matrix (refer to literature)

Risk level	Buzzard probability	Starling probability
Low	0.82	0.96
Medium	0.16	0.04
High	0.01	0

Table 4-8: Risk analysis - Buzzard and Starling

4-3-2 Cost-benefit analysis

For the defined bird control effectiveness, the potential savings in damage cost with respect to the bird control costs can be analyzed in the context of a Cost-benefit analysis. The cost-benefit ratios for the two species are presented in the bar chart, and explained in the table below -



Bird specie	Average Bird control cost	Average Expected damage cost (without bird control)	Average Damage cost (with bird control)	Potential saving (with bird control)	Cost-benefit ratio
Buzzard	13,305	226,798	1,863	224,935	**16,91**
Starling	13,207	934,891	0,283	934,608	**70,77**

Table 4-9: Cost-benefit ratio matrix - Buzzard and Starling

Inference

As indicated in the methodology, a monetarily effective bird control is represented by a **higher CB ratio** and consequently lower risk.

The CB ratio calculations also indicate the significant savings using bird control for Buzzard and Starling. The comparison also highlights how the two species react differently (due to the difference in their biomass, and flocking behavior) to the similar bird control measures.

The combination of CB analysis and risk analysis build a good foundation for decision making and further research in other analysis framework like cost-effectiveness analysis, or parameter analysis with studying impact of bird control measures on the risk. This is further detailed in the conclusions and future work chapter.

Chapter 5

Conclusion and recommendations

This chapter summarizes the analytical process undertaken in this research to critically review the correlation of this work with the research objectives, and in broader sense the contribution to the body of knowledge in bird-strike risk mitigation strategy. The results obtained from applying the methodology on the Eindhoven airport serves as the proof of concept, and the value analysis is summarized in the first section. The limitations of this research work, and their importance in influencing the results are explained in terms of scope, assumptions and data analysis. The final section are the recommendations for the future work based on the problem definition and explore research opportunities that develop further understanding of the problem, and significant solutions that can serve as blueprint for a general airport.

5-1 General conclusion

The methodology to build a Probabilistic bird-strike risk matrix was applied on Eindhoven as a case study and the results were detailed in the previous chapter. The results conclude in a value analysis for two bird species that **strengthen the research hypothesis** but also highlight the dependencies. To put to context, the research examined if an optimum existed between investment in bird control and the expected damage costs from its ineffectiveness.

The key findings from the methodology, and case study are:

- A probabilistic bird-strike risk model represents a **good** quantitative approach for conducting a value analysis.
- The bird species chosen represent the global bird-strike risk spectrum; Eindhoven as an airport for case study with a high bird-strike risk rate. These inputs help achieve high model fidelity.
- The combination of risk analysis and cost-benefit compared, and concluded the need for a new bird-strike risk matrix to place bird species based on their risk levels, when compared to the earlier categorization.

- The research brought more focus on bird-strike mitigation for Buzzard than Starling.

The cost-benefit analysis of remaining four bird species - Kestrel, Lapwing, Swift and Canada Goose was also conducted, and can be referred from Appendix (A-2-9). This was done to have a complete overview of the bird-strike problem at Eindhoven, and that can serve as a meaningful input for the bird control management. However, the risk analysis couldn't be included as a part of the results due to the time constraint of the MSc graduation process.

The following conclusions about two bird species - Kestrel and Swift which have the lowest cost-benefit ratios is very relevant to the recommendations of future-work mentioned later in the report.

- The biomass of a Kestrel is 5 times and average flock size is 1/30th that of a Swift. From the MCS results:
    1. Without bird control, closely packed flock of Swift caused 4 times more damage than compared to Kestrel. This also explains the importance of using the bird-impact force to estimate severity (higher bird density is higher impact force) instead of considering only biomass.
    2. With bird control, the damage cost due to Kestrel reduced significantly (0.7% of damage without bird control), while that for Swift only by 50%. This difference can be explained because of the flying behavior of Swift - Large flocks fly with high speeds to catch worms and insects across the length of the runway which becomes very difficult to be dispersed by bird control measures, and leaves the only possibility to shut the runway for operations. [40]
- Kestrels are *returning birds* and have an influence on P(BS), but the results do not consider that factor in damage calculations. Separate studies at the Royal Netherlands Air force hence recognize the need of better bird control for Kestrel, and results of this research support that rationale. As a step further, a feasibility study is currently undertaken to assess the success ratio of bird control measures like *Catching and replacement* on Kestrel. Based on the literature, and expert interviews, the author concludes that the chosen measures are less "bird-friendly" and could be a bottleneck to implement them as accepted measures by environmentalist and bird protection agencies. This would further contribute to **loss of good public perception** which is a factor that needs to be weighed in for a cost-effectiveness study.

The overall conclusion based on results and analysis can answer the research question - *Can the value analysis of integral bird control measures improve the bird-strike mitigation at an airport?*. And the answer is **Yes, but partially**. The section on limitations will further elaborate on the reasons, list the research dependencies, and the recommend steps for the future-work.

Contribution to the body of knowledge

The significance of this research work lies in the novelty of using known statistical methodology and analysis techniques to the bird-strike problem.

- Explored a new perspective on bird-strike risk assessment in terms of improved definitions of probability and severity, for a specific airport with the possibility to replicate for any other airport. This becomes a good basis for comparison of bird-strike mitigation programs globally.

- Proved to be simple and effective way to quantify several aspects of the problem/solution known only qualitatively before.
- Piqued interest of stakeholders since the work specifies the interaction
- Set the tone for a structured future-work, and foster bonds of cooperation with industry/bird control agency like RNLAF.

