Estimating the frequency of bird collisions with wind turbines at sea

Guidelines for using the spreadsheet 'Bird collisions Deltares v1-0.xls' 'Bird collisions Deltares v1-0.xls'

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Report

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Client	
Title	Estimating the frequency of bird collisions with wind turbines at sea

Abstract

In predicting the frequency of bird collisions with wind turbines, three different calculation models or 'routes' are used. Two of these routes are based on observed collision probabilities, the third is based on collision probabilities estimated with a model. The objective of this guidance report is to provide clarity about these different calculation routes and to standardize them. This is done by giving a detailed description of the calculations, and by making the notation of their formulas consistent. Also, a spreadsheet is provided in which the three models can be applied simultaneously to a set of parameters provided by the user. This will facilitate a comparison of results of the three routes, and hopefully it will prevent unnecessary mistakes in future. The usage of this spreadsheet is explained in this document. Finally, the possibilities to deal with uncertainties in parameter values by means of a probabilistic analysis are discussed.

References	

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Contents

1 Introduction

For the estimation of the frequency with which birds collide with wind turbines at offshore wind farms in the Netherlands three different approaches or 'routes' have been proposed. Two of these routes are based on observed collision probabilities (e.g. Winkelman, 1992a), the third is based on collision probabilities estimated with a model (Band, 2000). The first two routes have been previously described by Ecofys (2007), and they have been used in several Dutch Environmental Impact Assessments (EIA) for offshore wind farms. So far, the third route has not been applied to offshore wind farms in the Netherlands, but it has been used to predict collision probabilities for seabirds in for instance the Moray Firth (Scotland; [330]). The three calculation routes partially overlap and have developed over time, which has lead to confusion about their proper application and in some cases to errors (van der Tol, 2007).

The objective of this guidance report is to provide clarity about the different calculation routes of the bird collision rates and to standardize them. This is done by describing the three routes in detail, and by making the notation of their formulas consistent. Also, a spreadsheet is provided in which the three models can be applied simultaneously to a set of parameters provided by the user. This will facilitate a comparison of results of the three routes, and hopefully it will prevent unnecessary mistakes in future.

In chapter 2 an overview of the three routes is presented together with a description of their main similarities and differences. Chapter 3 describes the layout of the spreadsheet. Chapter 4 contains instructions for the collection of data needed to enter parameter values into the spreadsheet. Finally the possibilities to extend the approach with uncertainty analyses is discussed in chapter 5.

2 Calculating the bird collision rate

As mentioned in the introduction, three different routes to calculate bird collision rates have been proposed. All three routes consist of the same components:

1. The bird flux

This is the number of birds per unit of time flying through the rotor area, i.e. the area swept by the rotors. The value depends on the number of individual birds involved and the number of times each individual crosses the rotor area. In paragraph 4.1 the possible influence of repeated crossings is discussed.

2. The probability of collision

This is the probability of collision with (the rotor blades of) a turbine when flying through the rotor area. Here, the term ‘collision’ includes any side effects, like fatalities caused by the turbulence created by the moving rotors.

3. Scaling factor

A factor used to scale up the effect to the total farm size.

The main difference between the three routes exists in their starting point: two of the routes are based on the number of collisions observed in one or more reference farms, which number is then corrected for the differences between the reference farm and the farm of interest. The third route is based on collision probabilities estimated (with a sub-model) for the park of interest (see figure 2.1), and thus follows a bottom-up approach in which all parameters refer only to the park of interest. Clearly, the applicability of the first two routes depends on whether empirical data on the number of bird collisions in one or more reference farms can be translated to the wind farm and species of interest. The applicability of the third route depends on the availability of all the underlying parameters that are needed in the (sub-)model, which are many. More comments on differences and (dis)advantages of the three routes are given in paragraph 2.4.

First, in the three paragraphs below, each of the three routes is presented in more detail. Hereby, a certain level of aggregation was applied to the input parameters. This means that the parameters are not split up into their smallest possible components. For instance, the “bird flux” (i.e. the total number of bird-crossings per year) is not split up in “the number of bird individuals” and “the number of crossings per individual”. As a result, the user thus has to multiply these two terms before filling in their product in the spreadsheet. This aggregation of parameters is used because it leads to more transparency in the formulas, but more importantly, it also provides generality by allowing the parameters to be pre-calculated in several ways. This is necessary as local differences or the in-availability of data may require different handling. It is up to the user to decide which pre-calculation is most appropriate in his or her case. Clearly, this makes it of crucial importance that users document well which parameter values they use and how they have calculated these. To minimize the amount of errors to be made in this step, detailed definitions and the most common possibilities for (pre)calculating the parameters are given in chapter 4.

