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Heinz Nabielek

Proposal for the Derivation of a Predictive Correlation for Avian Mortality by Wind Turbines

Abstract

The result from the Monte-Carlo simulations predicting the number of fatalities *CC* per wind turbine per year is given by

$$CC = .429[1 - x_a]\, WT^{1.6} {v_m}^{0.6},$$

where x_a is the avoidance factor, *WT(MW)* turbine power at nameplate capacity, and $v_m(m/s)$ mean wind speed at the specific wind farm. The leading constant will depend on spatial and temporal distributions of bird swarms.
The correlation should be validated by field observations.

Introduction

On the whole, bird deaths by rotating wind turbines are rare. A risk factor between 1 and 7 was defined based on early observations[1] and used for the display of recent observations[2],[3] of bird mortality by anthropogenic causes, Figure 1 and Figure 2 : Wind is the lowest, by far. But there are some special cases[4],[5]: soaring birds are particularly vulnerable including vultures, raptors, gulls when crossing wind farms.

The main causes for declining global vulture population include collisions with power line infrastructure, electrocutions, poisoning, and deliberate persecution, Figure 3. In this study, we concentrate exclusively on avian mortality by rotating wind turbines although this is only a very minor contribution.

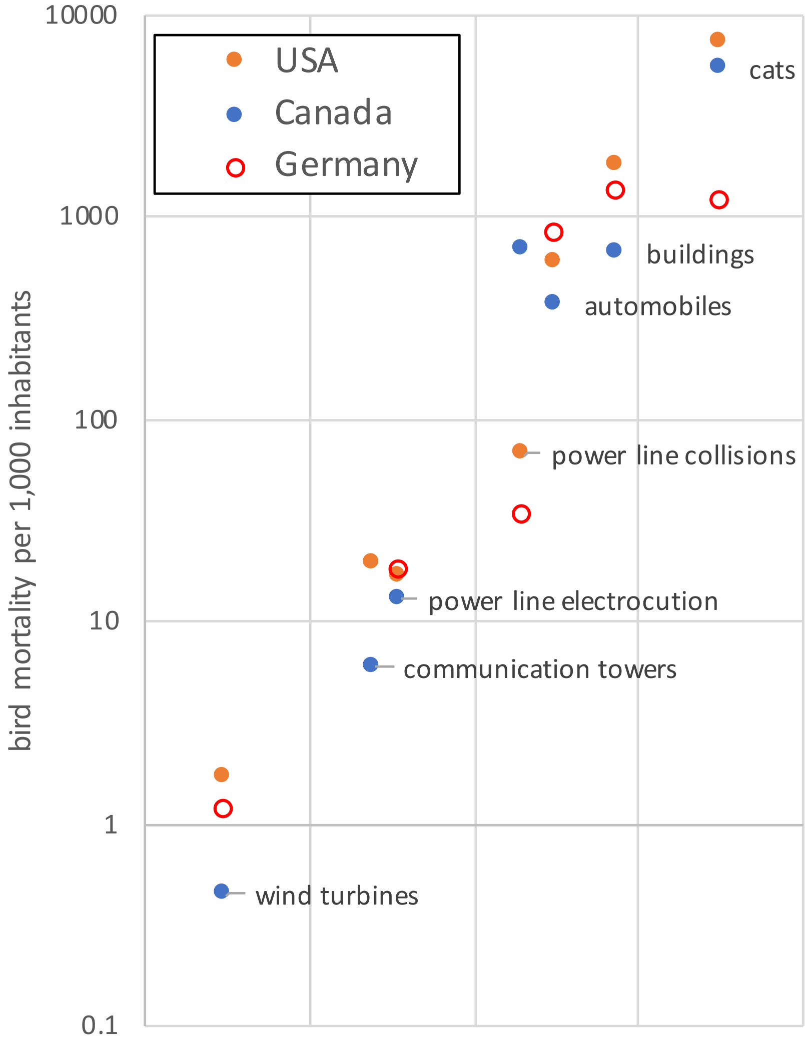

Figure 1 Account of the number of bird deaths by civilizational risks in the USA, Canada and in Germany. Feral cats are highest and wind turbines are lowest.