5-2 Limitations of current work

Due to the novelty of this research, and the definition of ambitious research objectives, several limitations in terms of scope, assumptions, and data analysis surfaced. The limitations are discussed in the category mentioned to give a clear understanding of what can be done as a follow-up of this research work:

1. Scope: The limitations in the scope give the difference between planning, and achieving the research objectives in the course of this research work.
   (a) The value analysis planned could not include *Cost-effectiveness study* that quantifies the benefits of non-monetary parameters in the bird-strike problem (public perception, safety, airport capacity, etc.) over the investment in bird control.
   (b) The thresholds for damages used in risk analysis for Buzzard and Starling are hypothetical and are based on logical know-how and industry practice. the remaining bird species (except Buzzard and Starling) could not be entirely conducted.
2. Model assumptions and their implications: The modeling framework that describes the analytical process used several assumptions - some logical, and some hypothetical.
   - The performance of bird control measures in different conditions (weather, airport specific, etc.) and a "not-average-day" was not included, and rather "fixed" probabilities of usage and effectiveness (from historical database) were used for the chosen bird species. The author estimates the difference between the assumption and reality to be significant since evidence supports poor performance that played a role in the bird-strikes of 2015.
   - Using *one* bird control measure per bird inspection is a theoretical assumption to make the model implementation simpler. In practice, depending on the bird specie, several measures can/are used in an inspection to perform the dispersal action. Canada Goose for example is listed as a *Zero tolerance* bird specie, i.e. bird controllers are obliged to disperse 100% of the birds observed to prevent any potential bird-strike due to high damage risk levels.
   - Aircraft movement is hypothetically assumed to be positive during/just after a bird inspection, which makes all movements bird-strike prone. In practice, bird inspections may or may not coincide with flight operations. Rather a bird control action is planned in advance to anticipate aircraft movement.
   - Bird-strikes for departing and arriving aircraft have different cost impact. The model considers no difference in the flight phase of the aircraft.
3. Data:

- The supplied data from the RNLAF was not normalized, and while normalizing bird count for bird species (Swift and Lapwing), negative values were observed. This was due to either no bird count observed and recorded for the inspection, or other unknown inconsistencies. The solution was reached to use a non-normalized bird data (raw) for the bird species.
- The MCS was performed based on bird inspections done for 2015, hence only a year. This choice was based on the high bird-strike rate recorded in 2015 compared to other years. The missing rationale for the choice was a limiting factor in terms of scientific acceptance of model.
- The damage costs in repair/replacement and AOG are broad assumptions due to lack of real data from airline maintenance, and other sources. Best efforts were done to source data from open-source database like that provided by FAA.
- Too many "unknown" and not explored parameters were present in supplied data from the RNLAF.

5-3 Recommendations for future work

Having defined the limitations of this research, it is important to focus on adding perspectives and exploring further research opportunities to mitigate bird-strike related problem furthe than the current efforts, also involving a multi-stakeholder ecosystem. In this concluding section of the report, the recommendations for future-work is explained in terms of targets, interaction and vision for the three stakeholders - Bird control management, Aircraft operator (Airlines), and Research & Development.

General recommendations

The most important recommendation lies common to all the stakeholders, and its significance is realized at a broader level, i.e. sustainable and cost-effective program for bird-strike mitigation. The following summarize this goal:

- To customize or introduce a Safety Management System (SMS) model catered to the bird-strike problem that applies to all the stakeholders by implementing a combination of tested tools. This should include setting thresholds for risk analysis.
- Improving information sharing among stakeholders - **Data**, analytics and combined expertise of industry experts and scientific community.
- Open discussion on shared liabilities and impact with stakeholders. This will push result-driven approach to solving the problem.

5-3-1 Bird control management

The bird control management consists of bird control planners, SMS experts on bird-strikes, and bird controllers. The following recommendations are in addition to the existing working procedure/interaction of these stakeholders:

Bird controllers

- Improving the quality of data collection, and active participation in studies involving *User-in-the-loop* studies. Being the stakeholder delegated with higher responsibility, this can equalize the efforts to other stakeholders
- More autonomy should be given to ensure higher human performance in the dispersal tasks

Bird control planners

The bird control planners, and SMS experts at the airport are responsible for setting up targets to mitigate the number of damaging bird-strikes. The recommendations are:

- Define realizable trade-offs for achieving operational KPIs. This drives specificity and incentive for meaningful collaboration with R&D to offer a well-defined input. Example: Setting up a trade-off between achieving highest safety standards (minimum number of damaging bird-strikes for existing aircraft movement) and willingness to invest in expensive bird control. This should be done to set up a locally defined ALARP value.
- Conducting more audits for iterative development of mitigation programs. This thought is inspired from the lean-process in business development.
- Using academic researches (like this) and other assessment studies an input, to work with technology vendors and develop the relevant cost-effective bird control management program, that is both environment and user (bird controller) friendly.
- Assess the integration of the above with regulatory framework.
- Invest in building advisory tools for enhanced awareness of the pilot crew

5-3-2 Aircraft operator/ Airlines

- For improving predictive maintenance for inevitable bird-strike related accidents, work with the bird control planning and R&D (technology developers) to share accurate damage data (costs, and aircraft components hit).
- Ascertain the operational safety-risk for growth potential (capacity) for a certain airport. Example: Defining a trade-off for increasing/reducing capacity for an airport with low/high bird-strike risk.

5-3-3 Research & Development

1. Harness the academic potential by designing and building tools in close cooperation with the industry, and other stakeholders in the bird-strike mitigation ecosystem . The means improving or defining new methodologies focused on user-input and interaction, for better performance and achieving realizable targets.