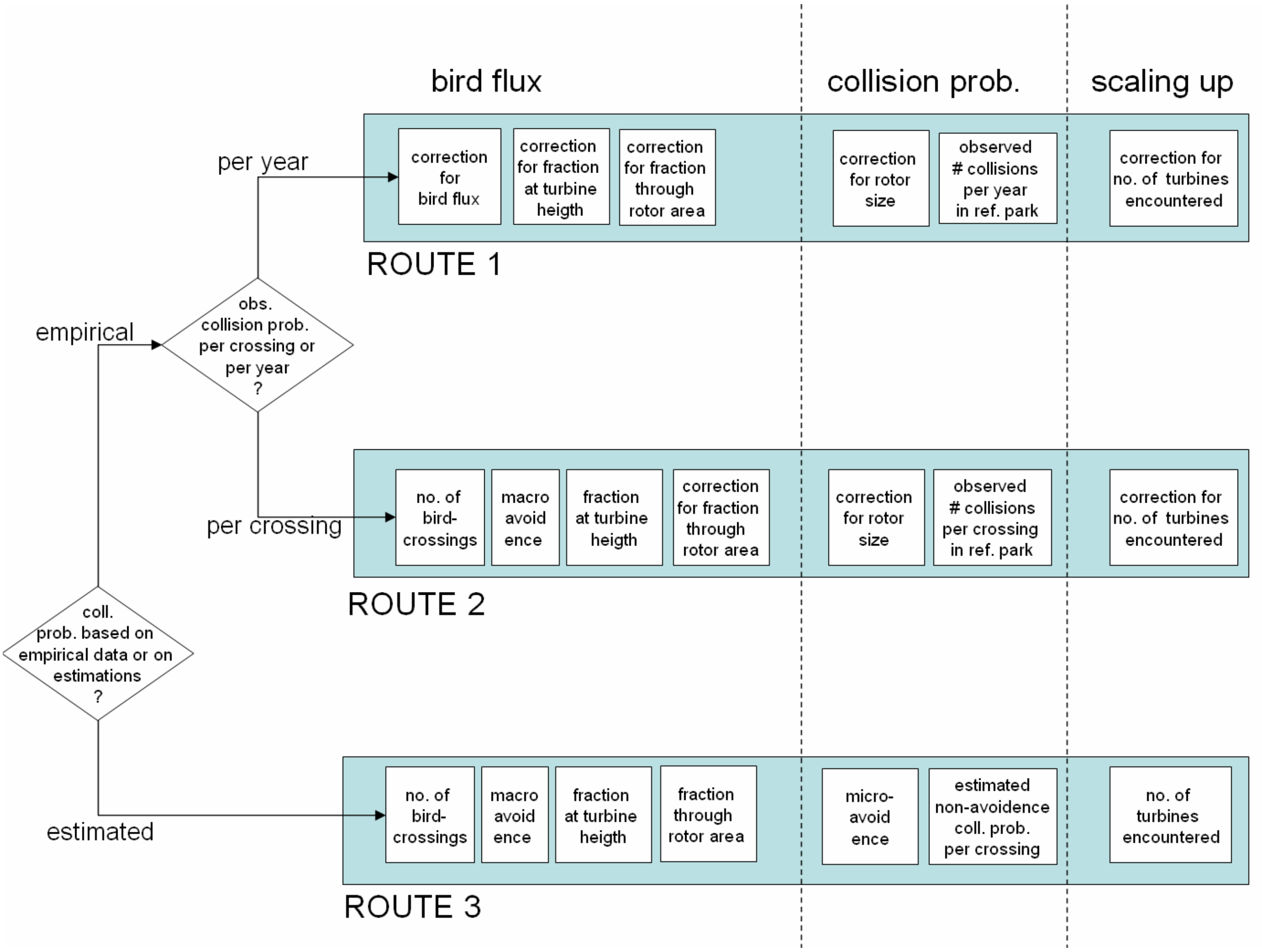


Figure 2.1. Overview of the three routes for calculating collision probabilities.

2.1 ROUTE 1

The collision rate in route 1 (c1) is based on the average number of bird collisions per year observed in a reference farm (p1), which then has to be corrected for any differences between the reference farm and the farm of interest.

These corrections are related to a different bird flux through the wind farm as a whole (b_rel), a different fraction of birds flying at collision-risk heights (h/h_ref), and a different chance of flying through the rotor area (r/r_ref). Also, a correction is needed for the difference in size between the two wind farms, for which not the number of turbines is of importance, but rather the number of turbines that is encountered per crossing (e/e_ref). Finally, a correction (p_cor) has to be made due to the fact that the probability of a bird colliding with the moving rotors decreases with increasing rotor size (Tucker 1996, see paragraph 4.2). The resulting formula is given by:

c1 = b_rel * h / h_ref * r/r_ref * e/e_ref * p_cor * p1

where
c1 = no. collisions per year in the farm of interest calculated with route1
b_rel = relative no. of bird crossings per year with respect to reference farm
h = fraction of birds flying at turbine height[1]
h_ref = fraction of birds flying at turbine height in reference farm
r = ratio of rotor area and passage area per turbine[2]
r_ref = ratio of rotor area and passage area per turbine in ref. farm
e = average no. of turbines encountered per crossing
e_ref = average no. of turbines encountered per crossing in the reference farm
p_cor = correction of p1 for differences in turbine size with reference farm
p1 = average no. of collisions per year in reference farm(s)
(More information on these parameters is given in chapter 4.)

