

Zwarte Wiek Expansie van Monitoring door Technologie

ZWEMT

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ZWEMT

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Summary

The *ZWEMT* project, officially titled "ZWEMT Zwarte Wiek Expansie van Monitoring door Technologie", was an initiative aimed at enhancing the monitoring of wind turbines to study their impact on bird behaviour and collisions. The project, which started on June 1, 2023, and ended on January 31, 2025, was a collaboration between TNO, power company RWE and funded by TKI offshore energy, the projectgroup "Zwarte Wiek" represented by the Province of Groningen, and the WOZEP program of Rijkswaterstaat. Waardenburg Ecology provided ecological support.

The primary goal of the overarching Zwarte Wiek project was to investigate the effectiveness of painting one blade of a wind turbine black to improve its visibility to birds and reduce collisions. The *ZWEMT* project was an additional effort aiming at increasing data quality through the use of additional instrumentation. Various sensors, including vibration sensors, thermal cameras, visual cameras, and microphones, were installed in and around the turbines to monitor bird behaviour and collisions. The project also employed a 3D bird radar to map flight behaviour in the vicinity of the turbines.

Preliminary results indicate that the presence of a black blade does not significantly affect the flight height, speed, or straightness of flight of birds within a 200 m radius of the turbines. However, the WT-Bird® system, which uses vibration sensors to detect collisions, faced challenges due to the non-ideal placement of sensors and noise from the turbines. Despite these setbacks, the project has registered some bird collisions and provided valuable insights into bird behaviour around wind turbines. Additionally, the cameras, especially the thermal cameras, provided valuable insight into the behaviour of birds near the turbine.

The project has also explored the use of microphones as a cost-effective alternative to vibration sensors for detecting bird collisions. While the TNO microphone showed promise, the limited number of collisions detected by the WT-Bird® system prevented a comprehensive comparison.

Overall, the *ZWEMT* project has made significant strides in understanding the impact of wind turbines on bird behaviour and collisions, and it has created opportunities for further research and development in this field.

Contents

Summary	3
Contents	4
List of tables and figures.....	5
1 Introduction.....	7
2 Methodology.....	9
2.1 Test site	9
2.2 Installed sensors	9
2.3 Sensor data evaluation	11
3 Results.....	14
3.1 Insight into the behaviour of birds around the (regular and black blade) turbines based on radar and cameras.....	14
3.2 Demonstrate that the WT-Bird® system is a more accurate way to measure collisions than regular victim survey	19
3.3 Validate impact monitoring with microphones	32
4 Discussion and conclusions.....	36
References.....	38

List of tables and figures

Tables

2.1	Robin Radar 3D MAX® installation.....	10
2.2	Sensors installed in wind turbine 21 (White blade).....	10
2.3	Sensors installed in wind turbine 20 (Black blade).....	11
3.1	Explanation of categorisation of tracks in Figure 3.5	17
3.2	Overview of investigated solutions.....	22
3.3	Accelerations on probe locations FE model for 1.1kg bird.....	24
3.4	Accelerations on probe locations FE model for 8g bird.....	25
3.5	Added optical sensors on 30th of July 2024 in turbine 20	26
3.6	Birds found in the search on the 10th of September 2024.....	29
3.7	Overview of impacts detected by WT-Bird®.....	32
3.8	Examples of recognisable sounds in the surroundings.....	33

Figures

2.1	Location of turbines near Eemshaven, derived from Google Maps.....	9
2.2	Setup with Waardenburg Ecology (left) and TNO (right) 3D MAX® radar, left picture provided by Waardenburg Ecology.....	10
2.3	Picture of turbine 21 with two pairs of cameras mounted on either side.....	11
2.4	Picture of turbine 20 with two pairs of cameras on either side (in blue) plus an additional thermal camera for stereography tests (in green).....	12
2.5	Compound image of airplane passing WT21 on the 14th of March.....	12
2.6	Bird track classification.....	13
3.1	Average flight height around the different turbines split by day and night, reproduced from [5].....	14
3.2	Comparison between bird activity based on camera (top) and radar (bottom), sine wave shows the elevation of the sun (day/night), screenshot from Robin Radar's insight software.....	15
3.3	Comparison between bird activity around turbine 20 and 21 for the 12-20th of March.....	15
3.4	Still of a compound image from the thermal cameras showing the full rotor disk.....	16
3.5	Categorisation of 116 tracks from 12-14 March 2024, Turbine 21.....	16
3.6	Still of initial stereo image of a single bird. Distance between red and blue gives an indication of the height.....	17
3.7	Estimated flight height of objects detected with the stereo setup of WT20.....	18
3.8	Zoom in of estimated flight height of objects detected with the stereo setup of WT2018.....	18
3.9	Tracks per km ² per hour at different distances from the turbine based on radar data for the month of March, figure adapted from Waardenburg Ecology.....	19
3.10	Tracks per km ² per hour based on camera data for the 14th of March.....	19
3.11	Location of sensors in a blade (preferred: green, current position: orange), edited screenshot from Ansys software.....	20
3.12	Picture of sensors mounted in a blade.....	21
3.13	5 min sample: First 1 min no noise, afterwards peak at each rotation.....	21
3.14	Actual bird impact signal.....	21
3.15	Noise impact signal.....	22
3.16	Section of FE model with 1.1kg bird modelled as water droplets just before impact, screenshot from Ansys software.....	23

3.17	Locations of acceleration probes in the model, edited screenshot from Ansys software	23
3.18	Snapshot of shockwaves travelling through the structure, screenshot from Ansys software	24
3.19	Sensor signals of the sensors closest to the blade roots with signal noise	25
3.20	Correlation of blade pitch set point (SCADA) and noise (spikes)	26
3.21	Screenshot of TNO WT-Bird® interface with victim circled in red	27
3.22	Signals of sensors in blade 3 of turbine 21 on the 3rd of January 2024 with signal peak of impact circled in red	27
3.23	Screenshot of TNO WT-Bird® interface with victim circled in red	28
3.24	Signals of sensors in blade 3 of turbine 21 on the 10th of September with signal peak of impact circled in red	29
3.25	Still from the compound image with birds track just before impact on the 10th of September	30
3.26	Radar tracks (mostly clutter) around the turbine 21 around the time of impact on the 10th of September 2024, map based on OpenStreetMap	30
3.27	Potential track of bird victim the turbine 21 around the time of impact on the 10th of September 2024	31
3.28	Locations of the victims found during the search on the 10th of September, reproduced from [5]	31
3.29	Signals of sensors in blade 3 of turbine 20 on the 11th of September with signal peak of impact circled in red	32
3.30	Microphone at the base of turbine 20	33
3.31	Example of audio output from acoustic setup	34
3.32	Picture of on tower microphone of Eologix-Ping in the Eemshaven	34
3.33	Picture of in blade microphone of Eologix-Ping and picture of the microphone installed in the blade of the turbine. Left picture by Eologix-Ping	35

1 Introduction

The installed capacity of offshore wind energy in the North Sea is increasing rapidly. The Netherlands alone have set goals to have 21 GW installed in 2032 and 70 GW in 2050. With this increase in capacity the impact of the wind turbines on the ecological balance around them also grows. Therefore, dedicated research into the effect turbines have on birds is required.

At the end of 2021, the Province of Groningen and power company RWE commissioned research into whether painting one blade of a wind turbine black helps birds fly safely between wind turbines. The reasoning was that a black wind turbine blade could potentially improve the visibility for birds, making them more likely to avoid them. Previous research in Norway, on the island of Smøla, showed that painting one blade of a wind turbine black results in 70 % fewer bird casualties among certain species of birds [1]. The Dutch *Zwarte Wiek* (Dutch for *Black Blade*) project studied whether this also applies to the situation in the Netherlands, with different bird species and landscape. It ran until the winter of 2024/25 and was a partnership between private parties in the wind industry (RWE, Vattenfall, StatKraft, Eneco, Pure Energie and Groningen.NL Energy), several public authorities (Ministry of EZK/LNV, Rijkswaterstaat and the provinces of Groningen, Flevoland, Overijssel, Gelderland, Noord-Brabant, Limburg, Zeeland, Zuid-Holland and Noord-Holland) and the nature sector (Vogelbescherming). One blade of each of RWE's seven existing turbines in Eemshaven wind farm, with a tip height of 140 m, was painted black. Interim results of the *Zwarte Wiek* project have been published at the beginning of 2024 [2].

In this study, the number of birds that may have flown into a turbine was counted by hand. This approach provided limited insight into when and how collisions occurred. In addition, there was no insight into any differences in bird behaviour around a turbine with a black blade and a turbine without a black blade. Therefore, TNO, together with power company RWE, the Province of Groningen, and other public and private partners, extended the *Zwarte Wiek* study by placing sensors in and around wind turbines at wind farm Eemshaven. This *Zwarte Wiek Expansie van Monitoring door Technologie* (Dutch for *Black Blade Extension of Monitoring using Technology*) or short *ZWEMT* project ran from 01.06.2023 to 31.01.2025. The present report details results obtained during the project. These also bear significance for future offshore wind farms, where manual measurements and counting are not possible.

Using additional sensor technology, TNO aimed to study the conditions under which birds fly into a wind turbine with and without a black blade and the effect the black blade has on bird behaviour. The study ran for a little over a year to monitor different seasons. During this period, TNO's so-called WT-Bird® sensors were installed in two turbines, one with a black blade and one without. The sensors are located inside each blade and use vibration measurements to record each collision. The collision detection performance of the WT-Bird® system was recently evaluated in a separate multi-sensor validation study, in which controlled collision trials and field measurements demonstrated reliable detection of objects as small as 8 g. In that study, fatality estimates derived from WT-Bird® detections were within the 90% confidence interval of estimates obtained from conventional ground-based carcass searches, indicating performance comparable to established post-construction monitoring methods [3, 4]. Additionally, thermal cameras were installed around the turbines for verification and species recognition. The camera images can also be used to map the behaviour of birds near the turbine. Microphones were added to the WT-Bird® system on the unpainted turbine to detect birds and possible impacts acoustically. To map flight behaviour in the vicinity of the turbines,

a dedicated **Robin Radar 3D MAX® system** was installed.

Installation and monitoring of the systems were done by TNO with support from RWE. Part of the ecological evaluation was contracted to Waardenburg Ecology in collaboration with Altenburg & Wymenga. The project was supported by TKI Offshore Energy, Rijkswaterstaat's ecological research programme on offshore wind energy Wozep (commissioned by the Ministry of EZK), and the Black Blade project group led by the Province of Groningen.

For the *ZWEMT* project, four research goals were formulated:

1. To examine the effectiveness of the black blade with different sensors.
2. To gain insight into the behaviour of birds around the (regular and black blade) turbines based on radar and cameras.
3. To show that the WT-Bird® system is a more accurate way to detect collisions than regular searches and, therefore, applicable offshore.
4. To validate the use of microphones as method to monitor impacts, such that a significant cost reduction can be achieved with respect to the regular WT-Bird® system.

The remainder of this report is built up as follows: Chapter 2 describes the research methodology, including a description of the test site, the installed sensors and the data evaluation. The results are discussed in Chapter 3 along the lines of project goals 2 - 4 as defined above. Finally, the results are discussed in relation to research goal 1 in Chapter 4, and conclusions are drawn.

2 Methodology

2.1 Test site

The measurement campaign was conducted in Groningen near the Eemshaven. The turbines are Enercon E82 machines, which are part of the Westereems wind farm of RWE. Two pairs of turbines are part of the project, each pair consisting of a standard turbine (white blade) and a turbine with one blade painted black (black blade). The turbine pairs are turbine 18 (black blade) and 19, and 20 (black blade) and 21. The test site and the mentioned turbines are depicted in Figure 2.1.



Figure 2.1: Location of turbines near Eemshaven, derived from Google Maps

2.2 Installed sensors

During the project, several sensors were installed in and around the turbines at several locations. Below is an overview of all the sensors installed per location.

2.2.1 Robin Radar 3D MAX®

A Robin Radar 3D MAX® was installed at the location shown in Figure 2.1 with a power supply from the nearby Lagerweg L136. For the first month, the Robin Radar 3D MAX® of Waardenburg Ecology was installed, which was replaced by the TNO 3D MAX® at a later stage. Photos of the two radar systems are given in Figure 2.2. The location of the TNO radar was similar, with a small distance of less than 10 m.

Table 2.1 gives an overview over the installed radar systems.