   Out of the few research opportunities identified, the most prominent follow-up for this work is proposed:

(a) Design and build a *Time-based simulation tool* for bird control operations at an airport. The likely features include:

- Collecting hourly (or other time unit) data of bird species and their count using an avian radar (as compared to manual), aircraft movements from surface movement radar, and bird control activities (inspections, toolbox, dispersal success) for a fixed duration of building the tool.
- Integrating data streams to implement a predictive risk model that could significantly lower bird-strike impact, and give a clear direction to most cost-effective bird control toolbox. As mentioned above, the goal should be using such models as blueprint to customize for use at any airport globally.
- It should transform as a tactical decision-making support tool for the future

(b) For future quantitative models, *Scenario discovery* (static policy) is a good mathematical tool to identify the goodness of assumptions and helps robust decision making. [51]

Appendix A

A-1 Input data

A-1-1 Bird specie(s), biomass and count

The bird species, and their biomass is provided by the Royal Netherlands Air Force. The biomass data is not a standard representative of the selected species worldwide, and hence could vary with another country/ecosystem. For this research, the following data was used for Eindhoven airport :

Bird specie	Biomass (per bird in Kgs)
Buzzard	0.86
Canada Goose	4.5
Kestrel	0.22
Lapwing	0.22
Starling	0.08
Swift	0.04

Table A-1: Bird specie biomass [40]

The bird counts (unprocessed, and normalized for modeling) as provided by the Royal Netherlands Air Force are attached electronically with this report as confidential database under the Non-disclosure agreement, and hence is not a part of this section.

A-1-2 Data for damage cost estimation

The input data tables for damage costs based on bird-impact force and aircraft component sourced from a combination of literature documents [10] and airline MRO personnel :

Damage type	Bird-impact force (min)	Bird-impact force (max)	Engine (POW)	Windshield (WIN)	Nose/Radome (NOS/RAD)	Fuselage/Landing gear (FUS/LAN)	Wing (WING)	Lights (LIG)
Low damage	0	30000	200,00	200,00	200,00	200,00	200,00	200,00
Medium damage	30001	60000	100.000,00	100.000,00	50.000,00	50.000,00	50.000,00	1.000,00
High damage	60001	100000000	5.000.000,00	100.000,00	100.000,00	100.000,00	100.000,00	5.000,00

Table A-2: Damage categories: Direct repairs/replacement costs [41][25]

Damage type	Bird-impact force (min)	Bird-impact force (max)	Engine (POW)	Windshield (WIN)	Nose/Radome (NOS/RAD)	Fuselage/Landing gear (FUS/LAN)	Wing (WING)	Lights (LIG)
Low damage	0	30000	1.500,00	1.500,00	1.500,00	1.500,00	1.500,00	1.500,00
Medium damage	30001	60000	36.000,00	36.000,00	72.000,00	72.000,00	72.000,00	3.000,00
High damage	60001	100000000	108.000,00	36.000,00	72.000,00	72.000,00	72.000,00	6.000,00

Table A-3: Damage categories: Aircraft-On-Ground costs [41][25]

A-1-3 Bird control usage and effectiveness

The usage and effectiveness of bird control measures for chosen bird species based on the historical database supplied by the RNLAF [40] are given in this section:

Buzzard

	Sound dispersal	Pyrotechnics	Shooting	Lights	Bird control vehicle
Usage	42%	46%	6%	1%	5%
Effectiveness	90%	89%	100%	50%	100%

Table A-4: Bird control measures for Buzzard - Eindhoven data 2000-2016

Starling

	Sound dispersal	Pyrotechnics	Shooting	Lights	Bird control vehicle
Usage	44%	53%	0%	0%	3%
Effectiveness	96%	96%	-	-	92%

Table A-5: Bird control measures for Starling - Eindhoven data 2000-2016

Canada Goose

	Sound dispersal	Pyrotechnics	Shooting	Lasers	Bird control vehicle
Usage	7%	65%	4%	14%	10%
Effectiveness	67%	93%	100%	100%	100%

Table A-6: Canada Goose - Woensdrecht data 2000-2016

Kestrel

	Sound dispersal	Pyrotechnics	Shooting	Bird control vehicle
Usage	32%	23%	31%	14%
Effectiveness	82%	96%	100%	80%

Table A-7: Kestrel - Eindhoven data 2000-2016

Lapwing

	Sound dispersal	Pyrotechnics	Shooting	Lights	Bird control vehicle
Usage	49%	46%	1%	0%	3%
Effectiveness	97%	96%	100%	97%	93%

Table A-8: Lapwing - Eindhoven data 2000-2016

Swift

	Sound dispersal	Pyrotechnics	Bird control vehicle
Usage	25%	70%	5%
Effectiveness	40%	21%	100%

Table A-9: Swift - Eindhoven data 2000-2016

A-1-4 Bird control costs

The input data tables are for bird control cost functions, sourced from a combination of literature documents, Bird Control Group, and Royal Netherlands Air Force.

The indicated cost headings for various bird control measures, remuneration of bird control personnel are expressed in €and apply to Eindhoven airport, the Netherlands :

Bird control measure	Cost in (€) per usage/day*/one-time acquisition**
Sound dispersal (Bioacoustics/distress calls)	5,00
Pyrotechnics (Flare guns)	12,00
Shooting (Shot gun/ other ammunition)	5,00
Propane gas cannon	15,00
Falconry	500,00*
Caracasses	3,70
RPAS (Remotely piloted aircraft system)	2.500,00**
Lasers	8,33
Lights	30,00
Bird control vehicle	15,00

Table A-10: Reactive bird control costs

Fixed bird control	Costs in (€) per bird inspection
Bird control vehicle	26,24
Bird controller salary	32,88
Habitat management	13,70
Field administration	0,96

Table A-11: Fixed bird control costs

These costs are considering following assumptions (not in chronological order):