2.2 ROUTE 2

The collision rate in route 2 (c2) is based on the collision probability per single bird-crossing of the wind farm at turbine height observed in a reference farm (p2). Note that p2 has different units than p1: as p2 involves the number of collisions per crossing, route 2 also requires the absolute number of birds that cross the wind farm at turbine height, which is calculated by the absolute bird flux (b), the fraction at turbine height (h), and the macro-avoidance (a_macro); micro-avoidance is already included in the collision probability (p2). Still, p2 has to be corrected for some differences between the reference farm and the farm of interest. These corrections again include a different ratio of the rotor area and the passage area (r/r_ref), and a different number of turbines that is encountered when crossing the farm (e/e_ref). Finally also a correction (p_cor) has to be made due to the fact that the probability of a bird colliding with the moving rotors decreases with increasing rotor size (Tucker 1996, see paragraph 4.2). The resulting formula is as follows:

1. *Turbine height is defined as the distance between the (sea) surface and the highest tip of the rotors.*
2. *The passage area of a single turbine is defined as the total area surrounding a turbine, including both the rotor area and the area that is not swept by the rotor. See also paragraph 4.1*

c2 = b * h * a_macro * r/r_ref * e/e_ref * p_cor * p2

where
c2 = no. collisions per year calculated with route2
b = no. of bird crossings per year
h = fraction of birds flying at turbine height
a_macro= fraction of birds avoiding the farm as a whole
r = ratio of rotor area and passage area per turbine
r_ref = ratio of rotor area and passage area per turbine in ref. farm
e = average no. of turbines encountered per crossing
e_ref = average no. of turbines encountered per crossing in the reference farm
p_cor = correction of p2 for differences in rotor size with reference farm
p2 = average no. of collisions per crossing of the reference farm at turbine height
(More information on these parameters is given in chapter 4.)

2.3 ROUTE 3

Starting point of this third route is the probability of a bird colliding with the rotor blades if it crosses the rotor area without showing avoidance behavior (p3). This probability should be estimated with the use of an appropriate sub-model such as the SNH-model (Band 2000). This sub-model requires data regarding the rotor blades (the number of rotor blades, their radius, their angular velocity, their chord width and pitch angle), and data about the bird species (length, wingspan, aspect ratio, flying velocity, and whether it is a gliding or flapping species).

Because the collision probability p3 is estimated directly for the farm of interest, and not for a reference farm, no corrections are needed as is the case in routes 1 and 2. Instead, route 3 requires absolute values for the bird flux (b), the fraction at turbine height (h), the ratio of rotor and passage area per turbine (r), and the macro-avoidance (a_macro), to calculate the number of birds that cross the rotor area. The micro-avoidance (a_micro) is also needed as this is not included in the estimated collision probability (p3). Finally, the (absolute) number of turbines encountered per crossing (e) is required to scale up to the total wind farm size. The full formula for c3 is then given by:

c3 = b * h * a_macro * r * e * a_micro * p3

where
c3 = no. collisions per year calculated with route3
b = no. of bird crossings per year
h = fraction of birds flying at turbine height
a_macro= fraction of birds avoiding the farm
r = ratio of rotor area and passage area per turbine
a_micro= fraction of birds at collision course avoiding the rotors
p3 = estimated no. of collisions per crossing of the rotor area of a single turbine
e = average no. of turbines encountered per crossing
(More information on these parameters is given in chapter 4.)

Route 3 has not yet been applied to Dutch wind farms, but an application to the Beatrice Wind Farm Demonstrator Project can be found in the corresponding report by Talisman Energy (UK) Limited (2005).

2.4 Comments on choosing between routes

The three routes for calculating collision rates have three limitations. First, the calculations can only be done for a single species (or group of similar species) at a time. This is inherent to the input parameters, which are mostly species-specific (or at best species-group specific). The second limitation is that the models only concern birds that are migrating through the farm. If birds spend time foraging, resting or protecting their territory within the farm itself, the model parameters should be adjusted as to correspond to the specific behavior of the birds. The third limitation is that the models only deal with the effect of a single wind farm. Though some of the underlying lines of thought can be extended to multiple wind farms, it will be difficult to express their effect on the collision probability in quantitative terms.

Route 1 may be especially useful when no data on the total bird flux and avoidance behavior is available. This is because not the absolute bird flux, but the relative bird flux (with respect to the reference farm), is required in the formula. Also, it does not involve the micro- or macro-avoidance, parameters about which much uncertainty exists.

Route 2 is preferred over route 1 when relevant data on the absolute bird flux is available, as well as on macro-avoidance. Though it involves more parameters than route 1, route 2 still requires less parameters than route 3.