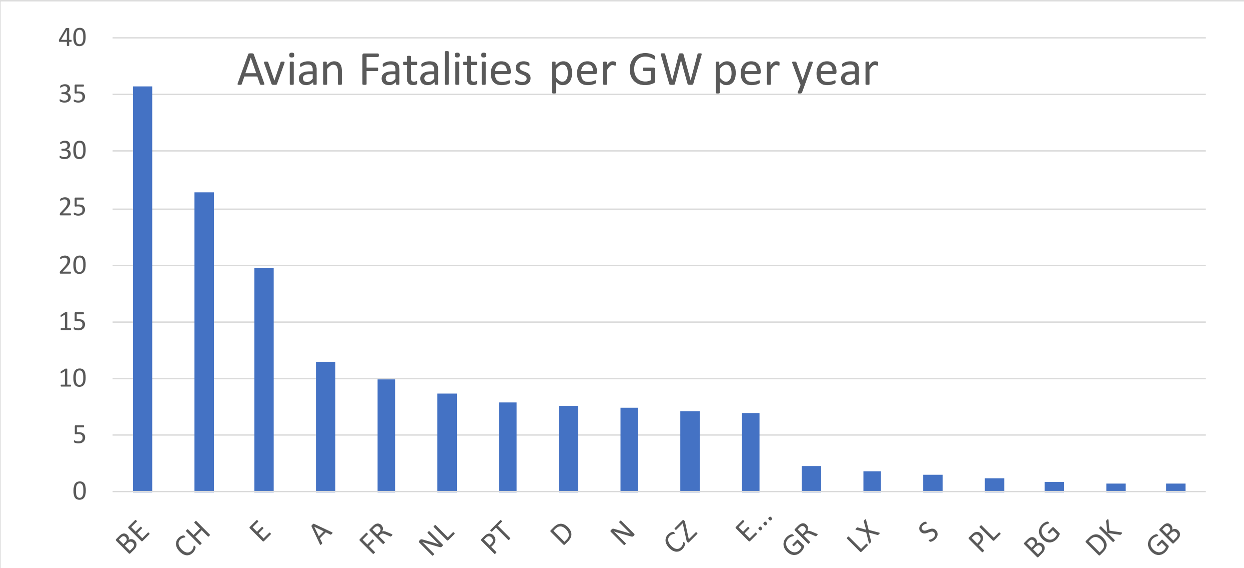

Figure 2 Landesamt für Umwelt Brandenburg[6] registered wind turbine bird fatalities in Europe since 2000.

Figure 3 Real-life photo of birds crossing wind turbines.

Avoidance of wind turbines

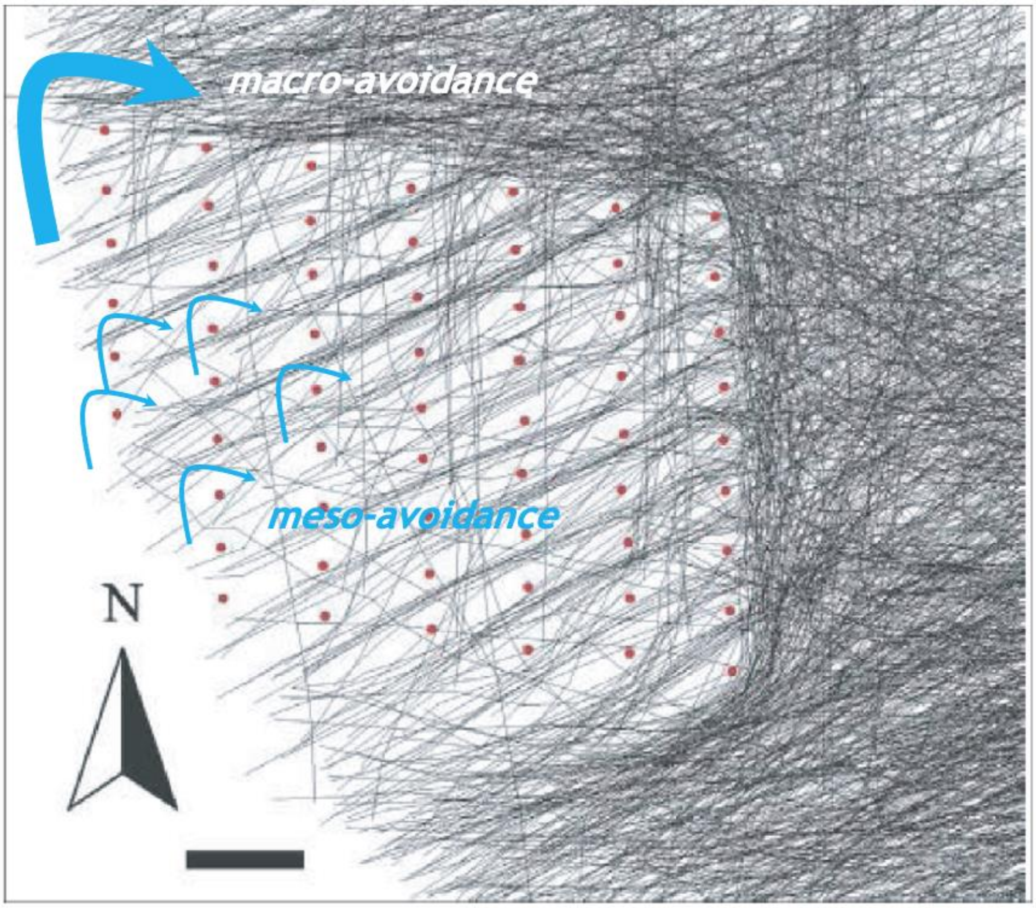

Figure 4 Bird avoidance of wind turbines as measured at the Baltic[7],[8],[9]. Micro-avoidance is the avoidance of individual rotor blades.

Table 1 Bird avoidance factors[10],[11],[12].

Northern ganne/ Morus bassanus	.995
Black-legged kittiwake/ Rissa tridactyla	.99
Lesser black-backed gull/ Larus fuscus	.995
Herring gull/ Larus argentatus	.995
Great black-backed gull/ Larus marinus	.995
Bewick's Swan/ Cygnus columbianus	.9962
Golden eagle/ Aquila chrysaetos	.995
Red-throated diver/ Gavia stellata	*.995*
Black-throated diver/ Gavia arctica	*.995*

Swans (all species)/ Cygni	*.995*
Geese (all species)/ Anser	*.998*
Red kite/ Milvus milvus	*.99*
Hen harrier/ Circus cyaneus	*.99*
Golden eagle/ Aquila chrysaetos	*.99*
White-tailed eagle/ Haliaeetus albicilla	*.95*
Kestrel/ Falco	*.95*
Great skua/ Stercorarius skua	*.995*
Arctic skua/ Stercorarius parasiticus	*.995*

Monte-Carlo simulations

The Monte-Carlo simulation models the interaction of birds statistically distributed in space and time with rotating turbine blades determined by statistically distributed wind speeds. The code contains the following components

- Random distribution of large numbers of birds in space
- Random distribution of bird arrival times crossing the plane of the rotating turbine
- Random distribution of wind speeds
- A mechanism to predict fatalities ("Band" collision risk model)

In the initial approach, bird flight speeds and bird flight directions are not accounted for, but are planned for later analyses.