- The cost of a measure is sampled for per usage, or one-time cost divided by a product of life expectancy of the measure and bird inspections per year.
- Total inspections per year do not exceed 3650, ie. 10 inspections per day
- Total distance travelled by the bird control vehicle for the entire day does not exceed 200kms
- Bird control vehicle costs include - Intervention time (time to drive), ATC communication, and fuel costs for the vehicle. Intervention time is 10 mins, and Average fuel cost per km - €1,23
- Average salary/remuneration for the bird controller is €60.000

A-2 Monte Carlo simulation results - All bird species

This section details the MCS results for all the six bird species, including Buzzard and Starling (in the case study). The results per bird specie, include

- Expected damage cost without bird control, and simulation parameters
- Damage cost with bird control, bird control cost, and simulation parameters
- Result inference table

A-2-1 Buzzard

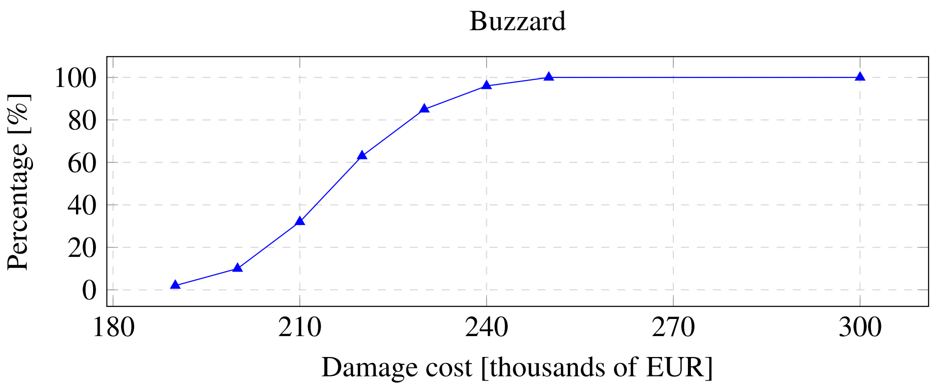


Figure A-1: Expected damage cost **without** bird control

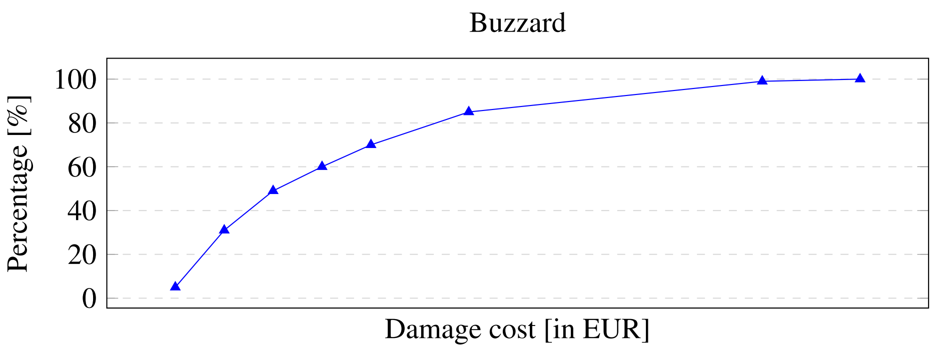


Figure A-2: Damage cost **with** bird control

Simulation parameters	Costs
Average damage	€226.798
Median	€226.664
Lowest	€185.305
Highest	€269.025
Standard deviation	€13.070

Table A-12: MCS summary for Buzzard - Damage costs **without** bird control

Simulation parameters	Costs
Average damage	€1.863
Median	€1.515
Lowest	€239
Highest	€7.899
Standard deviation	€1.345

Table A-13: MCS summary for Buzzard - Damage costs **with** bird control

Simulation parameters	Costs
Average bird control	€13.305
Median	€13.305
Lowest	€13.121
Highest	€13.475
Standard deviation	56

Table A-14: MCS summary for Buzzard - Bird control costs

Inference from the results

The inferences for Buzzard are explained in details in the case study chapter, hence skipped here to avoid repetition.