A disadvantage of both route 1 and 2 is that they are dependent on the availability of empirical data on the number of collisions, which observations are difficult to make. Primary cause of the difficulty is that collision occurrences are generally quite rare and happen quickly. It thus involves either a long-term measuring campaign and/or coverage over a large number of turbines to obtain reliable values.

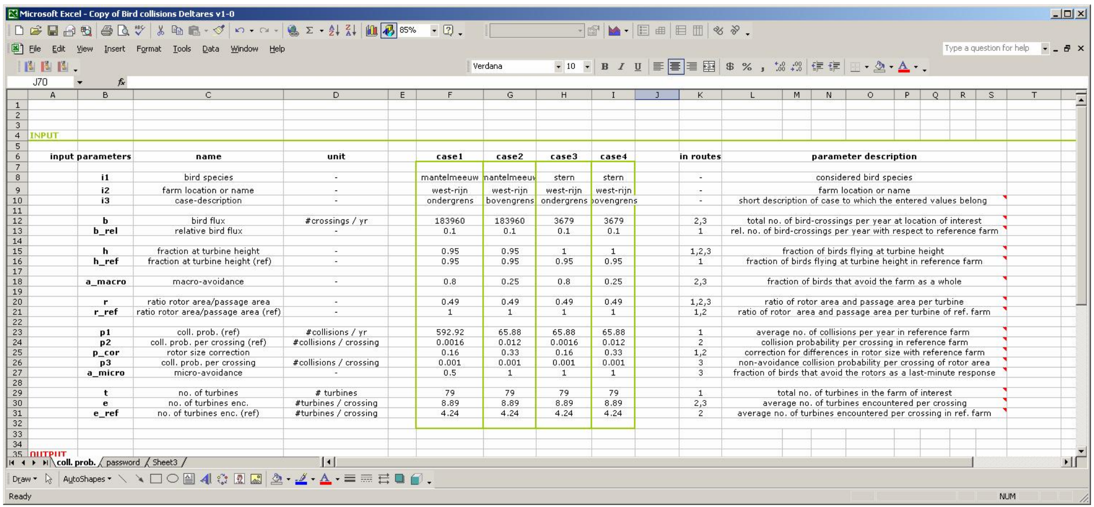
Route 3 may be especially useful when no data on collision probabilities is available at all, or when the relevancy of the data with respect to the farm or species of interest is doubtful. The disadvantage of route 3, however, is that many parameters are needed to calculate the non-avoidance collision risk. These parameters may be unknown, or may involve many (natural) variations, which leads to a large accumulation of uncertainties in the end-result. An approach to deal with these uncertainties is a so-called probability analysis, as is discussed in the final chapter of this report.

At the moment of writing, routes 1 and 2 are the only routes that have been applied to Dutch wind farms. In general, they are more easily applicable then route 3 because they require less parameter values. However, an uncertainty analysis on route 3 may show which uncertainties contribute most to the variability of its results, and if these uncertainties are caused by a lack of knowledge, further research to these parameters could be done so that in future the third route may become a more preferable option.

3 Spreadsheet

The spreadsheet consists of two parts: the upper (green) part is used for parameter input (figure 3.1) , and the lower (red) part is used for output (figure 3.2). In this chapter, the contents and usage of the two parts are presented.

3.1 Input



input parameters	name	unit	case1	case2	case3	case4	in routes	parameter description
i1	bird species	-	mantelmeeuw	nantelmeeuw	stern	stern	-	considered bird species
i2	farm location or name	-	west-rijn	west-rijn	west-rijn	west-rijn	-	farm location or name
i3	case-description	-	ondergrens	bovengrens	ondergrens	ovengrens	-	short description of case to which the entered values belong
b	bird flux	#crossings / yr	183960	183960	3679	3679	2,3	total no. of bird-crossings per year at location of interest
b_rel	relative bird flux	-	0.1	0.1	0.1	0.1	1	rel. no. of bird-crossings per year with respect to reference farm
h	fraction at turbine height	-	0.95	0.95	1	1	1,2,3	fraction of birds flying at turbine height
h_ref	fraction at turbine height (ref)	-	0.95	0.95	0.95	0.95	1	fraction of birds flying at turbine height in reference farm
a_macro	macro-avoidance	-	0.8	0.25	0.8	0.25	2,3	fraction of birds that avoid the farm as a whole
r	ratio rotor area/passage area	-	0.49	0.49	0.49	0.49	1,2,3	ratio of rotor area and passage area per turbine
r_ref	ratio rotor area/passage area (ref)	-	1	1	1	1	1,2	ratio of rotor area and passage area per turbine of ref. farm
p1	coll. prob. (ref)	#collisions / yr	592.92	65.88	65.88	65.88	1	average no. of collisions per year in reference farm
p2	coll. prob. per crossing (ref)	#collisions / crossing	0.0016	0.012	0.0016	0.012	2	collision probability per crossing in reference farm
p_cor	rotor size correction		0.16	0.33	0.16	0.33	1,2	correction for differences in rotor size with reference farm
p3	coll. prob. per crossing	#collisions / crossing	0.001	0.001	0.001	0.001	3	non-avoidance collision probability per crossing of rotor area
a_micro	micro-avoidance	-	0.5	1	1	1	3	fraction of birds that avoid the rotors as a last-minute response
t	no. of turbines	# turbines	79	79	79	79	1	total no. of turbines in the farm of interest
e	no. of turbines enc.	#turbines / crossing	8.89	8.89	8.89	8.89	2,3	average no. of turbines encountered per crossing
e_ref	no. of turbines enc. (ref)	#turbines / crossing	4.24	4.24	4.24	4.24	2	average no. of turbines encountered per crossing in ref. farm

Figure 3.1. The input part of the collision models spreadsheet.