Spatial distribution of birds

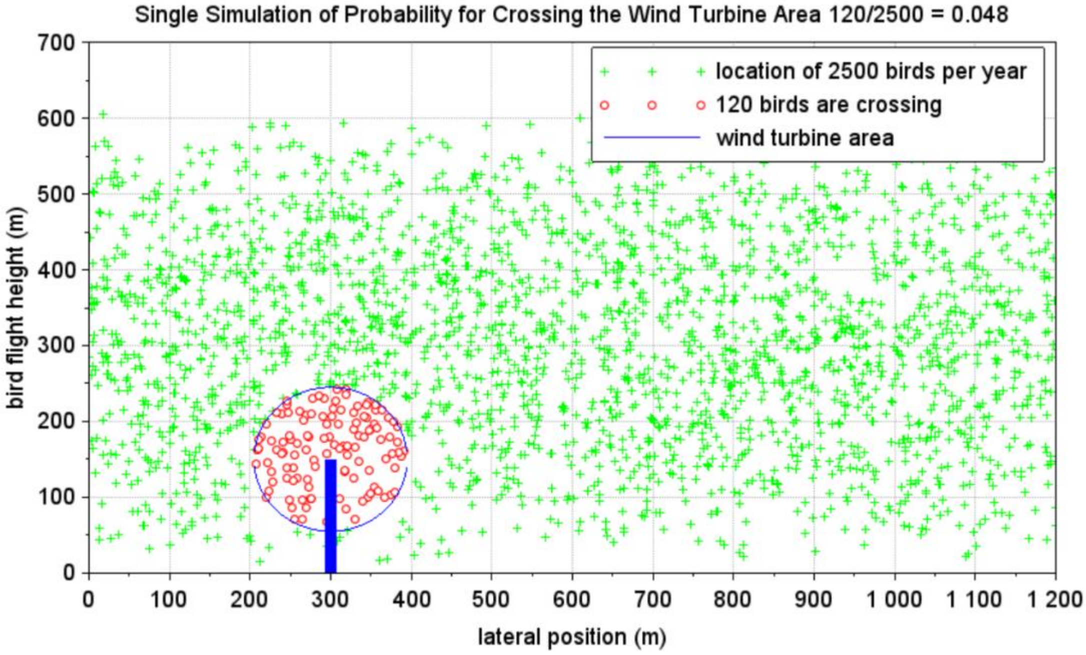

Figure 5 Monte-Carlo simulation of birds statistically distributed in space and time. Lateral uniform random distribution is over 1200 m and vertical random parabolic distribution around 310 m with a ± 300 m extension. In the model, only a small fraction of birds will be crossing the circular area of the rotating turbine blades.

Temporal distribution of bird arrival times

Figure 6 shows the statistical distribution of bird arrival times at the turbine plane modelled by an exponential distribution as is usual in queuing theory[13] for random events. In real-life applications, both spatial and temporal distributions will be provided by measured data.

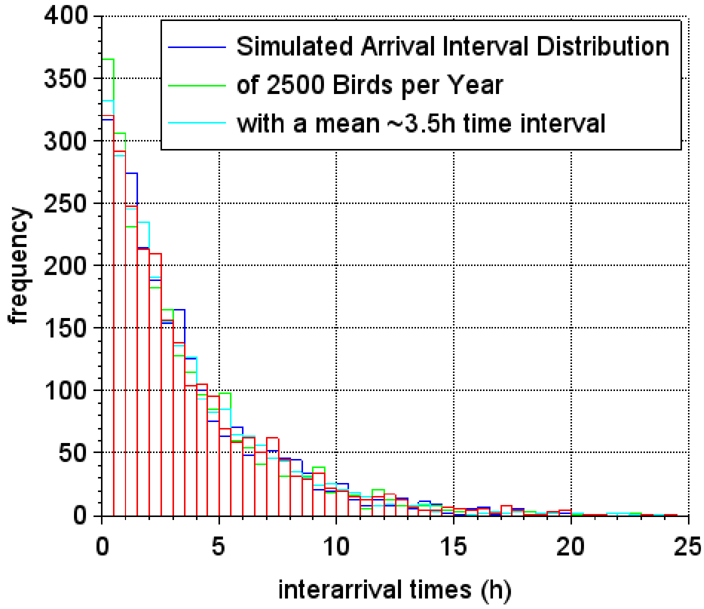

Figure 6 Monte-Carlo simulation of statistically random bird arrival times

Stochastic probability distribution of wind speeds

Figure 7 shows Monte-Carlo simulated wind speed distributions for mean values of 5 m/s and 7 m/s. All over the world, wind speeds show a Weibull distribution. In its cumulative form, it is given by $\mathrm{W} = 1 - \exp[-(\mathrm{v}/\mathrm{v_c})^{\mathrm{m}}]$, whereby v(m/s) is present speed, v_c(m/s) characteristic speed and m Weibull modulus, a shape factor. Mean value $\bar{\mathrm{v}}$ is given by $\bar{\mathrm{v}} = \mathrm{v_c} \cdot \Gamma\left(1 + {}^{1}/_{\mathrm{m}}\right)$. Most *m*-values are between 1.9 and 2.2, therefore *m*=2 is used in our predictive studies[14]. Wind speeds are not independent identically distributed variables, but are highly auto-correlated. From the examination of half a million measured wind speed data in three different locations, we have derived an autocorrelation of 98.68 %.