A-2-2 Starling

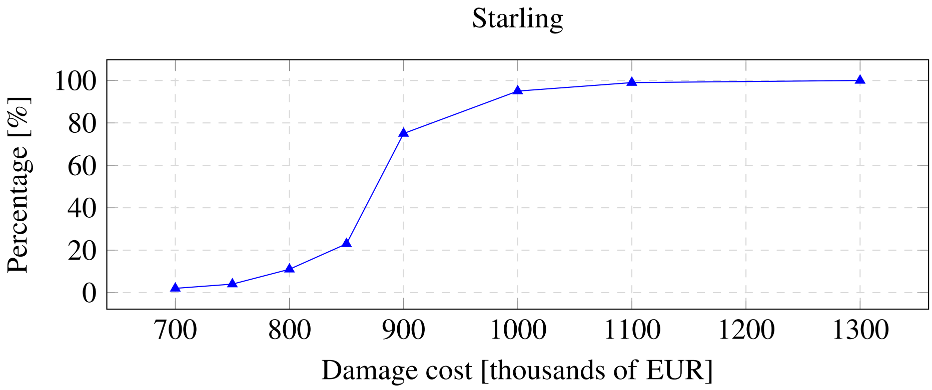


Figure A-3: Expected damage cost **without** bird control

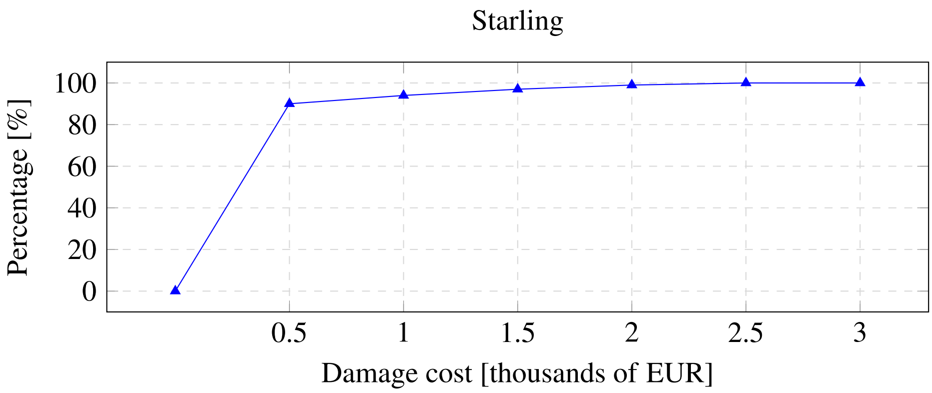


Figure A-4: Damage cost **with** bird control

Simulation parameters	Costs
Average damage	€934.891
Median	€925.796
Lowest	€685.020
Highest	€1.310.382
Standard deviation	€105.299

Table A-15: MCS summary for Starling - Damage costs **without** bird control

Simulation parameters	Costs
Average damage	€283
Median	€178
Lowest	€148
Highest	€3.021
Standard deviation	€355

Table A-16: MCS summary for Starling - Damage costs **with** bird control

Simulation parameters	Costs
Average bird control	€13.207
Median	€13.207
Lowest	€13.069
Highest	€13.346
Standard deviation	46

Table A-17: MCS summary for Starling - Bird control costs

Inference from the results

The inferences for Starling are explained in details in the case study chapter, hence skipped here to avoid repetition.

A-2-3 Canada Goose

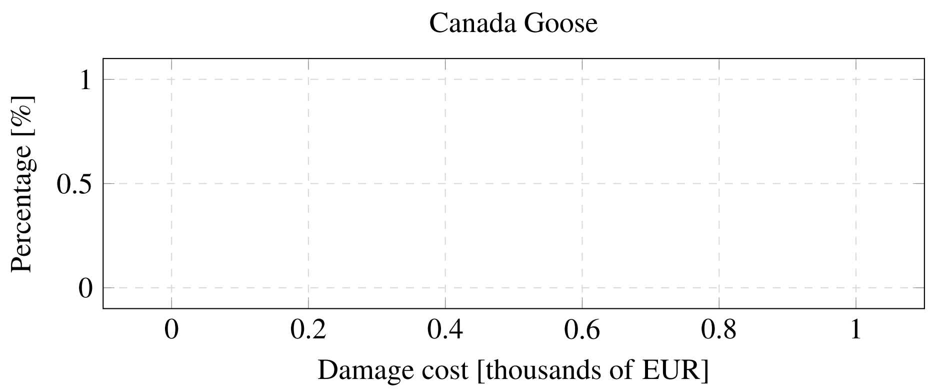


Figure A-5: Expected damage cost **without** bird control

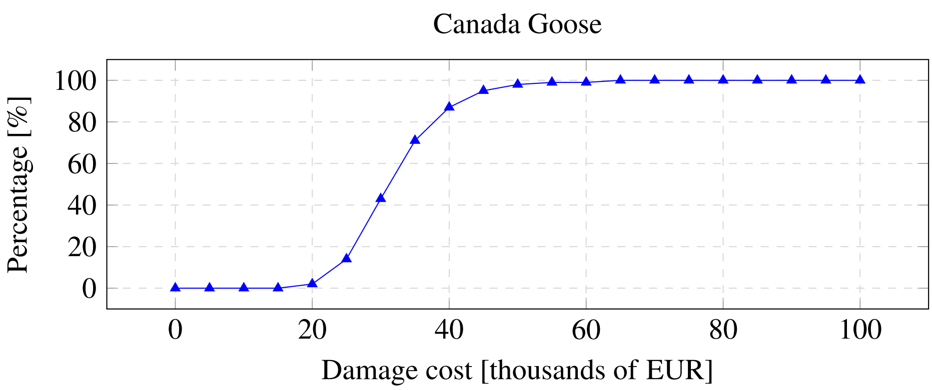


Figure A-6: Damage cost **with** bird control

Simulation parameters	Costs
Average damage	€492.425
Median	€487.949
Lowest	€344.360
Highest	€751.941
Standard deviation	€53.681

Table A-18: MCS summary for Canada Goose - Damage costs **without** bird control

Simulation parameters	Costs
Average damage	€37.096
Median	€36.169
Lowest	€22.075
Highest	€74.053
Standard deviation	€7.213

Table A-19: MCS summary for Canada Goose - Damage costs **with** bird control

Simulation parameters	Costs
Average bird control	€13.575
Median	€13.576
Lowest	€13.494
Highest	€13.637
Standard deviation	23

Table A-20: MCS summary for Canada Goose - Bird control costs

Inference from the results

Without bird control	As expected, the damage costs mostly vary between €350K, and as high as €670K. Due to the magnitude of the damages, bird control follow a 'Zero' tolerance policy
With bird control	Most of the damages are only 9% of those without bird control. Bird control costs remain in the range of €13K - €14K
	Laser is the most cost-effective, safe, and animal friendly (drawback: Weather/light dependent) to disperse a flock (average size of 20). In conjunction with Bird control vehicle, bird dispersal with almost close to 95% can be achieved. The combination is an obvious in practical sense