Columns

B: Input parameters
C: Parameter names
D: Parameter units
F: Parameter values for case 1.
G: Parameter values for case 2.
H: Parameter values for case 3
I: Parameter values for case 4
K: Routes in which a value of the corresponding parameter is required.
Note that input in rows 8-10 is optional. In these fields a description can be given to describe each case.
L: Input parameter description

Multiple parameter sets

The spreadsheet provides space for four different sets of parameter values. These parameter sets or "cases" may for example correspond to various scenarios, different wind farms or bird species. It allows for easy comparison between the cases.

Detailed information

More information on each of the parameters can be found in the note attached to the fields in column L. Red triangles in the upper-right corner of these fields indicate that such a note is present. The note is shown when the mouse is placed on the field of interest; clicking is not necessary. The information provided by the notes is also included in the fourth chapter of this report.

Protection measures
Only the input parameter value fields (in columns F-I) can be edited; all other fields are protected to prevent users from accidentally changing the formulas or text. This protection can be removed by unchecking the options offered by Excel (menu choices ‘Tools’, ‘Protection’, ‘Unprotect Sheet’).

Conditional formatting is used to prevent users from filling in invalid values. When an invalid value is entered in a field, it becomes red. For now, such warnings are only given for the parameters that are limited to values between 0 and 1, such as the macro avoidance. For the other parameter values, extra attention should be given as to fill in valid values that correspond to the units as described in the spreadsheet itself. In the future, additional warnings and conditional formats may be added as more becomes known of the valid ranges of the other parameter values.

Worked examples
To provide the users with some worked examples, the input fields in the spreadsheet have already been filled out. The provided values are based as much as possible on a document regarding the collision rate estimates as calculated by route 2 (van der Tol, 2007) for an existing Dutch Environmental Impact Assessment (West-Rijn offshore wind farm). The first case refers to an lower boundary estimate of the collision rate for the Lesser Black-backed Gull, the second case to an upper boundary estimate; the third and fourth case refer to the lower and upper estimates for the collision rates regarding the Sandwich Tern. Input values in rows 12, 15, 18, 24 and 26 can be obtained from the document (van der Tol, 2007). The values in rows 29 and 30 are the square-roots of the number of turbines in the park of interest and the reference park, respectively (e=sqrt(79), e_ref=sqrt(18)). Because the base-document does not provide separate values for the relative rotor areas, we used the provided correction value (0.49) in row 20 and neutralized row 21 by giving it a value of 1. Values for input parameters needed for the first and third route are not based on existing cases, but were chosen arbitrarily.

3.2 Output

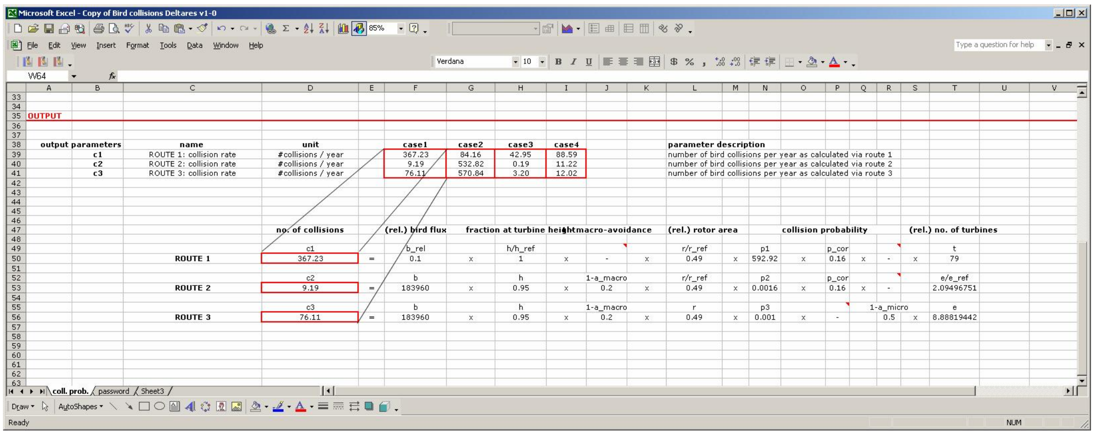


Figure 3.2. The output part of the collision models spreadsheet.