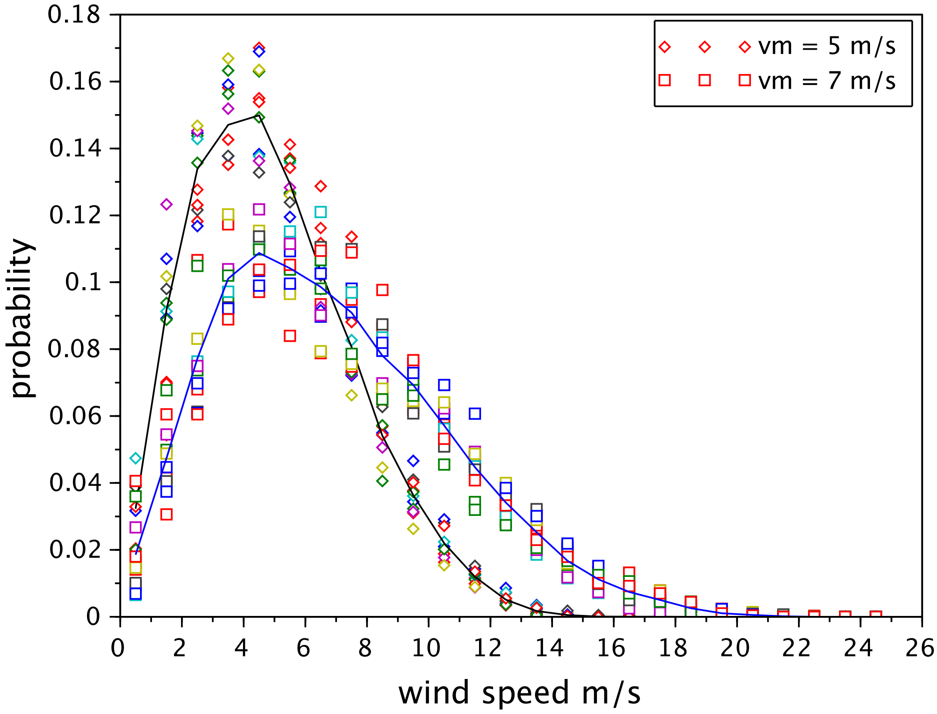

Figure 7 Monte-Carlo generated distributions of 10,000-sized samples of wind speeds with v_m=5 and v_m=7 m/s mean values of respective wind farms. Full lines are mean values of specific simulation set.

Autocorrelation of wind speeds

Although wind speed frequencies are nicely Weibull distributed, simulation of wind speeds as Weibull deviates is unacceptable, because they are not i.i.d. (independent and identically distributed) variables, see middle-diagram in Figure 9. Obviously, when the wind blows, it will most likely also blow at the succeeding 10-minute interval and when no wind blows, it will not blow most likely in the succeeding 10-minute interval. To take account of this behaviour, we have to look at the auto-correlation[15] of wind speeds, Figure 8, and we have to build autocorrelation into the wind speed simulation.

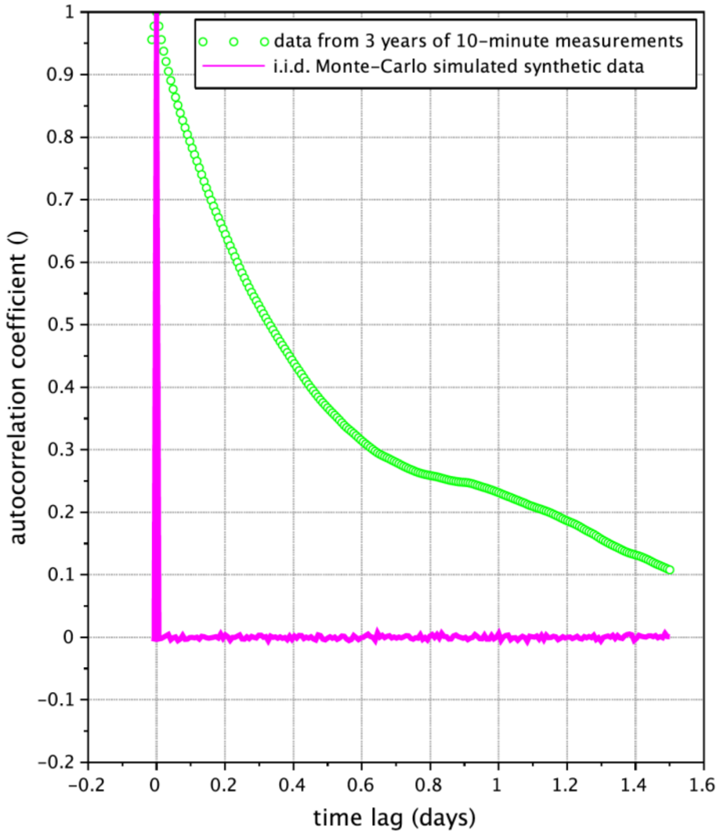

Figure 8 Finite 1.4-day autocorrelation of measured wind speeds versus lack of autocorrelation in i.i.d. Weibull deviates whereby i.i.d. = independent and identically distributed random variables. Measured data from Parndorfer Platte station #1, station #2, and station #3. Resulting primary autocorrelation coefficient is ρ~= 0.987 derived from the exponential decay during the first day.

Figure 9 shows the comparison of wind speed data over one week:

- Measured at the meteorological tower of the Forschungszentrum Jülich
- Independent Weibull deviates with same characteristic wind speed and modulus
- Weibull deviates with in-built 98.7% autocorrelation.