Figure 2.2: Setup with Waardenburg Ecology (left) and TNO (right) 3D MAX® radar, left picture provided by Waardenburg Ecology

	Installation data	Removal date	Remark
Waardenburg Ecology	7 September 2023	23 October 2023	Location Latitude: 53.45383300 Longitude: 6.80900170
TNO	1 November 2023	Beyond end of the project (31 January 2025)	Location Latitude: 53.453815 Longitude: 6.8084803

Table 2.1: Robin Radar 3D MAX® installation

2.2.2 Sensors in and around turbine T21 (white blade)

The sensor system in and around turbine T21 (white blades) is listed in Table 2.2.

Type	Description	Installation date	Removal date	Remark
In-blade sensors (WT-Bird®)	3 sensors per blade	11 October 2023	11 December 2024	
2 Thermal cameras (WT-Bird®)	AXIS Q1952-E 480x600	11 October 2023	11 December 2024	Most videos stored since 27 February 2024
2 Visual cameras (WT-Bird®)	4K resolution AXIS Q1798-LE	11 October 2023	11 December 2024	Most videos stored since 27 February 2024
1 On-tower microphone	Eologix-Ping	19 August 2024	Still installed	
3 In-blade microphones	Eologix-Ping	18 September 2024	26 February 2025	

Table 2.2: Sensors installed in wind turbine 21 (White blade)

Most sensors (WT-Bird® in-blade sensors and cameras) were removed on the 11th of December 2024 after the measurement period of the project and the last ground searches (16th of October 2024) had been concluded.

Figure 2.3 shows turbine T21 with two pairs of cameras installed on the ground.

2.2.3 Sensors in and around turbine T20 (black blade)

The sensor system in and around turbine T20 (black blade) is listed in Table 2.3.

Figure 2.4 shows turbine T20 with two pairs of cameras installed on the ground.



Figure 2.3: Picture of turbine 21 with two pairs of cameras mounted on either side

Type	Description	Installation date	Remark
In-blade sensors (WT-Bird®)	3 sensors per blade	13 February 2024	Added for functional tests and replacement Removal of sensors after failure of hub cabinet on 19 September 2024
	4 additional sensors	30 July 2024	
	Removal	4 November 2024	
2 Thermal cameras (WT-Bird®)	AXIS Q1952-E 480x600	18 January 2024	Most videos stored since 6 March 2024
2 Visual cameras (WT-Bird®)	4K resolution AXIS Q1798-LE	18 January 2024	Most video stored since 6 March 2024
1 Additional Thermal camera (WT-Bird®)	AXIS Q1952-E 480x600	18 January 2024	For stereography tests. Most video stored since 6 March 2024
1 Microphone on the ground		13 February 2024	continuous data from 18 Sept 2024 - 29 Nov 2024
1 On-tower microphone	Eologix-Ping	19 August 2024	Still installed
3 In-blade microphones	Eologix-Ping	18 September 2024	
	Removal	26 February 2025	

Table 2.3: Sensors installed in wind turbine 20 (Black blade)

2.3 Sensor data evaluation

2.3.1 Robin Radar 3D MAX® data

The radar data was evaluated by Waardenburg Ecology. It gives insight into, for example, flight speed, flight height, and flight straightness.

2.3.2 (Thermal) camera data

Evaluation of the camera data could be done by just looking at the visual cameras, using the thermal cameras or by using the stereography setup. The Intelligent Imaging department of TNO was approached to help in the processing and evaluation of the data. They used their software to detect moving objects (birds) in the video footage of the WT-Bird® system and to



Figure 2.4: Picture of turbine 20 with two pairs of cameras on either side (in blue) plus an additional thermal camera for stereography tests (in green)

filter out the blade movement. The software can be applied to both the visual and thermal camera footage.

During the project, the visual cameras seemed less suitable for 24/7 observations even though the resolution is much higher compared to the thermal cameras. Compound images (see Figure 2.5) using both thermal cameras on either side of the towers were quite insightful and are also available for both turbines. The stereography setup gave additional information on the flight height of the objects. However, this was only tested on turbine 20 (black blade).

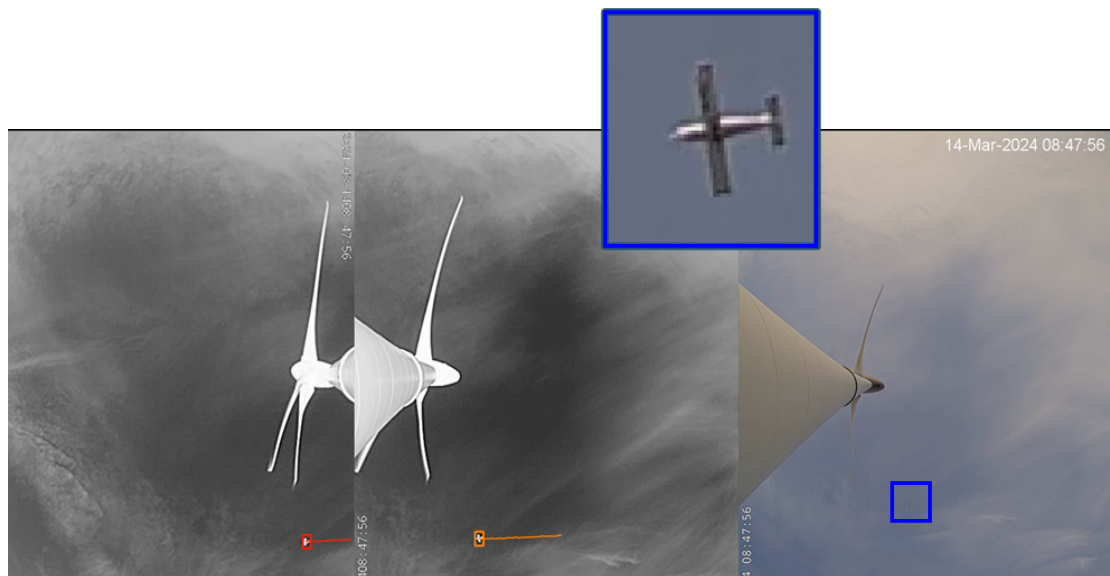


Figure 2.5: Compound image of airplane passing WT21 on the 14th of March

2.3.2.1 Detection algorithm

A relatively simple method was used to detect moving objects in the videos, the so-called 3 frame + noise method. This method achieved already good results with the standard settings and was further tuned. It had almost no problems with moving clouds and also very small birds (pixel size) are detected.

The second step is to filter out the false tracks from the rotor blades. As they are big objects,

this is based on the amount of nearby detections. After this, the detections are classified based on several parameters, mainly location with respect to the rotor blades and speed of the object. An overview of the classification strategy is given in Figure 2.6.

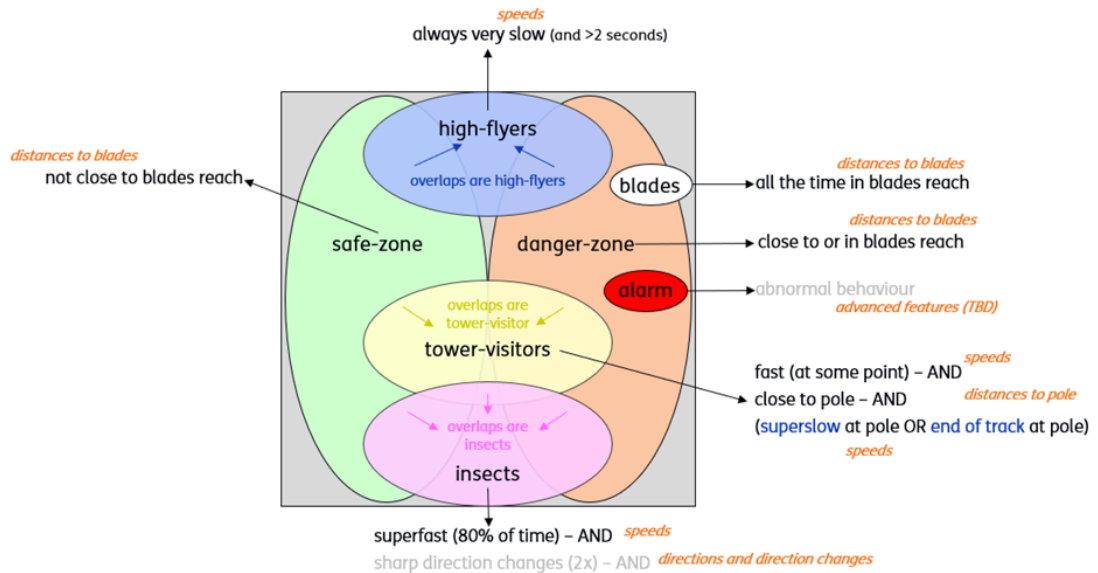


Figure 2.6: Bird track classification

2.3.3 WT-Bird® vibration data

The WT-Bird® system, developed by TNO, is a collision monitoring solution for wind turbines [3]. It uses optical fiber vibration sensors to detect bird and bat impacts, even from objects weighing just a few grams, while filtering out environmental noise like rain or ice. The system comprises subsystems installed in the turbine tower, nacelle, hub, and blades. The sensors are installed inside the leading edge of the blades at several spanwise locations. The number of sensors depends on the size of the blades. Integrated camera systems at the base of the tower provide visual confirmation of collision events. WT-Bird® stores time-series data and images for detailed post-event review.

When a bird hits a blade, this results in a peak in the measurements of the sensors, especially in the sensor closest to the impact. This gives an indication of where the bird came into contact with the blade. To distinguish between a bird hit and other vibrations, several factors are taken into account, like the frequency, shape of the peak, order of triggering of the sensors. For example, the sensors closest to the root are used to filter out signals from the hub/nacelle. If the inner sensors of all 3 blades trigger at the same time, it is likely that the signal is coming from the hub/nacelle and not from an impact on the blade. Based on the factors and signal thresholds, a likelihood is attached to the signal. Normally, only signals with a high confidence level are checked manually, but for this project, a deeper search was also conducted.

3 Results

In the following paragraphs, the results of the research with respect to the goals as presented in Chapter 1 are described. First the project goals 2, 3 and 4 will be discussed and in the last sub-chapter the results with respect to last project goal will be described using the answer to project goals 2, 3 and 4.

3.1 Insight into the behaviour of birds around the (regular and black blade) turbines based on radar and cameras

3.1.1 Based on Radar

The outcomes are presented as part of the final reporting of the overall Zwarte Wiek project. The short conclusion is: the presence of the black blade, to the extent measurable with the 3D MAX® bird radar, has no effect on the flight height, flight speed and the straightness of flight of birds within a radius of 200 m of the wind turbines. Figure 3.1 exemplarily shows the flight height measured around the four turbines at day and night. More results can be found in [5].

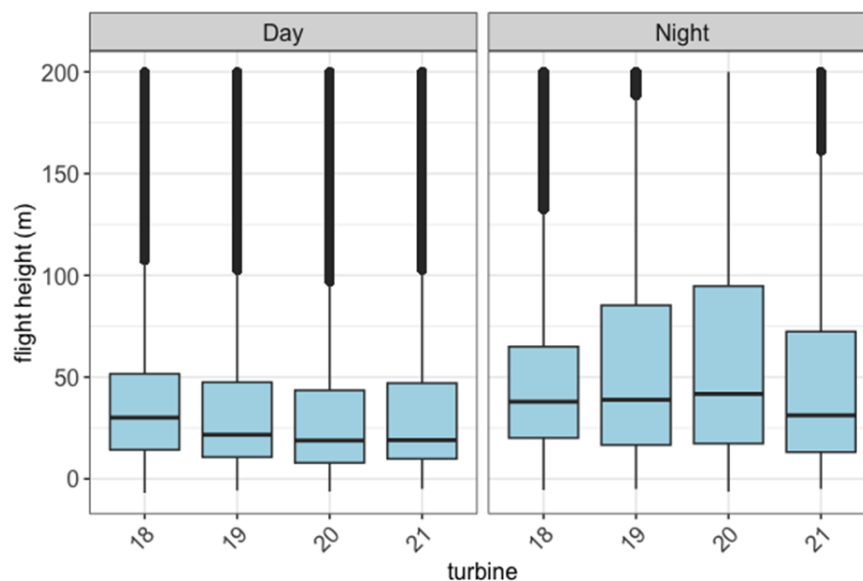


Figure 3.1: Average flight height around the different turbines split by day and night, reproduced from [5]

3.1.2 Based on cameras

3.1.2.1 Using the detection algorithm

The detection algorithm is currently not yet optimised and generates some false positives, mainly due to blades and insects. Also, especially when flocks of birds fly over, not all birds are detected individually. This makes it difficult to draw general conclusions about bird behaviour

around the turbines. However, a rough comparison between the camera detection and radar detection shows similar trends, see Figure 3.2.