Columns
B: Output parameters
C: Parameter names
D: Parameter units
F: Output values for case 1.
G: Output values for case 2
H: Output values for case 3
I: Output values for case 4
L: Output parameter description

Lower part
In the lower part of the output area (rows 46-55), the calculation of the bird collision rate for case 1 is shown in detail for each of the routes. This is to provide a quick insight into the used formulas. Also, it facilitates an easy comparison between the three routes. In case a parameter is not used in one of the routes, its field is left empty, and a note is included which explains why this parameter is not included.

4 Instructions for obtaining parameter values

In this chapter, the input parameters are presented in detail. They are grouped into the three main components of the calculations: the number of bird-crossings through the rotor area (paragraph 4.1), the collision probability (paragraph 4.2), and the scaling up of the effects to the total farm size (paragraph 4.3). In table 4.1 an overview of all parameters and their units is given.

Table 4.1. Overview of input and output parameters. 'ref' indicates that this parameter should correspond to the reference farm.

input parameters	parameter name	unit
i1	bird species	-
i2	farm location or name	-
i3	case-description	-
b	bird flux	#crossings / year
b_rel	relative bird flux	-
h	fraction at turbine height	-
h_ref	fraction at turbine height (ref)	-
a_macro	macro-avoidance	-
r	ratio rotor area/passage area	-
r_ref	ratio rotor area/passage area (ref)	-
p1	coll. rate (ref)	#collisions / year
p2	coll. prob. per crossing (ref)	#collisions / crossing
p3	non-avoidance coll. prob. per crossing	#collisions / crossing
p_cor	rotor size correction	-
a_micro	micro-avoidance	-
e	no. of turbines encountered per crossing	#turbines / crossing
e_ref	no. of turbines encountered per crossing (ref)	#turbines / crossing
output parameters	name	unit
c1	collision rate (ROUTE 1)	#collisions / year
c2	collision rate (ROUTE 2)	#collisions / year
c3	collision rate (ROUTE 3)	#collisions / year

4.1 Bird flux

- **bird flux** (b)

The bird flux (b) consists of the yearly number of bird-crossings of the species of interest through the wind farm (space) of interest. Here, the wind farm (space) is defined by the smallest box that fits all turbines including the area swept by their rotors, as is shown in figure 4.1. Though vertically the box includes all heights from ground (or sea) level to the highest tip of the rotors (i.e. turbine height, see figure 4.2), the bird flux is not restricted to birds flying at turbine height, but includes also birds at larger flying heights.

Furthermore, it should be taken into account that collision rates are generally calculated before a wind farm is build, so that the bird flux is determined at a moment when the birds do not show any avoidance-behavior yet. In existing farms (such as reference farms!) or farms under construction, however, the bird flux should also include the birds showing macro-avoidance.

In case the same bird individuals cross the farm multiple times per year, the bird flux is calculated as the number of individual birds multiplied by the number of times they cross the farm per year. If the number of crossings per bird is very large, some corrections may be needed. These include a correction of the bird flux for mortality at previous crossings, and a correction of the avoidance due to behavioral adaptation to the farm (learning). The effect of bird mortality at previous crossings can be included explicitly into the model, by carrying out the model-calculations for each crossing separately, in which case the bird flux remaining after the first crossing is used as input for the next crossing; a similar algorithm is used by Desholm and Kahlert (2006) for encounters with multiple turbine rows.

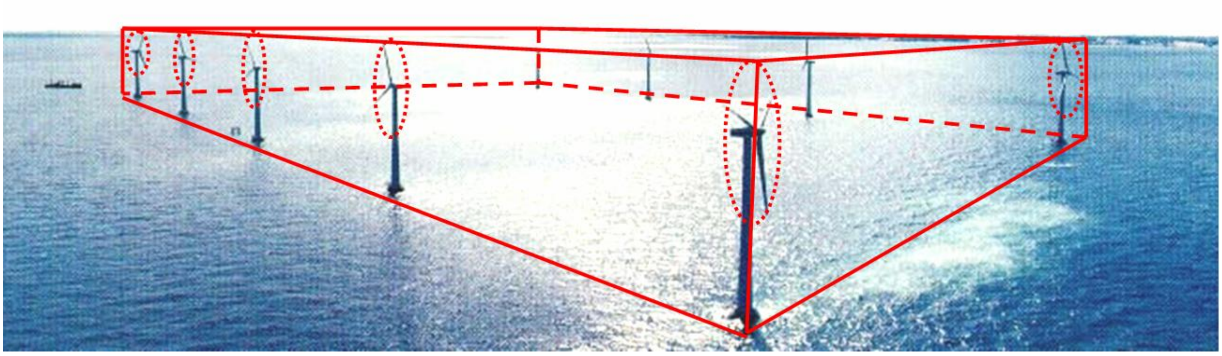


Figure 4.1. The wind farm space is defined by the smallest box that fits all turbines including the area swept by their rotors. In the figure this box is indicated in red.