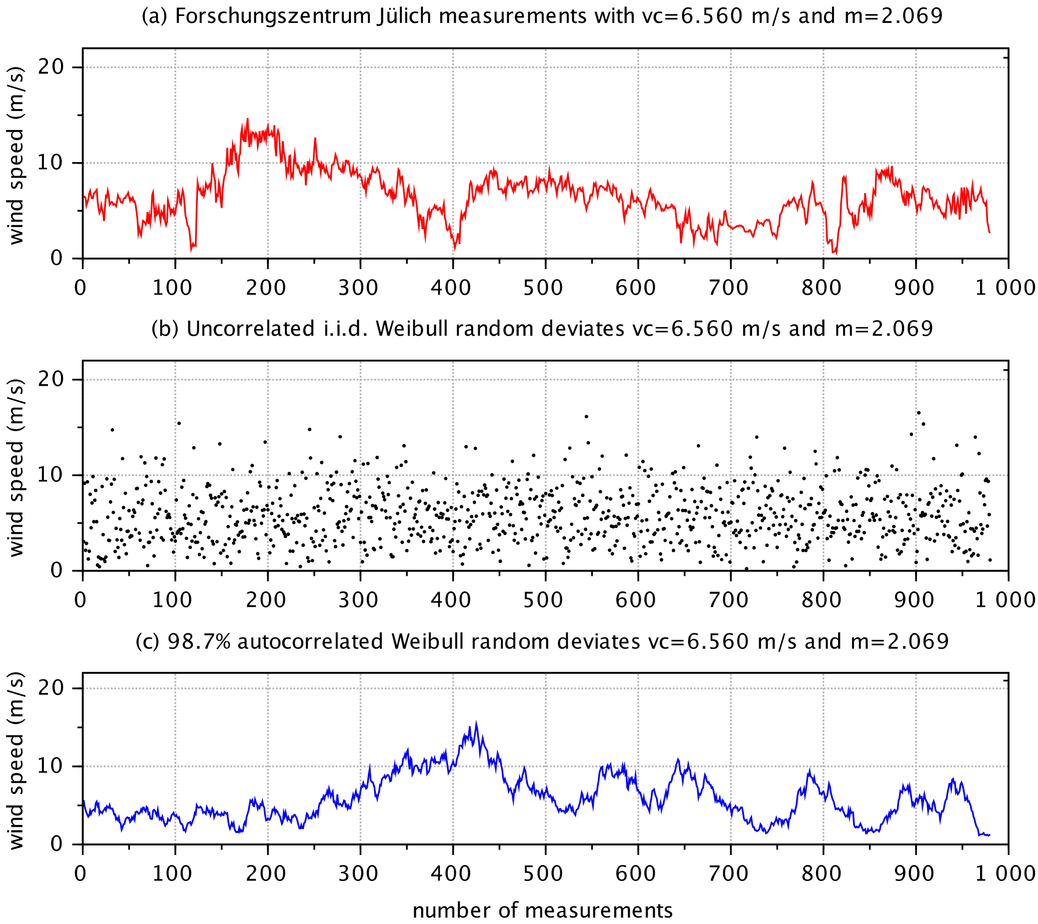

Figure 9 Forschungszentrum Jülich ten-minute wind speed measurements over one week (a). The frequency of wind speeds has a Weibull distribution, but Weibull random numbers do not reproduce wind speeds (b). A special procedure has been developed, below, to generate autocorrelated Weibull deviates that successfully simulate wind speeds (c).

As shown, independent Weibull deviates are unable to simulate realistic wind speeds.

The Band Collision Risk Model CRM

The collision of birds and bats with wind turbines is considered one of the main ecological downsides of wind power generation and much research has been going to “Collision Risk Models” CRM to enable timely predictions[16],[17].

The Band model[18],[19],[20] is used to statistically predict bird fatalities when crossing the area of the rotating turbine blades. Assumptions are:

- Birds survive when turbines are at standstill below 3 m/s and above 25 m/s wind speed.
- Birds are killed when turbines operate at full speed between 10.7 and 25 m/s.
- Birds may be killed between 3 and 10.7 m/s with a probability proportional to rotational turbine speed.

This is displayed in Figure 10 below. Since its early establishment, many more refinements and alternative approaches have been developed in CRM modelling[21],[22],[24]. For the present purposes, the original Band model is most transparent and straightforward.