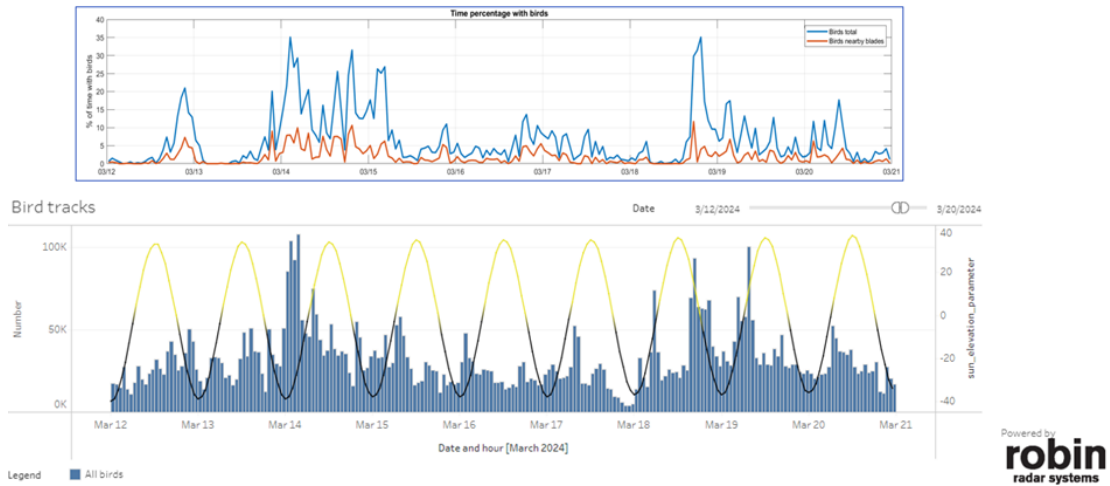


Figure 3.2: Comparison between bird activity based on camera (top) and radar (bottom), sine wave shows the elevation of the sun (day/night), screenshot from Robin Radar’s insight software

If the bird activity between the two different turbines is compared, there is no clear difference between the turbine with a black blade and the one without a black blade, see Figure 3.3. A more detailed analysis would need to be done to draw any final conclusions on this.

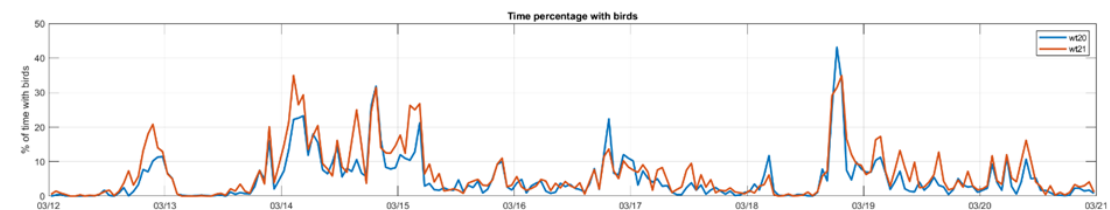


Figure 3.3: Comparison between bird activity around turbine 20 and 21 for the 12-20th of March

3.1.2.2 Using visual inspection of the compound images

Using compound video images of the thermal cameras, the behaviour of birds near the turbine can be studied. An example of such compound images with a detected track is shown in Figure 3.4.

Although the detection algorithm reduces the amount of footage by up to 95%, there are still hundreds of hours of video footage available. Within the ZWEMT project, there was not enough time to either manually evaluate the data or to improve the algorithm to a level where the correct classification could be automated. However, some specific behaviour is already observed based on a limited data set from the 12th of March till the 20th of March 2024. This week was selected because of the high bird activity (spring migration) and the fact that three victims were found near turbine 21 in that week. Unfortunately, the preliminary search for victims purely based on the video footage was not successful. Again, a more detailed analysis could lead to more insight. Some interesting examples of detectable bird behaviour include:

- › Birds landing on the ring halfway up the tower for resting or as lookout (birds of prey)
- › Birds “visiting” the tower at low altitude and flying away again.
- › Birds actively avoiding the blades while flying through the rotor disk

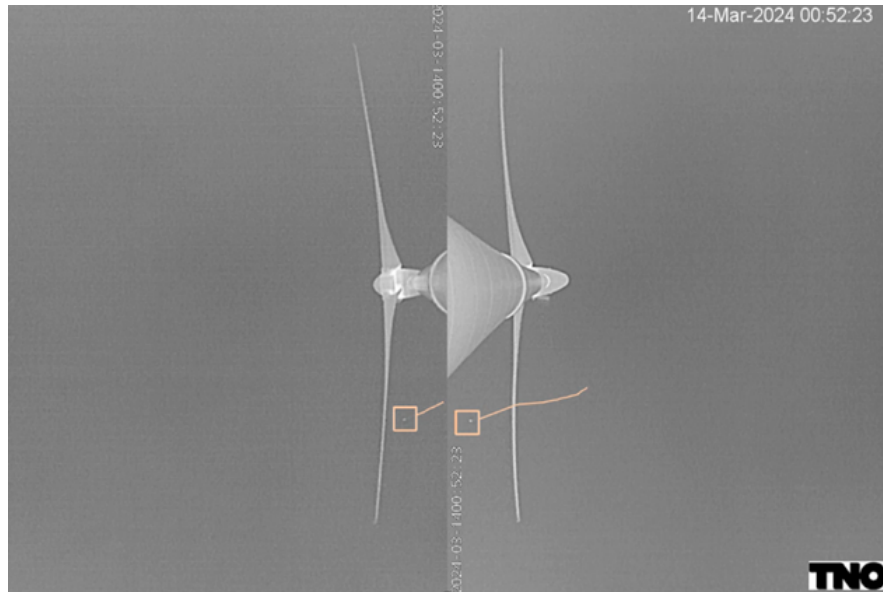


Figure 3.4: Still of a compound image from the thermal cameras showing the full rotor disk

The detected tracks within videos of a short amount of time (12th to 14th of March 2024) were evaluated by ecologists (Waardenburg Ecology and Altenburg & Wymenga) and categorised by TNO. This categorisation is shown in Figure 3.5 and an explanation of the categorisation is given in Table 3.1.

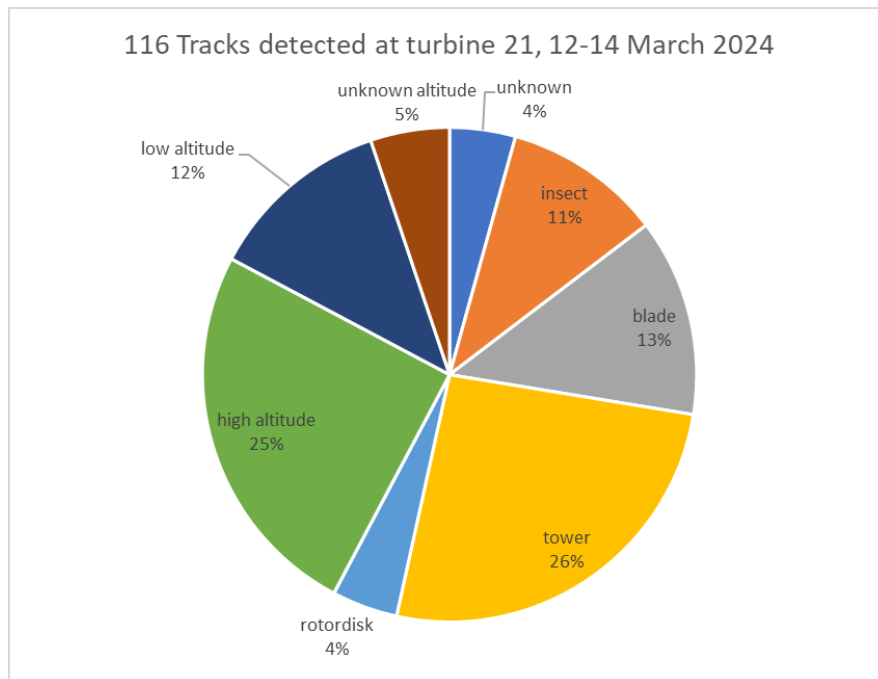


Figure 3.5: Categorisation of 116 tracks from 12-14 March 2024, Turbine 21

Based on this small dataset, the current version of the algorithm still has about 25% false positives shared between insects and blades. Also, around a quarter of the tracks are birds interacting with the tower of the turbine, either landing on the ring or “visiting” the tower at low altitude. The remaining 50% are birds passing on the turbine, most of them at much higher

Category	Explanation
Unknown	Track cannot be clearly categorised
Insect	Fast low-moving object, identified as insect
Blade	Tip of a blade not filtered correctly by the image detection algorithm
Tower	Bird/bat flying towards wind turbine tower and doing something on the surface of the tower
Rotor disk	Birds that seem to fly through the rotor disk
High altitude	Slow straight flight paths of single or flocks of birds that seem to fly at high altitude
Low altitude	Fast silhouettes of birds/bats passing low over the cameras
Unknown altitude	Birds whose altitude cannot be estimated based on the 2D information of the cameras

Table 3.1: Explanation of categorisation of tracks in Figure 3.5

altitude and only a small percentage seems to fly at rotor height, sometimes reacting to the blades. The height estimate was originally done visually and not very precise. Therefore, a test was done with a stereography setup at turbine 20.

3.1.2.3 Using the stereo camera setup

At turbine 20, a third thermal camera was placed on one side of the turbine to make a stereo pair with the already present thermal camera next to the visual camera (see Figure 3.6). Thus, there is a left and a right “eye”. With the stereo setup, the height of the birds can be estimated. This could give additional information on whether the birds fly in the danger zone near the rotor disk. With further analysis, it could also give an estimate of the size to give information on the species group.

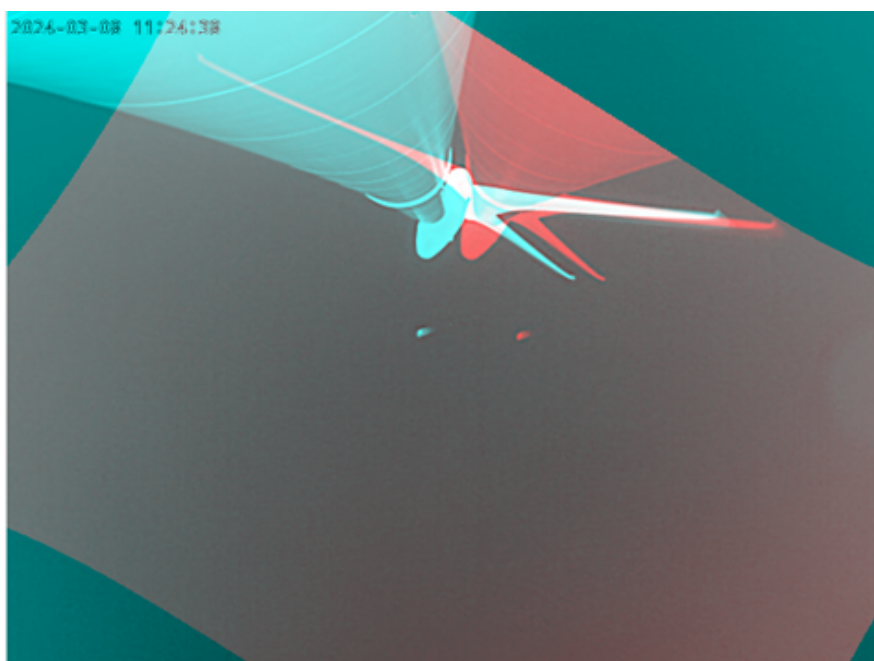


Figure 3.6: Still of initial stereo image of a single bird. Distance between red and blue gives an indication of the height

In Figure 3.6, the bird has a bigger distance between the left and right camera than the back of the nacelle of the wind turbine. This means that the bird is flying lower than the nacelle. The analysis of the flight height of the birds was done for a limited dataset from the 12th of

March to the 20th of March and is shown in Figure 3.7. Figure 3.8 shows a zoomed in version focussing on flight heights between 0 m and 200 m.