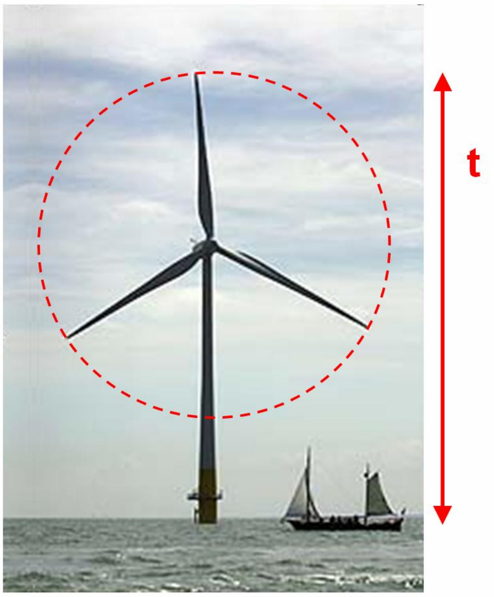


Figure 4.2. Turbine height (t) as indicated by the red arrow includes all heights from ground (or sea) level to the highest tip of the rotors.

- **relative bird flux** (b_rel)

The relative bird flux (b_rel) is the relative number of bird crossings in the farm of interest relative to those in the farm of reference. Usually, it is calculated as the ratio of the number of bird-crossings through the farm of interest (b) and those through the reference farm.

If the number of bird crossings at either farm is unknown, their ratio can for instance be estimated by using the ratio of the passage areas of the two farms. The passage area of a farm is the product of the turbine height (t) (see figure 4.2) and the total width (w) of the wind farm when observed at right angles to the main flight direction (see figure 4.3). It thus depends on the number of adjacent turbines and their distance, but also on the angle of the flight direction and on the rotor diameter. Note that figure 4.3 shows the situation in which the rotors are aligned in the plane of the passage area, whereas the actual angle of the rotors may be different (as determined by wind direction). Preferably, the passage area should be calculated for the dominant wind direction and thus for the most common rotor angle. However, for large wind farms, the differences in passage area due to differences in the rotor angle will be small.

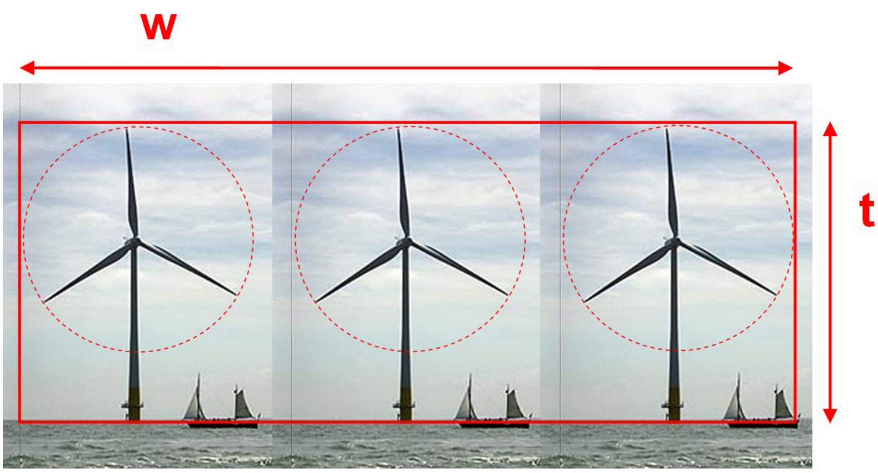


Figure 4.3. The passage area of a farm as indicated by the surface area of the red rectangle is the product of the turbine height and the total width of the wind farm when observed at right angles to the main flight direction.

- **fraction at turbine height** (h and h_ref)

The fraction at turbine height (h) is the fraction of the bird flux consisting of birds that are flying at turbine height through the farm. Turbine height (t) includes all heights from ground (or sea) level to the highest tip of the rotors (see figure 4.2). The reference fraction at turbine height (h_ref) is this same fraction but then corresponds to the reference farm.

If the fraction at turbine height is determined for a situation without wind turbines, any change in this fraction due to wind turbines should be included in the macro-avoidance.

- **macro-avoidance** (a_macro)

Macro-avoidance (a_macro) is the fraction of birds that avoid the farm as a whole. This fraction includes avoidance by flying sideways around the farm, as well as by increasing the flying height. In the latter case, though, it should be taken care that the fraction at turbine height (h) should correspond to a situation without wind turbines.

Macro-avoidance may be determined directly from radar images, or can be calculated indirectly as 1 – the ratio of the actual number of bird crossings through the farm (excluding the birds that avoid the farm) and the number of crossings through the farm space before the farm was build (including macro-avoidance).

In route 1, macro-avoidance is not needed, as it is already included in the collision probability (p1).

- **ratio rotor area/turbine passage area** (r and r_ref)

The ratio of the rotor area and the turbine passage area (r) is the fraction of birds that per turbine encounter will actually fly through the rotor area. It thus depends on the rotor area, but also on how closely the turbines are located next to each other (i.e. the turbine 'density'). It is calculated as the ratio of the rotor area of a single turbine and the total passage area per turbine (r = O / P).