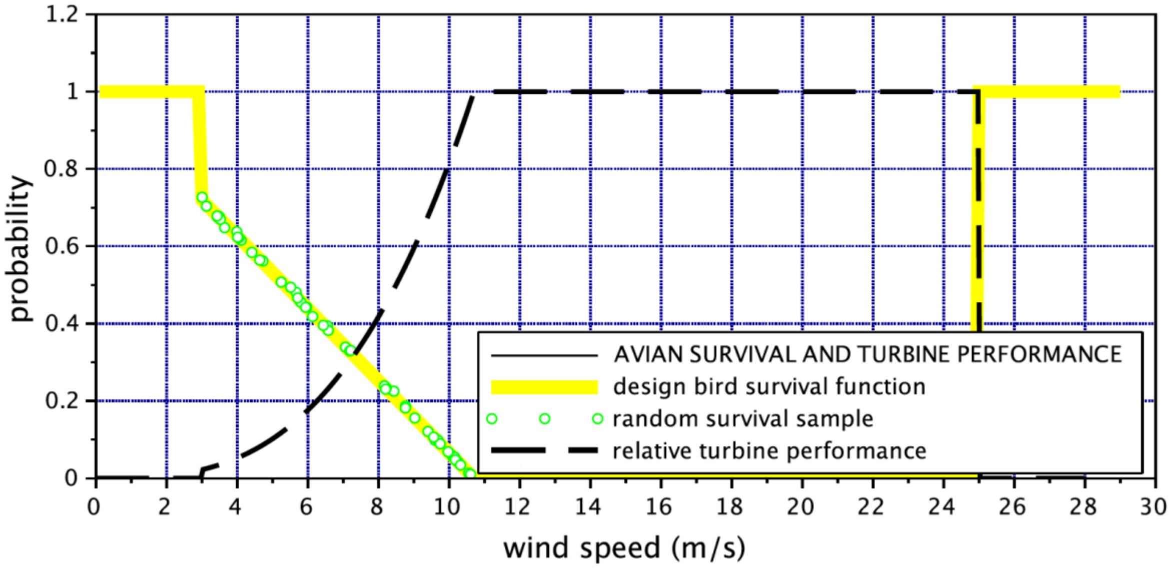

Figure 10 Juxtaposition of the avian survival probability with the relative turbine performance as functions of wind speed. The Band model[19] is the basis of the survival configuration in our statistical modelling.

The combination of turbine power, wind speeds and bird avoidance of wind turbines

The Monte-Carlo runs of this study have been conducted with a variety of assumptions and configurations simulating

- wind turbine power 2, 7 and 12 MW.
- wind farm mean velocity 5 and 7 m/s.
- bird avoidance[23],[24] factors between 10% and 99.9%.

With these parameter variations, results in terms of the fatal avian collision rate of very large numbers of simulation runs are shown in Figure 11. Comparison is also made to observed collision rates in France, Europe, Denmark as reported by the Landesamt für Umwelt in Potsdam[6].

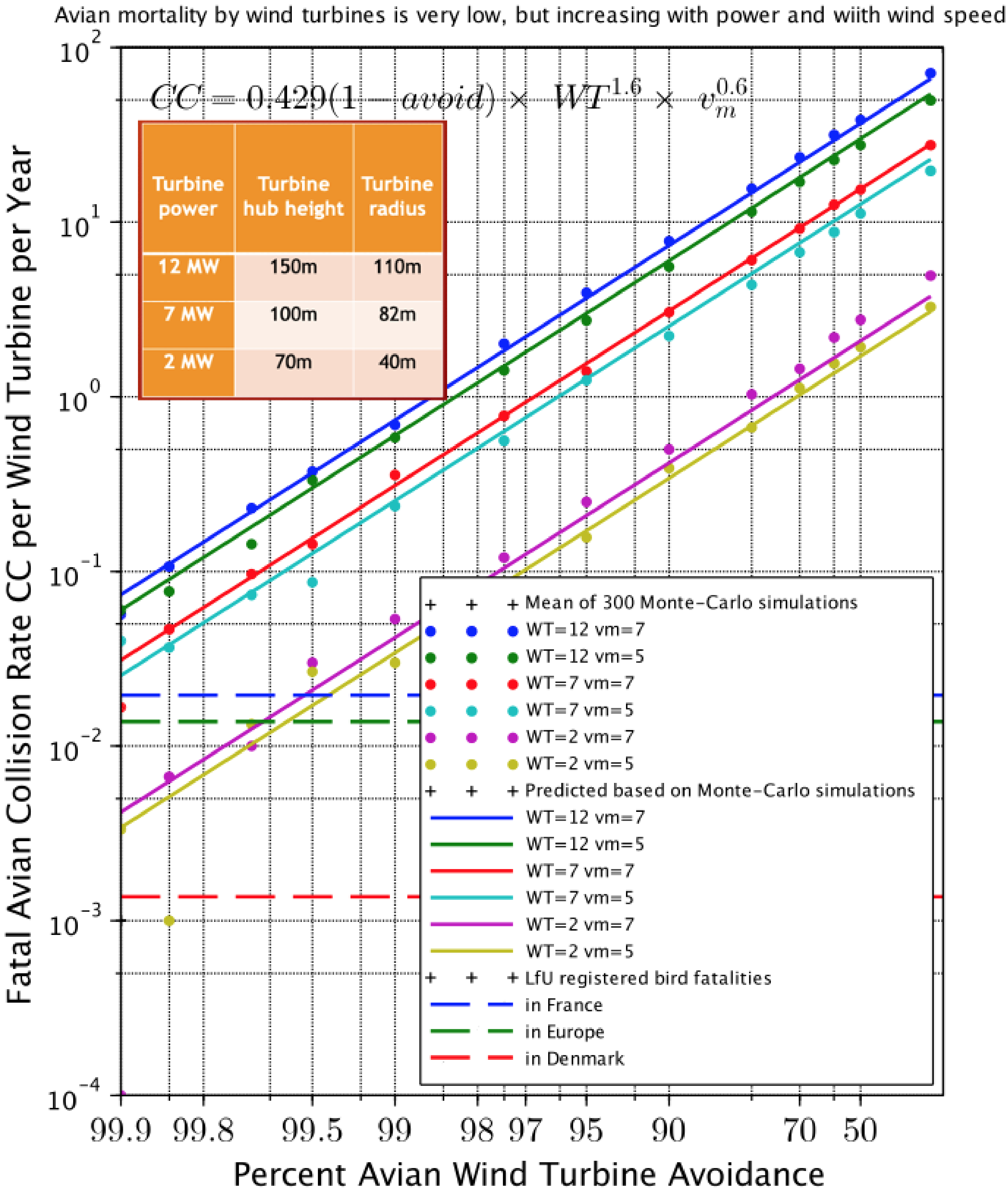

Figure 11 Collision risks of birds with wind turbines for a variety of environmental parameters. v_m(m/s) is the mean wind speed of a specific wind farm and WT(MW) is wind turbine nameplate power. The numerical correlation has been obtained by simultaneous least-squares fitting simulation data.