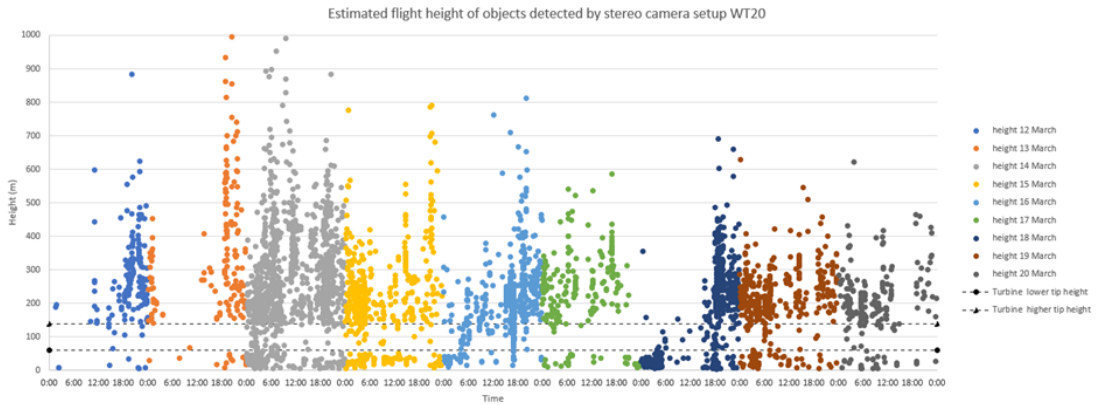


Figure 3.7: Estimated flight height of objects detected with the stereo setup of WT20

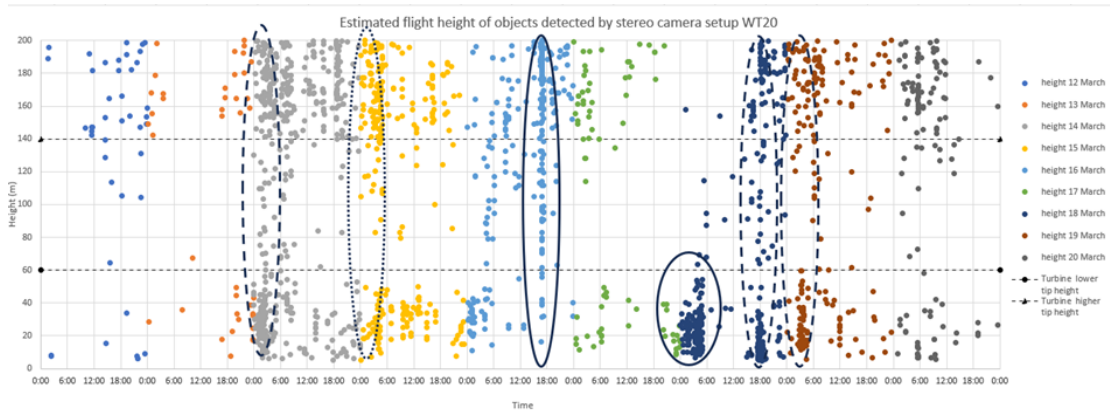


Figure 3.8: Zoom in of estimated flight height of objects detected with the stereo setup of WT20

This preliminary evaluation of the flight height of objects detected with the stereo setup is interesting because only a limited number of objects are detected at the rotor height of the turbine. It should be noted that the stereo setup is not yet working perfectly, as there are some clear miscalculations of the height. Some examples are circled in Figure 3.8. In light blue, on the 16th of March, there is a flock of birds flying over the turbine. Because the motion detection algorithm “jumps” between two birds which are flying close together, the height estimate, which is based on the distance between the “right” and “left” camera, is wrong. This leads to a detection of the flock at a lot of different altitudes. In the dark blue on the morning of the 18th of March, there is a big cluster at low height due to insects.

Additionally, the comparison with flight heights from the radar data shows deviations, compare Figures 3.9 and 3.10. In Figure 3.9, the numbers at the top of the four columns indicate the distance from the radar. From this comparison, it can be observed that the trend in camera and radar data is similar. Both show a dip close to the rotor height, which would be interesting to investigate in more detail. As it was not part of the original ZWEMT project scope, there was limited time to look into this. However, TNO is currently working on a new project to extract additional information from this data.

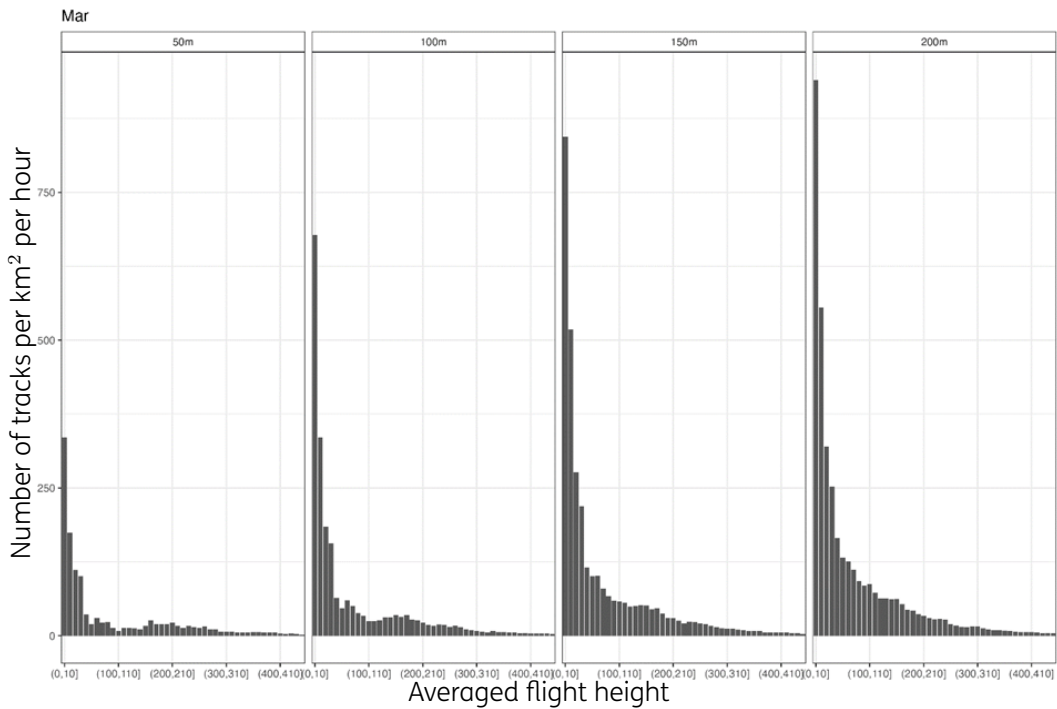


Figure 3.9: Tracks per km² per hour at different distances from the turbine based on radar data for the month of March, figure adapted from Waardenburg Ecology

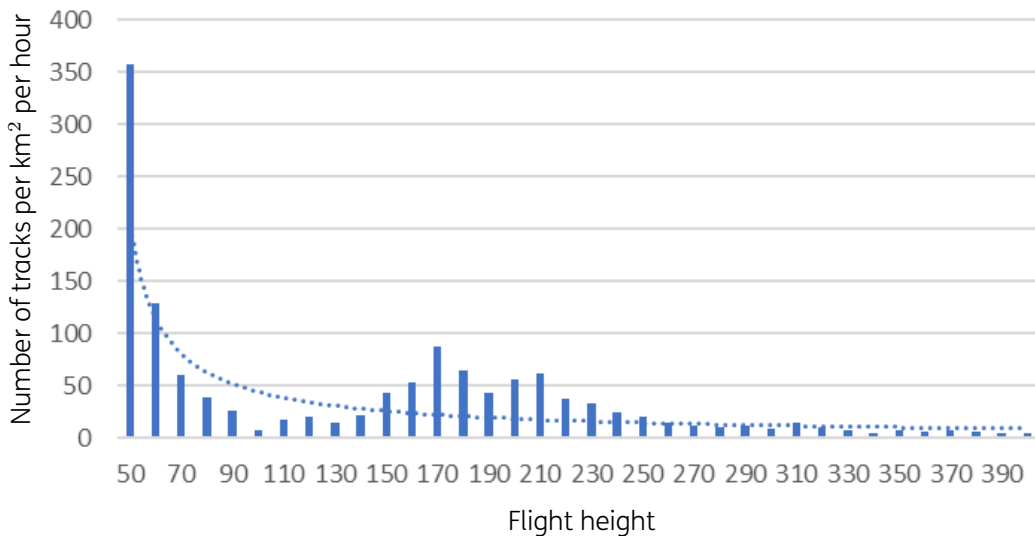


Figure 3.10: Tracks per km² per hour based on camera data for the 14th of March

3.2 Demonstrate that the WT-Bird® system is a more accurate way to measure collisions than regular victim survey

The original idea was that by using the vibration sensors in the blades, the amount of collisions could be determined in a more accurate way compared to the regular victim search

performed weekly by the ecologists, and that insight could be gained under which conditions (time, weather) collisions would occur. With this insight and based on enough collisions, it might have been possible to determine the impact of the black blade. Unfortunately, due to issues with WT-Bird® system, only two collisions were confirmed, of which only one could be coupled with a victim found on the ground. The issues resulted in a reduced sensitivity of the system, which was therefore incapable of detecting most of the collisions. These collisions did take place as victims were found on the ground during regular ground searches. Details of the detected collisions of WT-Bird® can be found in Table 3.7. WT-Bird® detections are described in an internal TNO table from which relevant pictures can be found in section 3.2.3.

3.2.1 Experienced issues regarding the WT-Bird® system

During the initial measurement period, three issues arose with the WT-Bird® systems within the turbines:

- › Location of the sensors
- › Noise of the turbine
- › Broken sensors

The combination of these three elements led to a decreased sensitivity of the WT-Bird® systems.

3.2.1.1 Location

During installation, it became apparent that the preferred location of the sensors, namely on the inside of the blade directly behind the leading edge (LE), was not accessible. This location is indicated as green dot in Figure 3.11. A fan installed for the LE heating system for de-icing blocked entrance to the LE cavity. Instead, the sensor was placed directly behind the shear web as indicated by the orange dot in Figure 3.11. Note that Figure 3.11 is an approximation of the turbine blade structure and, thus, not an exact design replica. Figure 3.12 shows the installed sensor.

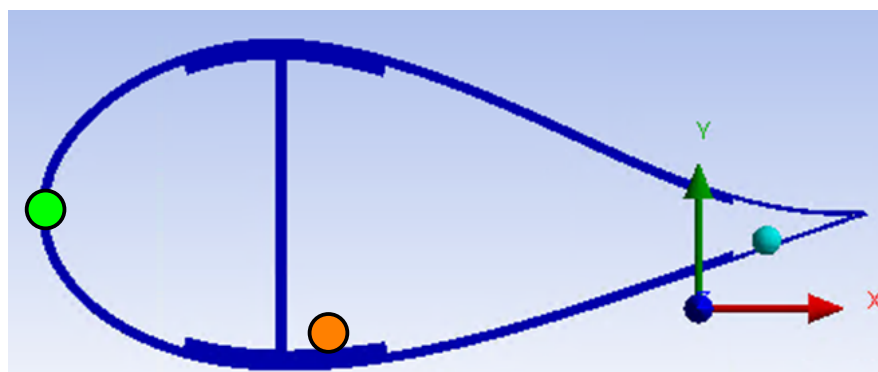


Figure 3.11: Location of sensors in a blade (preferred: green, current position: orange), edited screenshot from Ansys software

The current location of the sensors is not ideal and part of the signal is probably damped before it is registered.

3.2.1.2 Noise of the turbine

Under certain conditions, both turbines produce a cyclic noise signal as shown in Figure 3.13. These signals are very similar to a bird impact, compare Figures 3.14 and 3.15, and are classified



Figure 3.12: Picture of sensors mounted in a blade

by the system as likely to be an impact. While the noise is assigned only an 80% likelihood of being a collision, it reduces the sensitivity of the WT-Bird® system as it can result in more than 2000 false positives per day.