A-2-4 Kestrel

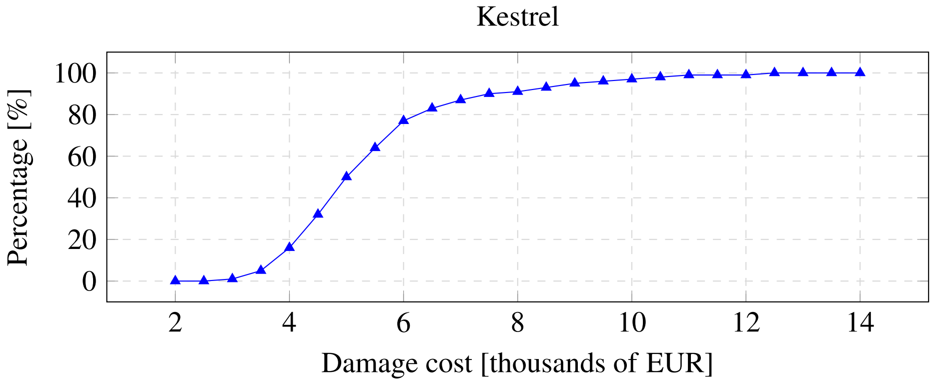


Figure A-7: Expected damage cost **without** bird control

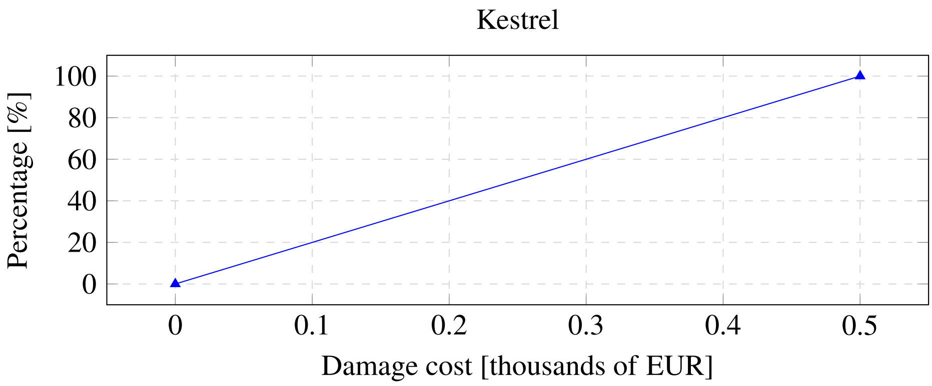


Figure A-8: Damage cost **with** bird control

Simulation parameters	Costs
Average damage	€5.911
Median	€5.540
Lowest	€2.387
Highest	€14.719
Standard deviation	€1.639

Table A-21: MCS summary for Kestrel - Damage costs **without** bird control

Simulation parameters	Costs
Average damage	€46
Median	€46
Lowest	€33
Highest	€56
Standard deviation	€4

Table A-22: MCS summary for Kestrel - Damage costs **with** bird control

Simulation parameters	Costs
Average bird control	€12.861
Median	€12.860
Lowest	€12.728
Highest	€12.995
Standard deviation	49

Table A-23: MCS summary for Kestrel - Bird control costs

Inference from the results

Without bird control	Almost all of the damages are below €10K. The average flock size of Kestrels is 2, and they don't have flocking tendency, the fact justified with low damage costs compared to other species in the same weight category
With bird control	Bird control costs (€12K - €13K) are much higher than for a minimum expected damage cost (order of €10)
	Pyrotechnics, and shooting are the most effective bird control measures but expensive and hence there is a need to investigate into other bird control measures (lights/just driving in the bird control vehicle). Reference to literature review and expert consultation.

A-2-5 Lapwing

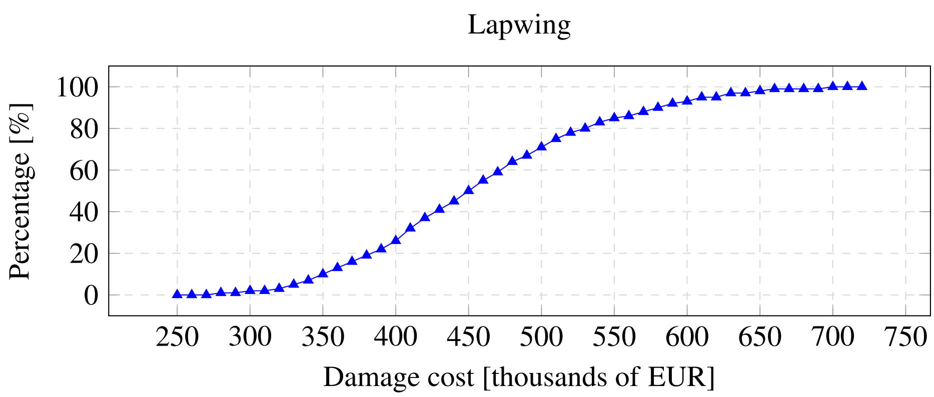


Figure A-9: Expected damage cost **without** bird control

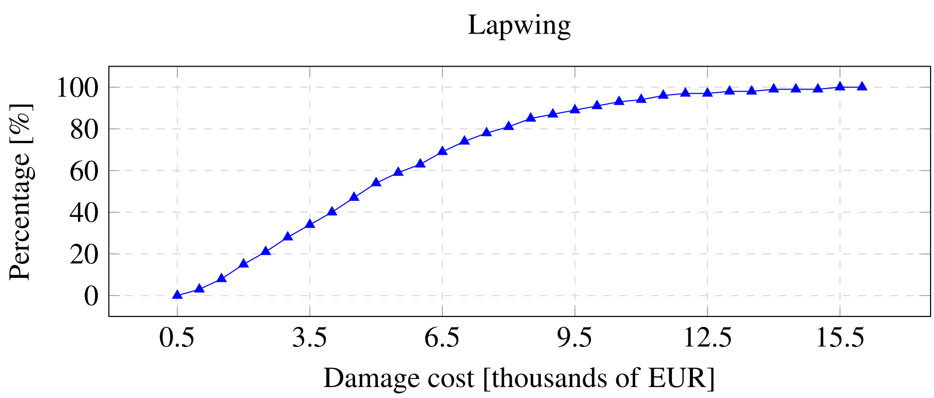


Figure A-10: Damage cost **with** bird control

Simulation parameters	Costs
Average damage	€473.187
Median	€468.945
Lowest	€261.348
Highest	€773.159
Standard deviation	€86.285