The world formula

Based on the simulations, a mathematical correlation is derived where numerical values in the resulting expression have been obtained by least-squares fitting. In an attempt to cover the wide range of parameters, the result from the set of all Monte-Carlo simulations predicting the number of fatalities *CC* per wind turbine per year can be approximated by

$$CC = 0.429\,[1 - x_a]\,WT^{1.6}{v_m}^{0.6},$$

where x_a is the avoidance factor, *WT(MW)* turbine power at nameplate capacity, and $v_m(m/s)$ mean wind speed at the specific wind farm. This correlation will have to be validated by field observations.

Under the specific modelling conditions chosen here – and at a farm with 5 m/s mean wind speed – mortality rates per GW power and per year of operation are given in Table 2. These numbers cover the range of data collections[6] recorded since 2000.

Table 2 Annual bird mortality rates per Gigawatt of turbine power at v_m= 5 m/s.

Turbine power	avoidance = 90%	avoid=99%	avoid=99.9%
12 MW	500 birds/a/GW	50 birds/a/GW	5 birds/a/GW
7 MW	362 birds/a/GW	36 birds/a/GW	4 birds/a/GW
2 MW	171 birds/a/GW	17 birds/a/GW	2 birds/a/MW

Based on this correlation, we can look at functional dependencies, Figure 12. While avian mortality is generally very low, it is distinctly increasing with the modern larger turbine stations. A 16-MW-system is already under development in China.

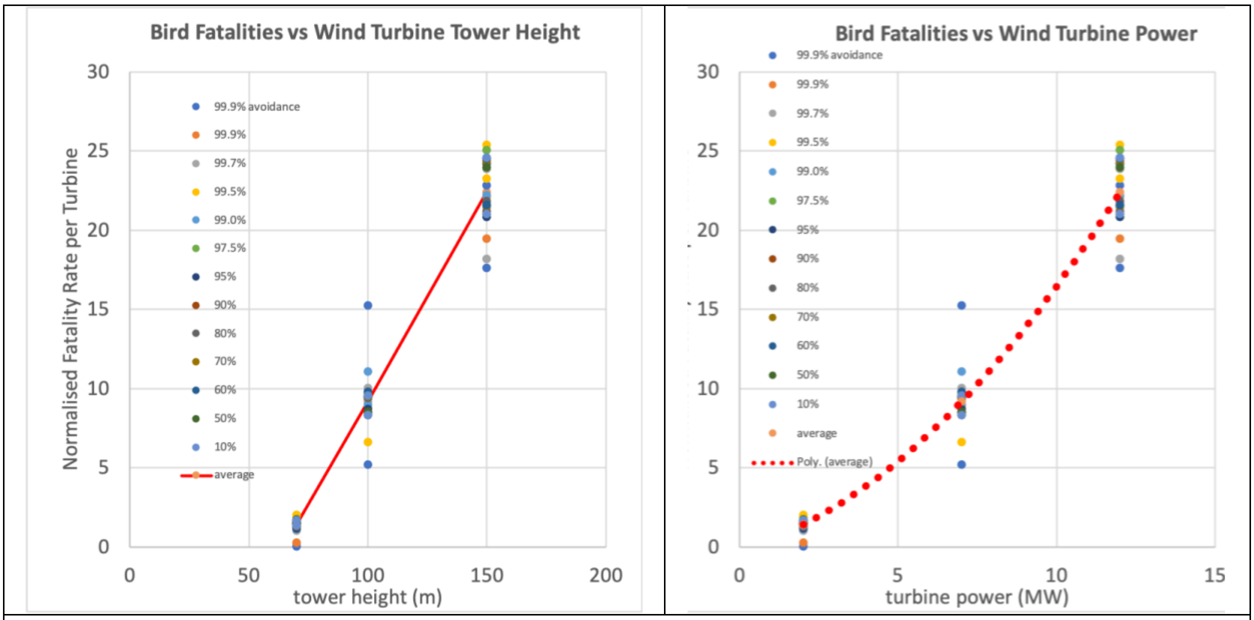

Figure 12 Bird fatalities depend on turbine height and turbine power. Every data point is the mean of 300 Monte-Carlo simulations. Normalisation is with respect to avoidance and wind speed.

The influence of flight altitudes

The existing code can be used to show the influence of various input parameters. Figure 13 shows the influence of flight altitudes on the given bird swarm. The model suggests that fatalities will be halved by 90 m higher flight altitudes of the bird swarm.

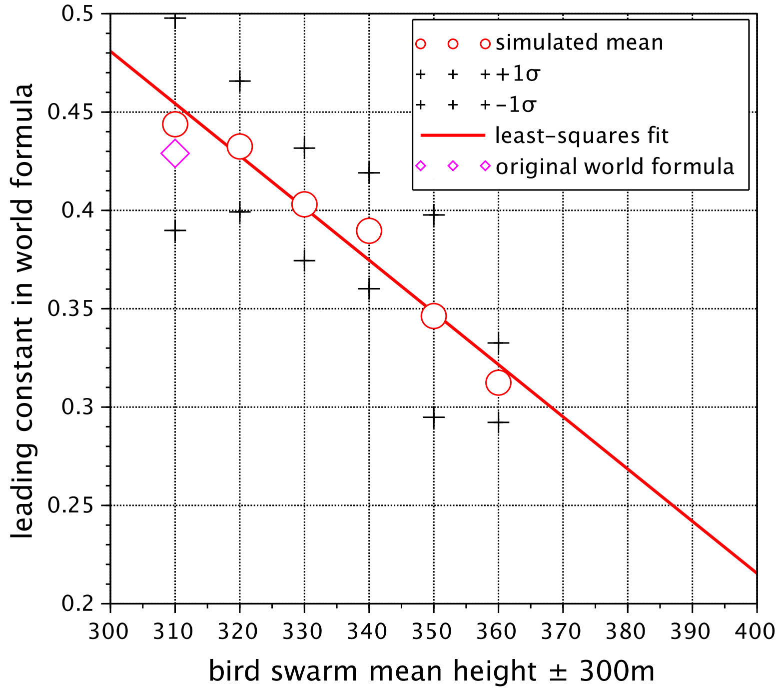

Figure 13 Model prediction to demonstrate lower fatalities in higher flight altitudes. Shown is the decrease in the leading constant of the world formula for the case of WT=12 MW wind turbines at wind farms with v_m=7 m/s wind speeds.