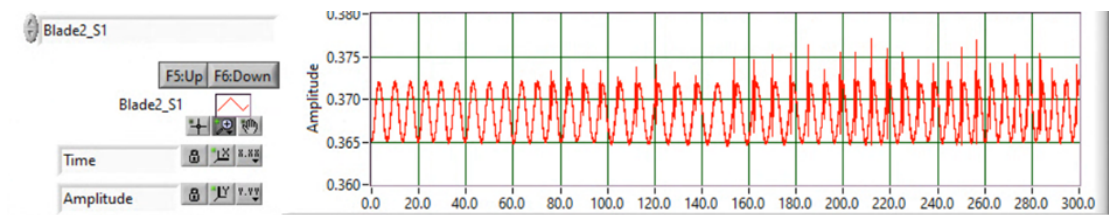


Figure 3.13: 5 min sample: First 1 min no noise, afterwards peak at each rotation

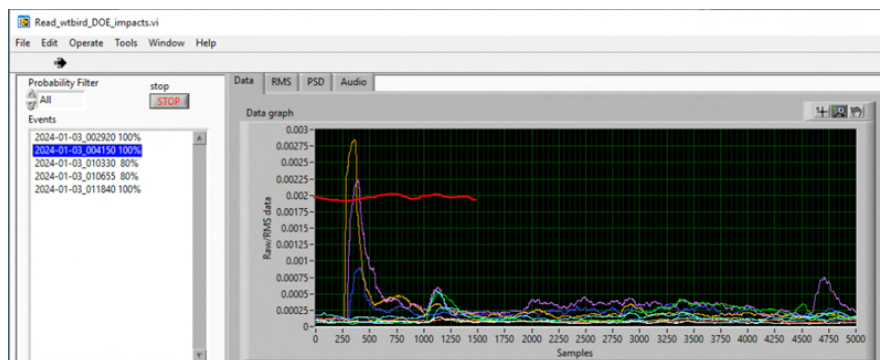


Figure 3.14: Actual bird impact signal

3.2.1.3 Broken sensor

For turbine 20 (black blade), sensors of an earlier installation were reused due to supply issues for new sensors. Unfortunately, during de- and re-installation, two sensors were broken, and one was damaged. The two broken sensors are located at the tip-most position of blade 1 and blade 2. This reduces the sensitivity of the WT-Bird® system for these blades.

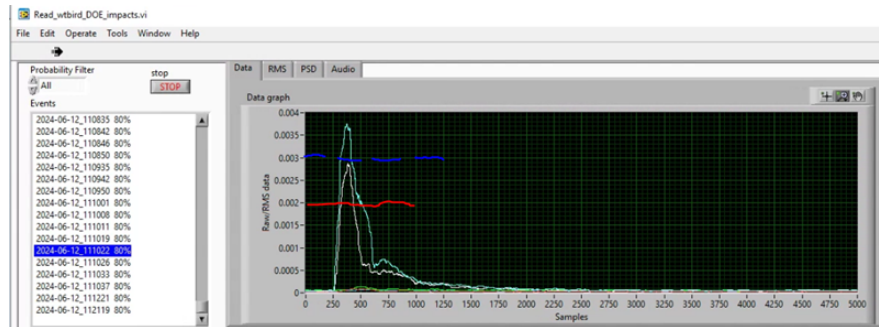


Figure 3.15: Noise impact signal

3.2.2 Applied solutions

During the project, several solution directions were investigated to improve the sensitivity of the setup and/or explain the reduced sensitivity. The solution directions per issue are listed in Table 3.2.

Issue	Solution 1	Solution 2
Location of the sensors	Better filtering	Finite Element Model signal dampening
Noise	Better filtering of signal	Track source of noise
Broken sensors	Add extra optical sensors	

Table 3.2: Overview of investigated solutions

Next to direct solutions to the issues in the sensitivity, additional actions are taken (see other paragraphs)

- › Added microphones at tower and in blade root
- › Analysis of video footage

3.2.2.1 Better filtering

For both the reduction of the signal due to the position of the sensors and finding the impact signal within the signal noise, different filtering options were explored. Originally, a promising route seemed to be a continuous wavelet transformation where the different frequency domains are plotted with time. In this way, the “signature” of the impact can be determined and all the other signals, including the noise, can be filtered out. In the end, this proved not to be better than the filtering that is currently applied.

For periods with suspected collisions (based on ground searches), the sensor data was re-filtered with more sensitive settings in order to find more possible noise peaks, which could point towards a collision. However, this detailed filtering did not result in extra triggers.

3.2.2.2 Finite element model signal damping

To investigate the amount of damping due to the non-ideal placement of the sensors, a finite element (FE) model was created to model the mechanical response of the wind turbine blade structure during an impact. Here, the goal was not to get exact numbers but to get an idea of the order of magnitude of damping, so this is an acceptable approach. The FE model contains:

- › Anisotropic material properties (different stiffnesses in different directions) to represent the composite materials

- › Elements that allow out-of-plane movements in order to properly model the vibrations
- › Force burst input at impact location to represent the bird impact
- › Bird is modelled with water particle
- › Blade is modelled with shell element with layered section
- › No material damping added
- › Fixed support on trailing edges
- › Bonding is not modelled

As the precise geometry of the Enercon blade is not known, the shape and material properties of a generic TNO demo blade section with material definitions from the UPWIND project is used. To simplify the model, a continuous section of 6 m with a 2.4 m chord was modelled. The bird was assumed to be a duck with a flight speed of 18 m/s and a weight of 1.1 kg, impacting at 12 m (30 % of the blade span). Using a rotational speed of 18 rpm, the impact speed is 41 m/s. The rotational speed of 18 rpm was chosen as conservative number, slightly larger than the maximum rotor speed found in the SCADA data. Figure 3.16 shows the FE model consisting of the extruded blade cross-section and the approximation of the impacting bird.

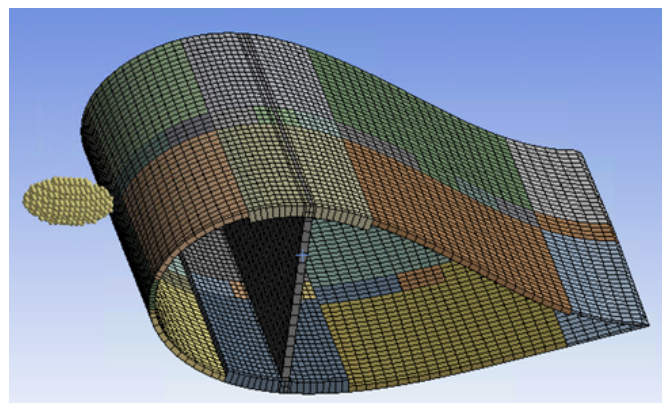


Figure 3.16: Section of FE model with 1.1kg bird modelled as water droplets just before impact, screenshot from Ansys software

Based on the model, the acceleration was determined at several chordwise locations in the cross-section (shown in Figure 3.17) and also at different spanwise locations of the blade.

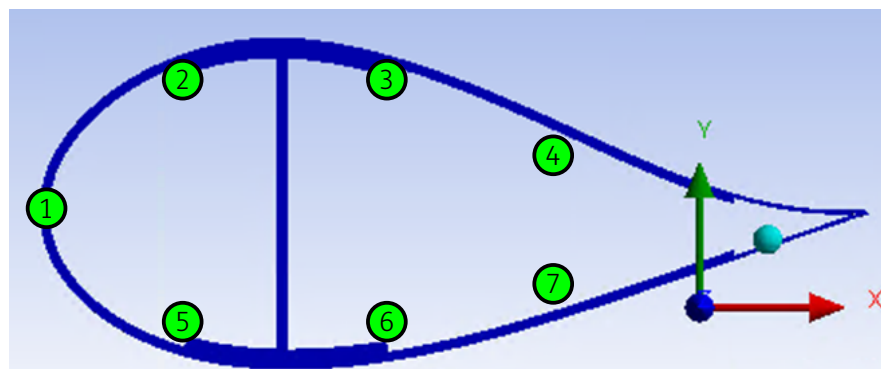


Figure 3.17: Locations of acceleration probes in the model, edited screenshot from Ansys software

For each probe location, the maximum acceleration as a ratio to the desired LE position 1 is listed in Table 3.3. If the bird were to hit exactly at the spanwise location of the sensor at

position 6, 97 % of the energy is lost. At a spanwise distance of 2 m, more than 99 % is lost. In general, there is a factor of 30-50 in signal strength between the desired leading edge position and the actual position behind the shear web.

Probe		Location	-2m	-1m	0m	1m	2m
1 ^a	Leading Edge		30,7%	42,2%	100,0%	44,4%	30,4%
2	Pressure side	Before web	0,9%	1,4%	3,6%	1,4%	0,9%
3	Pressure side	Behind web	0,6%	0,8%	2,5%	0,8%	0,6%
4	Pressure side	Middle aft	0,6%	1,0%	2,7%	0,9%	0,5%
5	Suction side	Before web	0,8%	1,1%	3,6%	1,2%	0,8%
6 ^b	Suction side	Behind web	0,7%	0,9%	2,9%	1,0%	0,6%
7	Suction side	Middle aft	0,6%	1,1%	3,1%	1,2%	0,5%

^a Desired sensor position

^b Actual sensor position

Table 3.3: Accelerations on probe locations FE model for 1.1kg bird

Interesting to see is that the shock waves are greatly impacted by the structure. The stiff laminate in the leading edge ensures that the wave travels relatively quickly in spanwise direction with a low amount of signal loss. This confirms that with only a couple of sensors along the span of the blade, impacts can reliably be detected. The much stiffer spar cap acts like a barrier, absorbing or reflecting much of the energy. This means that only a fraction of the energy reaches the probes in the other locations. A snapshot of the shockwaves travelling through the modelled body is given in Figure 3.18.

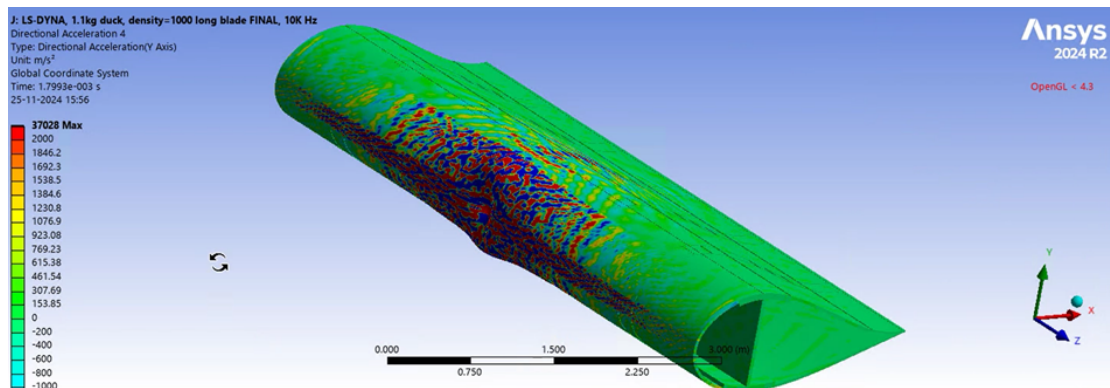


Figure 3.18: Snapshot of shockwaves travelling through the structure, screenshot from Ansys software

The simulation was also run for a smaller bird (8 grams) with the same impact speed. For this case, even less of the energy reached the probes, see Table 3.4. Here, there is a factor of 100-200 between the signal at the LE and the actual position of the sensor. It is clear from the FE simulations that the major cause of the decreased sensitivity of the sensors is their position. It is a clear lesson that the sensors should be positioned at the leading edge for maximum sensitivity.

Probe		Location	-2m	-1m	0m	1m	2m
1 ^a	Leading Edge		16.2%	24.1%	100.0%	20.5%	17.6%
2	Pressure side	Before web	0.2%	0.3%	0.5%	0.2%	0.2%
3	Pressure side	Behind web	0.1%	0.2%	0.4%	0.2%	0.1%
4	Pressure side	Middle aft	0.1%	0.2%	0.5%	0.2%	0.1%
5	Suction side	Before web	0.2%	0.3%	0.6%	0.2%	0.2%
6 ^b	Suction side	Behind web	0.1%	0.3%	0.5%	0.2%	0.2%
7	Suction side	Middle aft	0.1%	0.2%	0.5%	0.2%	0.2%

^a Desired sensor position

^b Actual sensor position

Table 3.4: Accelerations on probe locations FE model for 8g bird

3.2.2.3 Track source of noise

On TNO’s request, RWE conducted two inspections of the turbines to check for any obvious sources of the noise. Among others, bolts of various components were fastened and while other parts were slightly moved. Especially the last inspection (around 11th of June 2024) was quite elaborate. Unfortunately, the problem was not solved by this. Ensuing, TNO and RWE checked the SCADA data to see whether there is any relation between the noise and the operational state of the turbine. The most likely cause is wear of the gears in the pitch system, which then slightly move every rotation under the force of gravity. This is clear from the data of the sensors closest to the blade root and the correlation with the pitch set point taken from RWE SCADA data, see Figures 3.19 and 3.20.