Table A-24: MCS summary for Lapwing - Damage costs **without** bird control

Simulation parameters	Costs
Average damage	€5.501
Median	€4.851
Lowest	€325
Highest	€18.294
Standard deviation	€3.297

Table A-25: MCS summary for Lapwing - Damage costs **with** bird control

Simulation parameters	Costs
Average bird control	€13.031
Median	€13.031
Lowest	€12.906
Highest	€13.174
Standard deviation	45

Table A-26: MCS summary for Lapwing - Bird control costs

Inference from the results

Without bird control	Due to high population, slow speeds but high flocking tendency; Lapwings have the potential to cause significant damaging strikes most cost over €300K up to €800K.
With bird control	Bird control investment to upto €14K does get most of the damage down to under €20K.
	Bioacoustics (sound dispersal) and Pyrotechnics are the most cost-effective bird control measures

A-2-6 Swift

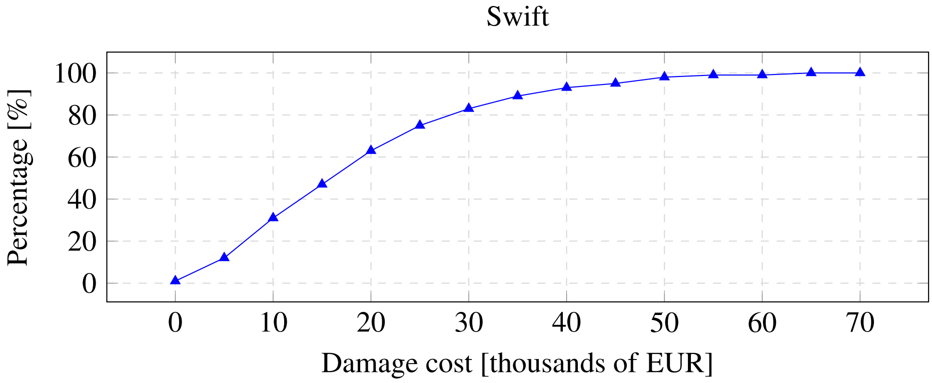


Figure A-11: Expected damage cost **without** bird control

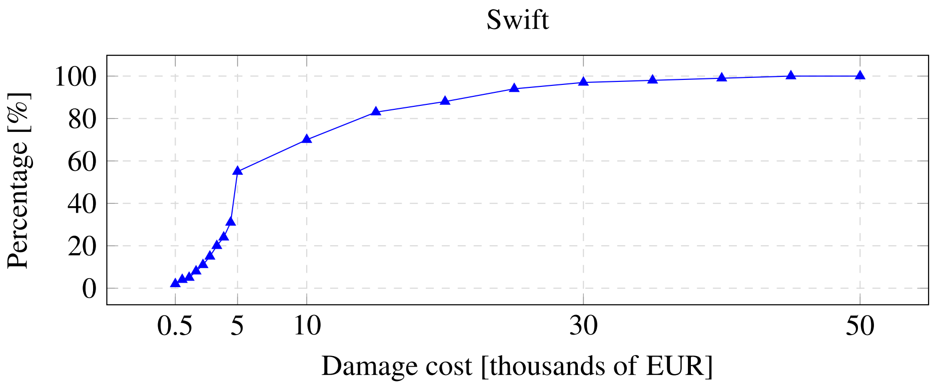


Figure A-12: Damage cost **with** bird control

Simulation parameters	Costs
Average damage	€22.921
Median	€20.140
Lowest	0
Highest	€86.686
Standard deviation	€13.007

Table A-27: MCS summary for Swift - Damage costs **without** bird control

Simulation parameters	Costs
Average damage	€11.673
Median	€8.608
Lowest	0
Highest	€77.303
Standard deviation	€9.879

Table A-28: MCS summary for Swift - Damage costs **with** bird control

Simulation parameters	Costs
Average bird control	€13.447
Median	€13.449
Lowest	€13.272
Highest	€13.554
Standard deviation	37

Table A-29: MCS summary for Swift - Bird control costs

Inference from the results

Without bird control	This particular specie is indifferent of whether bird control is done or not, and expected damages are within €75K
With bird control	Bird control cost is in the range of €13K - €14K
	Swifts are extremely difficult to disperse (Fact validation check by Hans Van Gasteren, RNLAF) and other industry experts. Pyrotechnics are the 'least' cost-effective but the most frequently used bird control measure.

A-2-7 Bird control - All species

The bird control costs for all species ranging between €12K to €14K, are plotted below. The significance of this plot is only in combination with the expected damage costs plots, and the comparison of different bird species :