References

1 Choose energy fact checker: "Do wind turbines lead to increased bird deaths?" <https://www.chooseenergy.com/news/article/fact-checker-do-wind-turbines-lead-to-increased-bird-deaths>.

2 Scott R. Loss, Tom Will, and Peter P. Marra, "Direct Mortality of Birds from Anthropogenic Causes", Annu. Rev. Ecol. Evol. Syst. 46 (2015), 99–120.

3 Lars Lachmann, "Das große Vogelsterben", NABU <https://www.nabu.de/tiere-und-pflanzen/voegel/gefaehrdungen/24661.html>.

4 Morgan Pfeiffer, "Ecology and conservation of the Cape Vulture in the Eastern Cape Province, South Africa", PhD Thesis, University of KwaZulu-Natal 2016.

5 Lemaître, J., & Lamarre, V., "Effects of wind energy production on a threatened species , the Bicknell's Thrush Catharus bicknelli, with and without mitigation", Bird Conservation International, 1–16 (2020). https://doi.org/10.1017/S095927092000012X.

6 Tobias Dürr, "Bird fatalities at wind turbines in Europe", Landesamt für Umwelt Brandenburg, Germany, 17 June 2022 https://lfu.brandenburg.de/lfu/de/aufgaben/natur/artenschutz/vogelschutzwarte/arbeitsschwerpunkte/auswirkungen-von-windenergieanlagen-auf-voegel-und-fledermaeuse/

7 Desholm , M. , and J. Kahlert, "Avian collision risk at an offshore wind farm", Biology Letters 1 (2005), 296 – 298.

8 Mark Desholm, "Wind farm related mortality among avian migrants", PhD thesis at the Institute of Biology, University of Copenhagen, August 2006.

9 Wim Turkenburg et al., *Renewable Energy*, Chapter 11 in IIASA 'Global Energy Assessment, Toward a Sustainable Future', International Institute for Applied Systems Analysis, Laxenburg 2012.

10 Bowgen, K., Cook, A., 2018. "Bird Collision Avoidance: Empirical Evidence and Impact Assessments", Joint Nature Conservation Committee Report 614 (2018), ISSN 0963-8091, Peterborough, UK.

11 Dan E Chamberlain, et al., "The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models", Ibis 148 (2006), 198-202.

12 Scottish Natural Heritage, "Avoidance Rates for the onshore SNH Wind Farm Collision Risk Model", SNH office at Stilligarry, South Uist, HS8 5RS, Scotland, September 2018.

13 Wei Wu Xiong, *Time Series Analysis: Univariate and Multivariate Methods*, China Renmin University Press, 1 August 2021.

14 IEC - International Electrotechnical Commission: Standard IEC 61400-26-1 "Wind energy generation systems – Part 26-1: Availability for wind energy generation systems", Geneva 1 May 2019.

15 Moisés Cordeiro-Costas, Daniel Villanueva, Andrés E. Feijóo-Lorenzo, and Javier Martínez-Torres, "Simulation of Wind Speeds with Spatio-Temporal Correlation", Applied Sciences 11 (2021), 3355.

16 Tucker V.A., "A mathematical model of bird collisions with wind turbine rotors", J. Sol. Energ. Eng. 118 (1996), 253–262.

17 Drewitt, A.L., and Langston, R.H.W., "Assessing the impacts of wind farms on birds", Ibis 148 (2006), 29–42.

18 Band W., Madders M. & Whitfield D.P., "Developing field and analytical methods to assess avian collision risks at wind farms". In: de Lucas M., Janss G.F.E. & Ferrer M. (eds) '*Birds and wind farms'* (2007), Quercus, Madrid.

19 Bill Band, “Using a Collision Risk Model to Assess Bird Collisions Risks for Offshore Wind Farms”, Strategic Ornithological Support Services Project SOSS-02, Thetford: British Trust for Ornithology, <https://tethys.pnnl.gov/sites/default/files/publications/Band%202012.pdf>.

20 JC Kleyheeg-Hartman, KL Krijgsveld, MP Collier, MJM Poot, AR Boon, TA Troost, S Dirksen, "Predicting bird collisions with wind turbines: Comparison of the new empirical Flux Collision Model with the SOSS Band model”, Ecological Modelling 387 (2018), 144–153.

21 Krijgsveld, Karen L., et al. "Collision risk of birds with modern large wind turbines", Ardea 97.3 (2009), 357-366.

22 Heritage, Scottish Natural. "Avoidance rates for the onshore SNH wind farm collision risk model", version 2 from September 2018.

23 Elizabeth Anne Masden, "Assessing the cumulative impacts of wind farms on birds", PhD Thesis University of Glasgow, Division of Ecology and Evolutionary Biology, April 2010.

24 E.A. Masden, and A.S.C.P. Cook. "Avian collision risk models for wind energy impact assessments", Environmental Impact Assessment Review 56 (2016), 43–49.