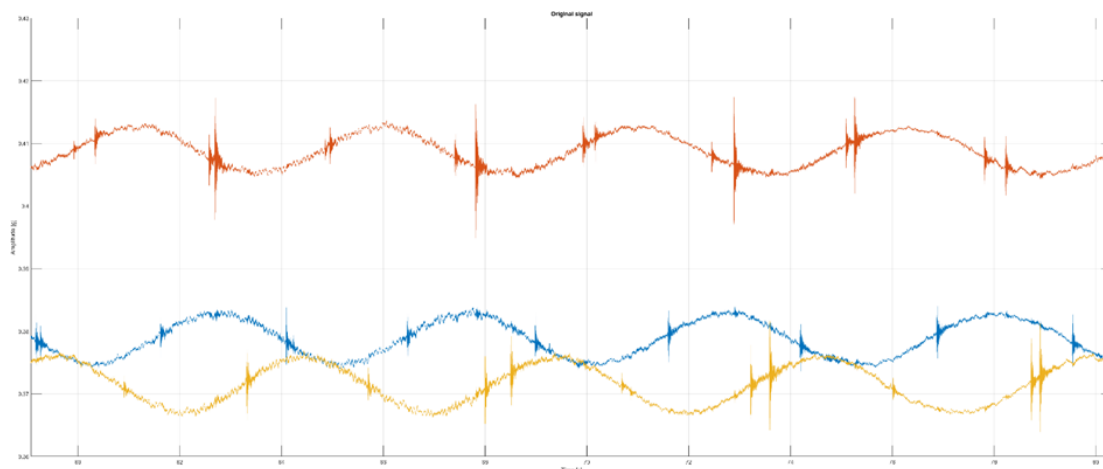


Figure 3.19: Sensor signals of the sensors closest to the blade roots with signal noise

With the reduced sensitivity due to the position of the sensors and the effort needed to locate and repair the noise source, no further action was taken in this direction.

3.2.2.4 Added extra optical sensors

In order to replace the broken sensors in turbine 20 and test new sensors, four extra sensors were placed in the turbine. On the 30th of July (see Table 2.3), additional sensors were placed to solve this issue.

The new sensors worked well but were also placed near the original sensors due to the same positioning constraints (no access to leading edge cavity due to heating system), so they shared the same limitation.

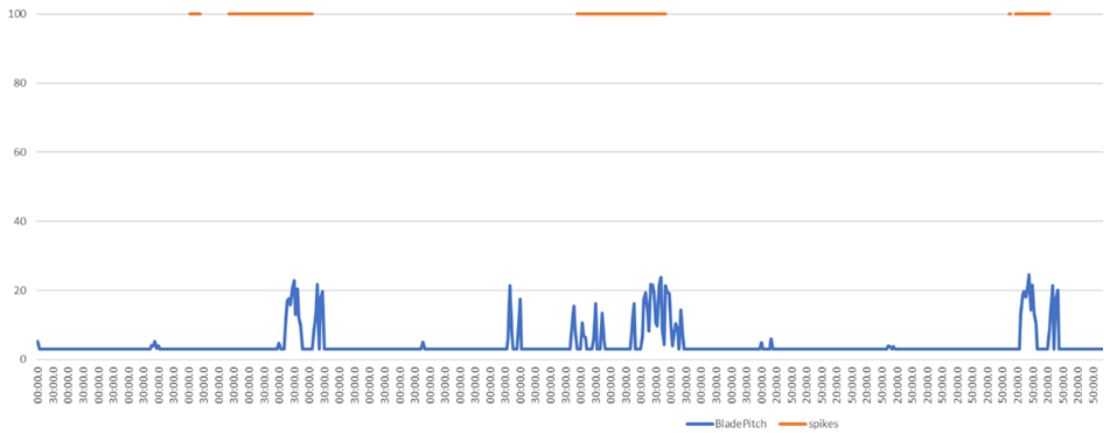


Figure 3.20: Correlation of blade pitch set point (SCADA) and noise (spikes)

Blade	Sensor	Status	Extra sensor
1	1	Works properly	
1	2	Works properly but noisy	Somni (new box added next to existing one)
1	3	Broken	Compass Angle Eye
2	1	Works properly	
2	2	Works properly	Compass Angle Eye (new box added next to existing one)
2	3	Broken	Somni

Table 3.5: Added optical sensors on 30th of July 2024 in turbine 20

3.2.3 WT-Bird® detections

During the monitoring period from October 2023 till December 2024 for Turbine 21 (see Table 2.2) and February 2024 till September 2024 for Turbine 20 (see Table 2.3), three impacts were detected with the WT-Bird® systems. Two of these impacts were on turbine 21 without a black blade. A third impact on turbine 21 is likely to have occurred, but less certain.

3.2.3.1 Impact 3 January

On the 3rd of January 2024, a collision was detected on turbine 21 and blade 3 at 00:41:52. Due to foggy conditions, the victim is difficult to see on video. Due to ice and snow, the first victim search after the detection was only conducted on the 24th of January, and no victim was found on the ground. Figures 3.21 and 3.22 show the measured data at the time of the impact.

The radar data was also checked, but as there was light rain at the time of collision, the radar data is not accurate. Additionally, the blades caused clutter tracks due to the radar reflections near the turbine.

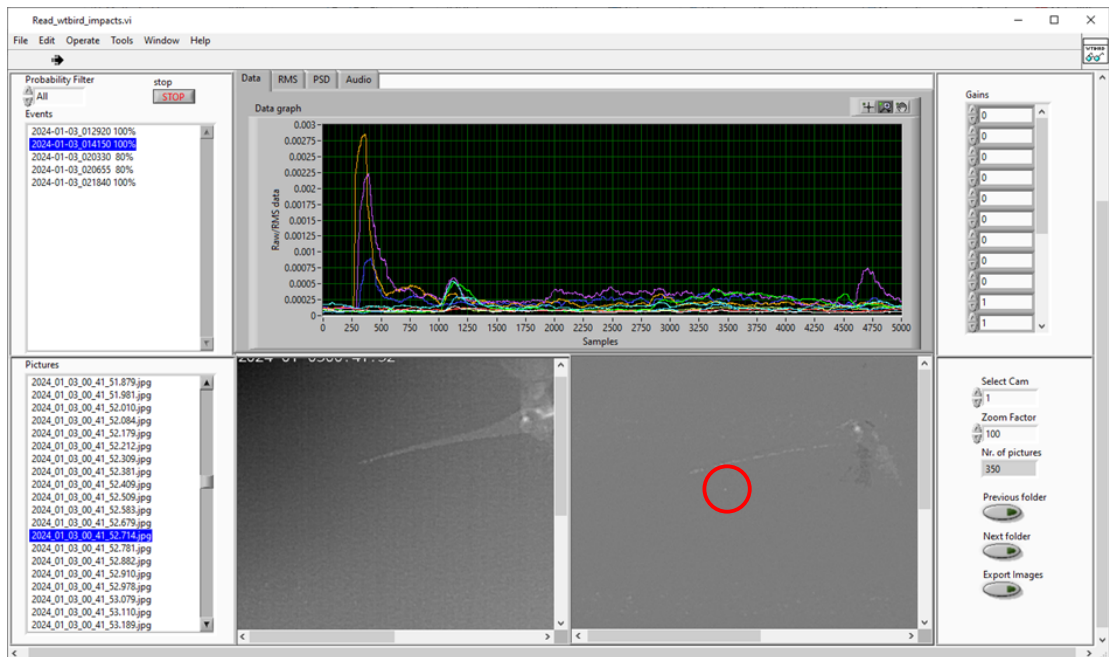


Figure 3.21: Screenshot of TNO WT-Bird® interface with victim circled in red

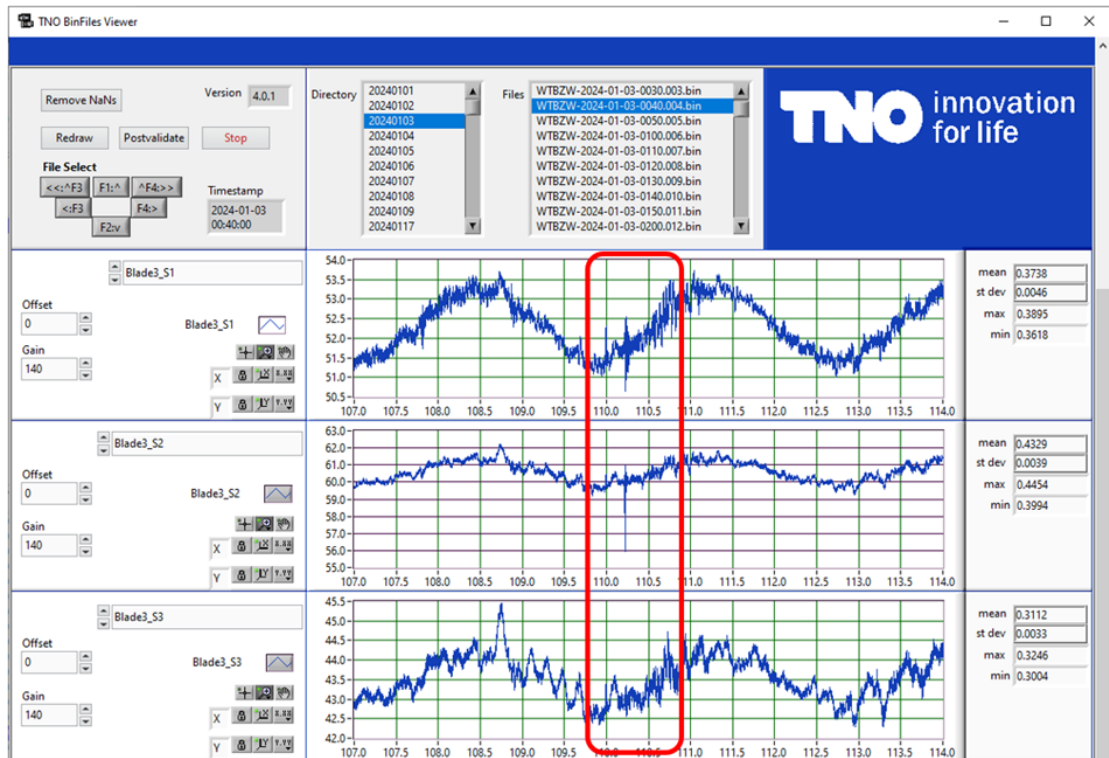


Figure 3.22: Signals of sensors in blade 3 of turbine 21 on the 3rd of January 2024 with signal peak of impact circled in red

3.2.3.2 Impact 10 September

A second impact was detected by the WT-Bird® system on turbine 21 in the night of the 10th of September. As the conditions were clear, the victim can also be seen on the compound video footage, see Figure 3.23. The impact causes a clear peak in the sensor data, as can be observed in Figure 3.24.