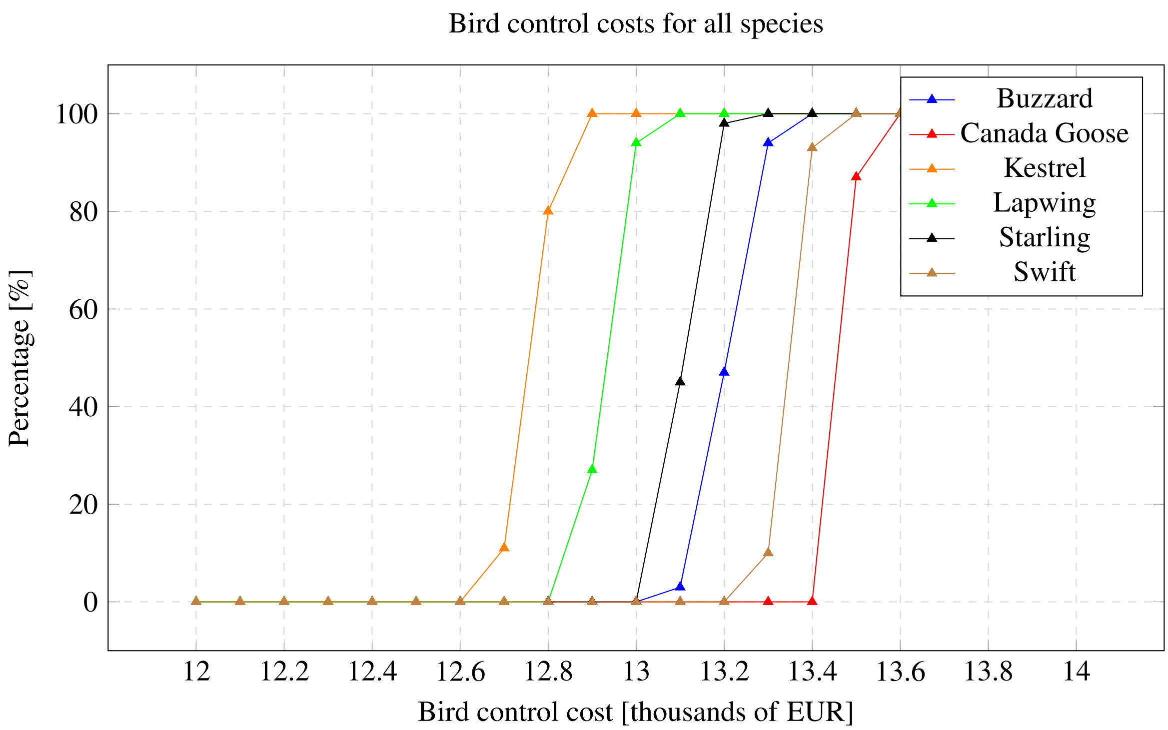


Figure A-13: Bird control costs for all species

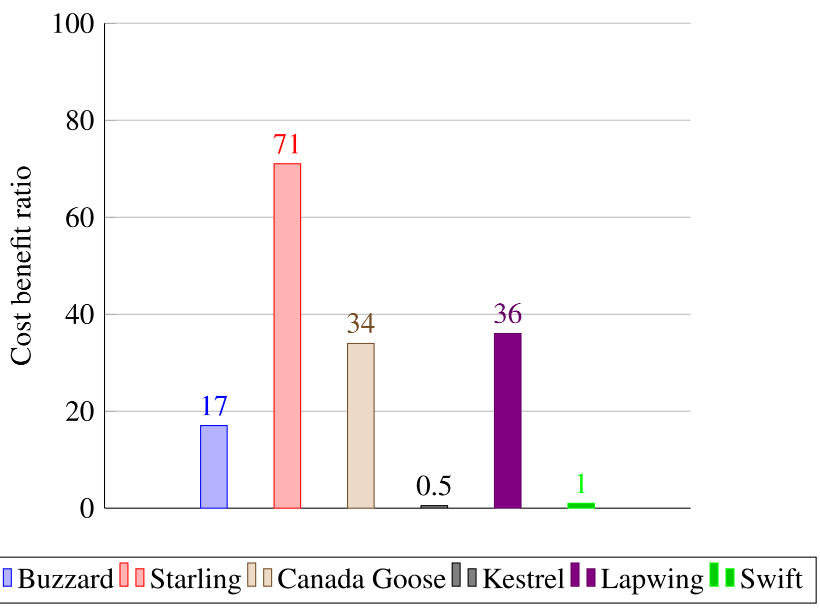
A-2-8 Risk analysis

The risk analysis thresholds are hypothesized based on literature and expert consultation. They are relatively scaled for the damaging strikes of bird species (Buzzard and Starling). The recommendation of this research work encourages to re-think and re-develop these thresholds.

Risk level	Damage cost
Low	€0 - €3000
Medium	€3000 - €6000
Heavy	€6000 - €10000

Table A-30: Risk levels - Buzzard and Starling

A-2-9 Cost-benefit analysis for all species



Bird specie	Average Bird control cost [€]	Average Expected damage cost [€] (without bird control)	Average Damage cost [€] (with bird control)	Potential saving [€] (with bird control)	Cost-benefit ratio
Buzzard	13,305	226,798	1,863	224,935	**16,91**
Starling	13,207	934,891	0,283	934,608	**70,77**
Canada Goose	13,575	492,425	37,096	455,329	**33,54**
Kestrel	12,861	5,911	0,046	5,865	**0,46**
Lapwing	13,031	473,187	5,501	467,686	**35,89**
Swift	13,447	22,921	11,673	11,248	**0,84**

Table A-31: Cost-benefit ratio matrix - All species

A-3 Bird-strike risk index

The bird-strike index for AAS and EIN is based on:

1. Probability distribution of bird specie presence:
   Based on the number of bird-strikes per 10,000 aircraft movement (BSR)

Very high	>2
High	1.5 - 2
Moderate	0.5 - 1.49
Low	0.15 - 0.49
Very low	<0.15

Table A-32: Probability categories

2. Severity distribution of bird specie:
   Based on the biomass of the bird specie, and the flocking behaviour

Very high	>1.8 kg (single) or 1.0 kg - 1.8 kg (flocks)
High	1.0 kg - 1.8 kg (single) or 0.3 kg - 1.0 kg (flocks)
Moderate	0.3 kg - 1.0 kg (single) or 0.05 kg - 0.3 kg (flocks)
Low	0.05 kg - 0.3 kg (single) or <0.05 kg (flocks)
Very low	<0.05 kg (single)

Table A-33: Severity categories

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