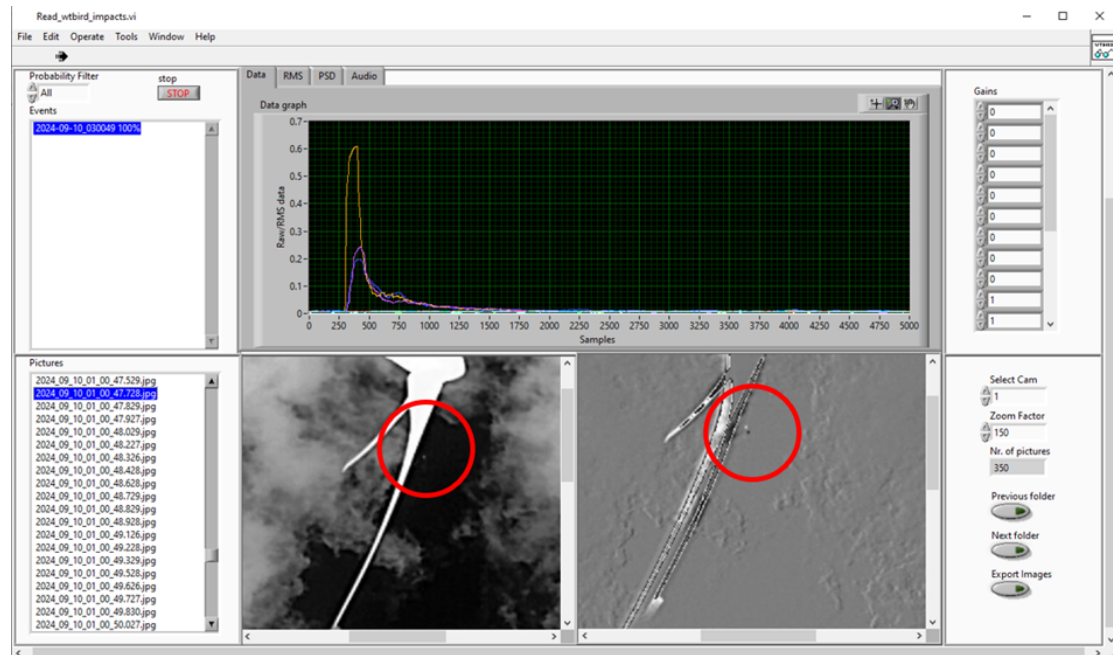


Figure 3.23: Screenshot of TNO WT-Bird® interface with victim circled in red

Inspecting the thermal camera footage at the time of the detected collision confirmed the presence of a bird. Figure 3.25 shows a still including the detected bird track at the time of the collision.

Again, the radar tracks around the time where investigated. Near the turbine, a lot of clutter tracks due to the radar reflections of the turbine and especially the blade tips were observed, see Figure 3.26. There is one longer track which ends near the turbine (in the radar shadow) around seven seconds before impact. This track, shown in Figure 3.27, could potentially be linked to the victim.

The impact occurred on the night of the 9th to 10th of September. During the day of the 10th of September, a victim search was conducted by ecologists of Waardenburg Ecology and Altenburg & Wymenga. Four potential victims were found. Their locations are given in Figure 3.28 and details are given in Table 3.6. Due to the state of the cadavers, the most likely victim detected seems to be the Ringed Plover.

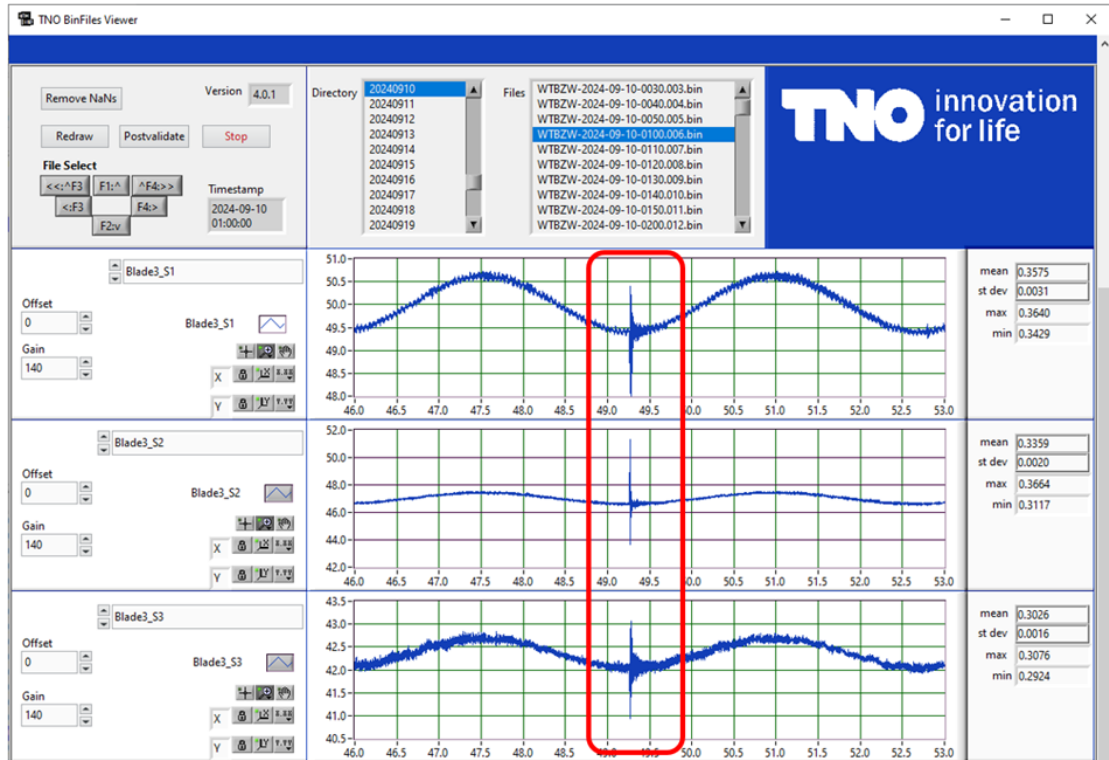


Figure 3.24: Signals of sensors in blade 3 of turbine 21 on the 10th of September with signal peak of impact circled in red

Number	Search date	Last search	Turbine	Species	Comments
425/426	10-sep-24	5-sep-24	21	Starling	Complete animal, but wet and deteriorated/chewed upon
422	10-sep-24	5-sep-24	21	Ringed plover	Intact
425/426	10-sep-24	5-sep-24	21	Starling	Major part cadaver, but dirty and partly eaten
424	10-sep-24	5-sep-24	21	Black-headed Gull	Wings, tail and sternum, but much deteriorated

Table 3.6: Birds found in the search on the 10th of September 2024

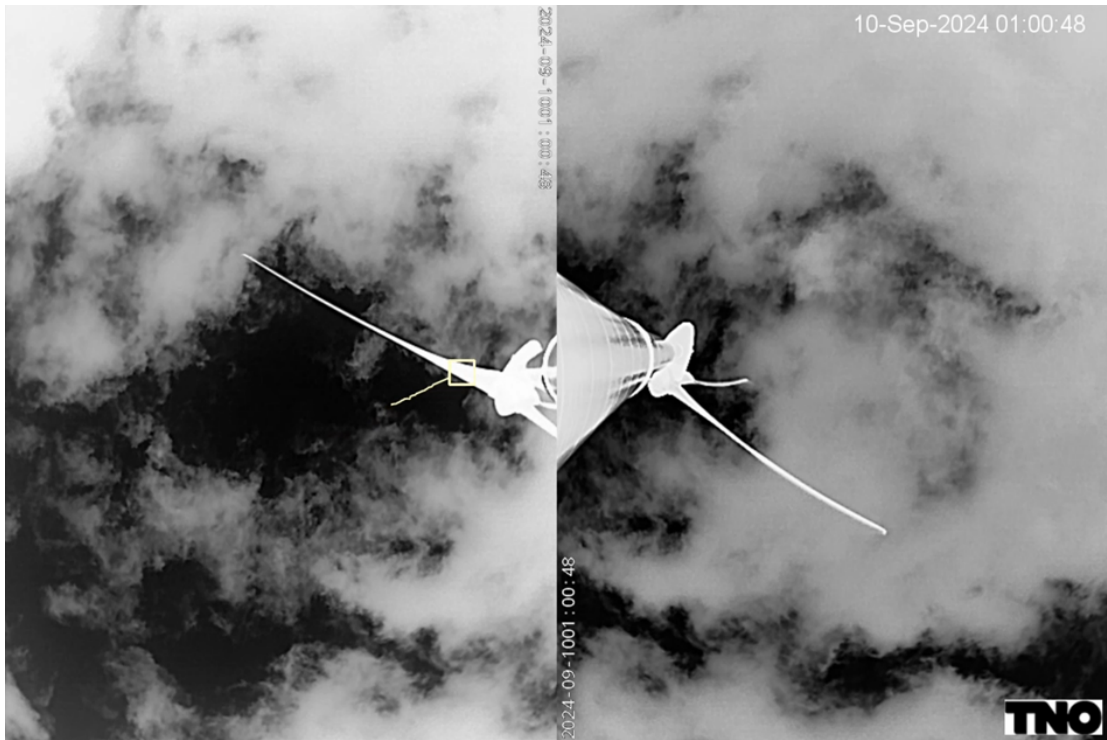


Figure 3.25: Still from the compound image with birds track just before impact on the 10th of September



Figure 3.26: Radar tracks (mostly clutter) around the turbine 21 around the time of impact on the 10th of September 2024, map based on OpenStreetMap

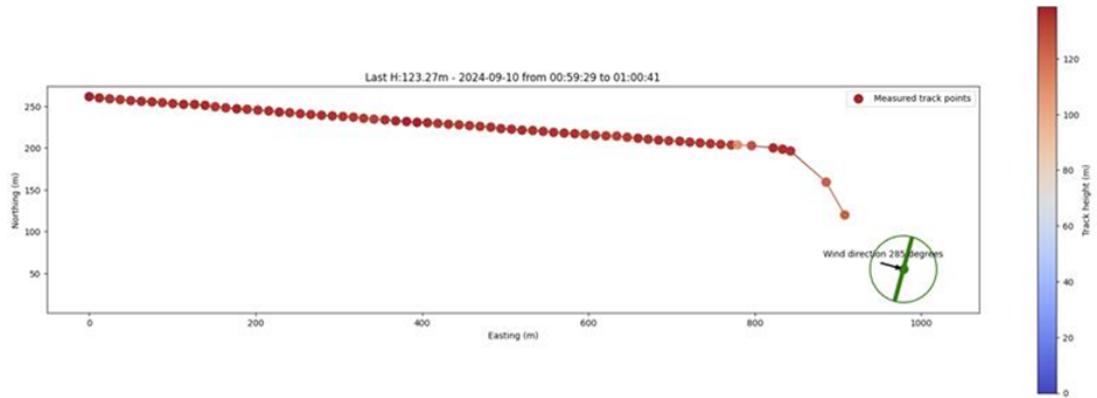


Figure 3.27: Potential track of bird victim the turbine 21 around the time of impact on the 10th of September 2024

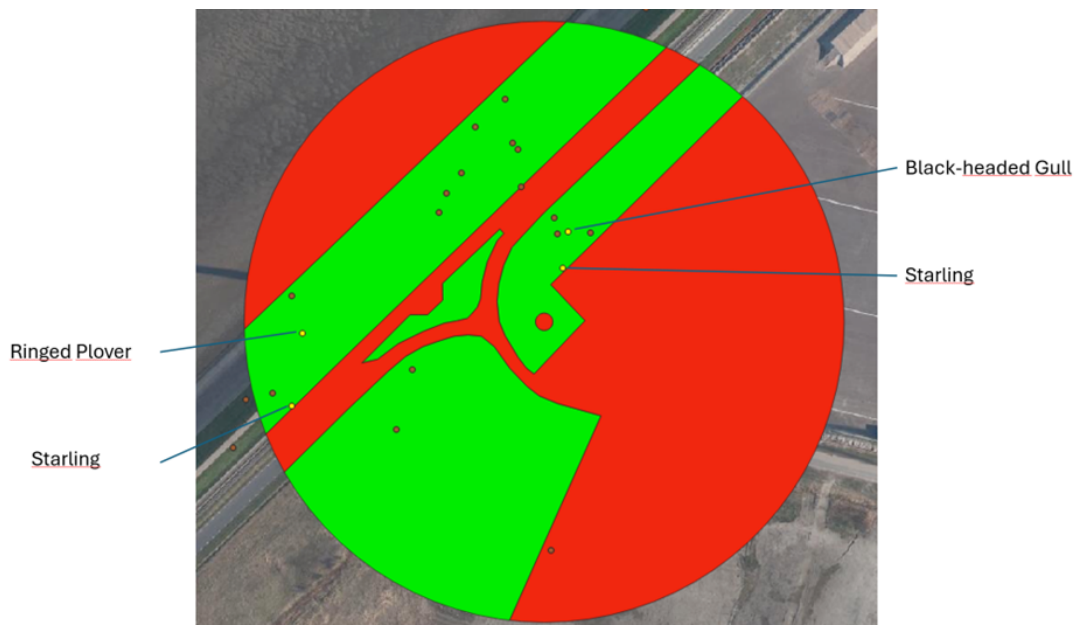


Figure 3.28: Locations of the victims found during the search on the 10th of September, reproduced from [5]

3.2.3.3 Impact 11 September

A third impact was detected on turbine 20 at blade 3 on the 11th of September, a bit before 10am. At the time it was raining, and no visual confirmation could be made on the basis of the cameras. Also, no victim was found on the ground in the search on the 18th of September. Figure 3.29 shows the detected peak in the sensor data.

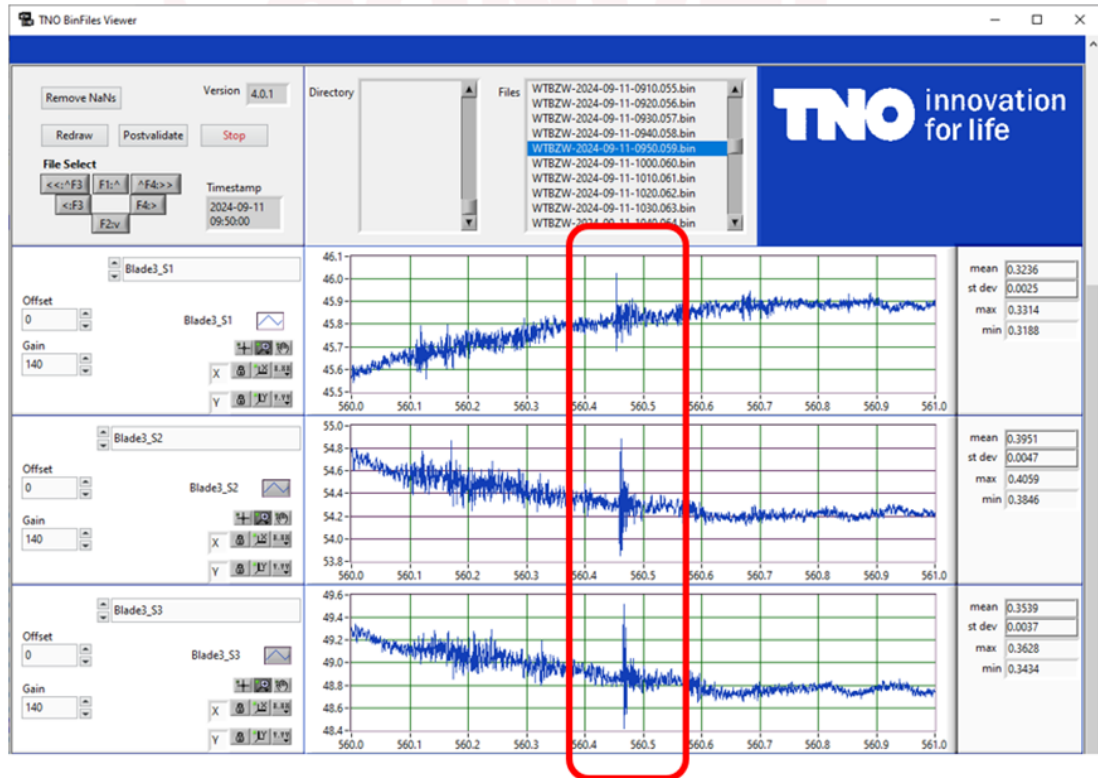


Figure 3.29: Signals of sensors in blade 3 of turbine 20 on the 11th of September with signal peak of impact circled in red

3.2.3.4 Overview impacts detected by WT-Bird®

Table 3.7 gives a short overview of the three detection methods (camera, ground search and radar) compared to the three detections of the WT-Bird® system. The radar is not expected to give clear results because it has limited detection capabilities near the turbines. On top of that, the conditions were unfavourable for good radar results during the first and last WT-Bird® detection.

Date	Turbine	Time	Camera	Ground search	Radar	Comments
3-jan-24	21	00:41:52 (Night)	Small dot in 1 frame	No victim	No	Very foggy
10-sep-24	21	01:00:47 (Night)	Yes	Ringed plover	Maybe	Ringed plover most likely victim
11-sep-24	20	09:58:21 (Day)	No	No Victim	No	Rain

Table 3.7: Overview of impacts detected by WT-Bird®

3.3 Validate impact monitoring with microphones

Part of the project was the development of WT-Bird® Light, which depends less on the sensors in the blades but on simpler and more cost-effective sensors. Microphones are a good candi-

date for this. If impacts are detected, these can be cross-referenced with the audio files from the microphone to see whether they also detect an anomaly. However, as only limited impacts were detected by the WT-Bird® system, this cross-reference option was limited. Within the ZWEMT project, microphones were installed at the turbine base, on the tower and at the blade root, all of which are discussed in more detail in the next subsections.

3.3.1 TNO ground-based microphone

A microphone setup, borrowed from the TNO acoustic department, was placed at the bottom of turbine 20 as shown in Figure 3.30. This setup is normally used for, for example, monitoring traffic. It was operational since February 2024, but not all data was stored due to limits in data storage. A full dataset is available from the 18th of September 2024 till the 29th of September 2024.



Figure 3.30: Microphone at the base of turbine 20

From the microphone data, surrounding sounds can be clearly recognised. A small list of examples is given in Table 3.8:

Birds	Cars	Motors	Trains
Lapwing	Emergency stop	Dirt bike	Passing
Gull	Car door		Train horn
Geese			

Table 3.8: Examples of recognisable sounds in the surroundings

But both the train track and road are relatively close to the turbine (15 m and 25 m, respectively). Therefore, it remained unclear whether the microphone would be sensitive enough to pick up a bird impact.

On the 23rd of September, feathers of a Lapwing were found underneath the turbines by the ecologists of Waardenburg Ecology and Altenburg & Wymenga. Unfortunately, at that time, the WT-Bird® sensors in the blades were no longer functional due to a defect on the 19th of September. However, the audio files from the microphone were available from the 18th of September. A visual search of the spectrograms, shown in Figure 3.31, indicates two anomalies on the 22nd of September, both around midnight (UTC). In the first instance, a bird can be heard, followed by a banging noise. The second is only a bang. The bird sound is most likely a Lapwing, which fits with the feathers found on the ground. The video images from the three

cameras do not confirm birds in the vicinity of the blades. So, it is questionable that the bang indicates a collision of a Lapwing with the blades, and it was concluded that it is more likely that the sound comes from the turbine itself.

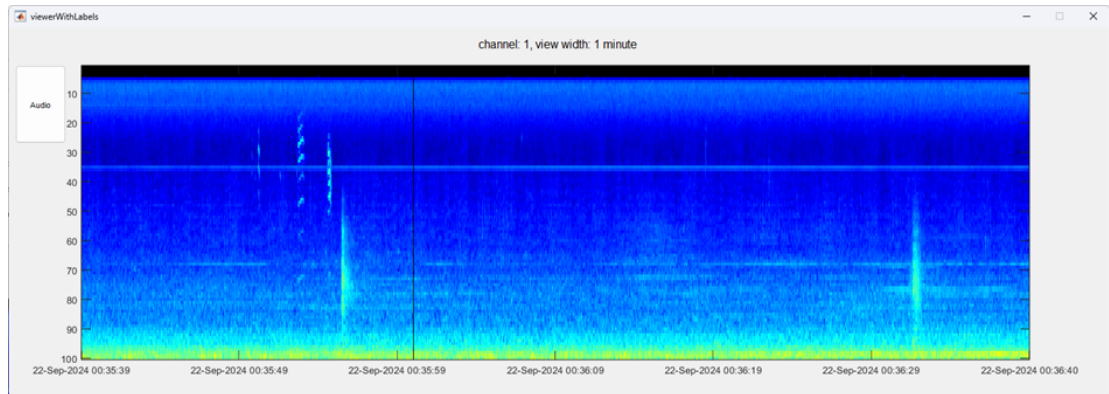


Figure 3.31: Example of audio output from acoustic setup

Nonetheless, the fact that the microphone is quite sensitive indicates that there is a good opportunity to use microphones on the ground as a cheap alternative to the sensors in the blade. However, due to the limited amount of impacts registered by WT-Bird®, no clear comparison could be made. TNO will try to do a deeper analysis linking the microphone data with the data of the camera, but this was outside of the scope of this project.

3.3.2 Commercial turbine-mounted microphones

Next to the ground-based TNO setup, two commercial solutions were deployed, both from the company Eologix-Ping. The systems are usually used to monitor turbines for blade damage. One of the two solutions is an on-tower setup, depicted in Figure 3.32.



Figure 3.32: Picture of on tower microphone of Eologix-Ping in the Eemshaven

3.3.3 Microphone at blade root

In order to be closer to the source, two additional sets of three in-blade sensors are ordered. These are mounted in the root of the blade and pointed at the blade cavity, see Figure 3.33.

Unfortunately, the software of the commercial off-the-shelf sensors did not allow to extract singular events over a longer period of time. TNO is currently still in discussion with Eologix-



Figure 3.33: Picture of in blade microphone of Eologix-Ping and picture of the microphone installed in the blade of the turbine. Left picture by Eologix-Ping

Ping about whether it is possible to extract other data, but this could not be solved within the timeline of this project.

4 Discussion and conclusions

As stated in the introduction of this report, the project had four main goals. For each of these goals, conclusions are drawn below.

1. [To examine the effectiveness of the black blade with different sensors:](#)

Within the *Black Blade* project, the conclusion was that, based on ground searches, there is no statistically significant effect of a black blade on collision victims [5]. In line with these findings, the sensors used in this project did not reveal a clear effect of the black blade.

a. [Vibration sensors in the blades – WT-Bird® system](#)

Because of the internal design of this particular type of wind turbine, it was not physically possible to install the sensors of the WT-Bird® on the leading edge as intended, but only behind the shear web. Therefore, the WT-Bird® system did not perform as planned and as expected based upon previous field tests in the US [3, 4]. FEM analysis confirmed a significant reduction of the impact signal by more than a factor of 100. For bigger birds, a reduction of approximately 97 % was modelled directly at the spanwise location of the sensor and a reduction of 99 % 2 m closer to or farther from the root of the blade. For smaller birds, this was even worse. Despite this setback, three collisions were registered, but that is not enough to conclude on the effectiveness of the black blade.

b. [\(Thermal\) cameras – WT-Bird® system](#)

Preliminary analysis showed no difference in bird activity around the turbines with a regular blade and the black blade.

c. [Robin Radar 3D MAX® bird radar](#)

Detailed analysis of the radar data showed that the presence of the black blade, to the extent measurable with the 3D MAX® bird radar, has no effect on the flight height, flight speed and the straightness of flight of birds within a radius of 200 m of the wind turbines [5].

d. [Microphones](#)

The commercial off-the-shelf microphones installed on the towers and in the blades did not perform as expected. The TNO microphone worked well, but was only installed under one turbine. Therefore, no conclusions can be drawn with regard to the black blade.

2. [To gain insight into the behaviour of birds around the \(regular and black blade\) turbines based on radar and cameras](#)

The analysis of the radar data (see point 1.c.) did give insight into the flight behaviour with regard to flight height, speed and straightness of flight. The cameras gave more detailed insight into flight behaviour close to the turbine. This includes evasive behaviour, but also birds using the turbine structure for resting, perching or feeding. Averaged over the species, radar data showed no difference in flight behaviour near the turbines with and without the black blade. Based on a smaller dataset, the cameras also showed no clear differences in behaviour. This is in line with the results from the manual searches within the *Black Blade* project.

3. [To show that the WT-Bird® system is a more accurate way to detect collisions than regular searches and, therefore, applicable offshore](#)

The limitations in installation significantly reduced the sensitivity of the WT-Bird® system. Despite the setback, three collisions were detected, two of which could be confirmed with a secondary system (camera or ground search). This is, however, insufficient data to conclude

anything regarding the applicability offshore. It should be noted that in other projects, WT-Bird® has shown to be accurate in its detections, also offshore. In the US trials, it was shown that the fatality point estimate derived from the WT-Bird® system was near the upper end of the 90 % confidence interval surrounding the bat fatality estimate based on traditional land-based survey techniques, with bats being notoriously difficult to detect as they are very small and light. As WT-Bird® was intended to be the primary sensor system in this project, the low number of registered impacts limited the cross-referencing of the WT-Bird® system with the other sensors. Positively, the reasons for this are clear and can be easily addressed in future projects.

4. [To validate the use of microphones as method to monitor impacts, such that a significant cost reduction can be achieved with respect to the regular WT-Bird® system](#)

Although only a limited dataset was collected using the TNO microphone, it proved sensitive enough to register birds and turbine sounds and, thus, is very promising. However, the limited collisions registered by the WT-Bird® system itself meant that no comparison between the two systems could be made.

References

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