The rotor area (O) is defined as

$$O = \pi * (½*d)^2$$

where d is the diameter of the rotors (see figure 4.4). Note that this formula concerns the situation in which the rotors are aligned in the plane of the passage area. However, we also use it for different rotor angles, as any reduction in cross-sectional area because the rotors are at an oblique angle is offset by the increased risk to birds which have to make a longer transit through the rotors.

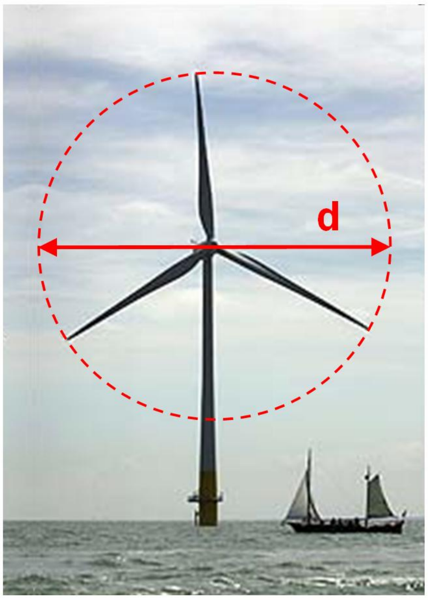


Figure 4.4. The rotor area (O) as indicated by the surface area of the red circle is defined as $O = \pi * (½*d)^2$, where d is the diameter of the rotors.

The turbine passage area (P) is the average passage area per turbine (thus not of the whole farm!, see figure 4.5); it includes both the rotor area and the “empty area” between adjacent turbines, and is calculated by dividing the total passage area of the farm (figure 4.3) by the number of adjacent turbines. Note that both figure 4.3 and 4.5 show the situation where the rotor area is aligned in the plane of the passage area; in reality, the rotors may be at a different angle. Preferably, the turbine passage area should be calculated for the dominant wind direction and thus for the dominant rotor angle. However, for large wind farms, the differences in (turbine and total) passage area due to the differences in the angle of the rotors will be small.

Note that the above calculations are based only on rotor area, and not on the cross-sectional area of the turbine base, as this area is supposed to be negligible in comparison to the rotor area.

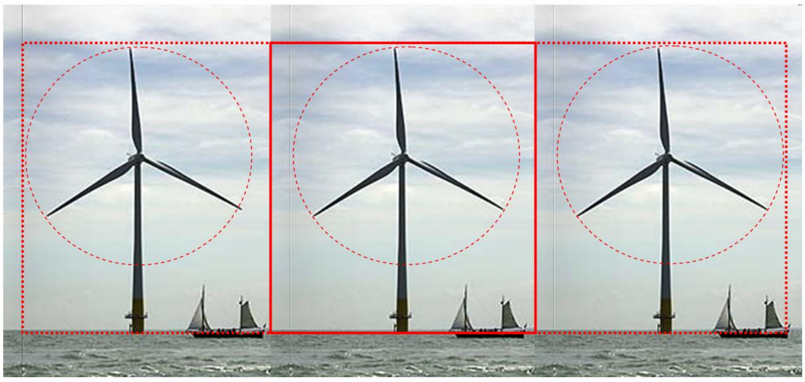


Figure 4.5. The turbine passage area (P) is the average passage area per turbine. In the figure, the turbine passage areas for three adjacent turbines are indicated by red rectangles.

4.2 Collision probability

- **ref. coll. rate per turbine** (p1)

The reference collision probability (p1) is the total number of collisions per year observed in a reference farm. Note that its units are different from the units of p2 and p3. As it is expressed per unit of time, it is referred to as a 'rate' rather than as a probability.

The value of p1 can for instance be based on the observations of Winkelman (1992). Make sure that the used value is corrected as to correspond to the number of collisions for the whole (reference) farm and over a whole year! This means that if the available collision rate is expressed per turbine, it should be multiplied by the number of turbines in the reference farm. Also, the observed collision probability should correspond specifically to the species of interest. Furthermore, note that collisions rate observations will mostly include both the collisions with the rotors and those with the turbine base; consequently, this will also be the case for the resulting number of collisions (c1) calculated for the farm of interest.

Alternatively, p1 can be based on an empirical relationship between rotor size and the number of collisions per turbine per year, which should then also be multiplied by the number of turbines in the reference farm. In this case, an additional correction for rotor size (p_cor) is no longer needed in the formula.

- **ref. coll. prob. per crossing** (p2)

The reference collision probability per crossing (p2) is the probability of a collision per bird-crossing of the wind farm at turbine height as observed in a reference farm. Note that though the units of p2 are the same as those of p3, their definitions are different.

Like p1, the value of p2 can be based on the empirical data on collision probabilities from Winkelman (1992). Again, note that such observations will mostly include both the collisions with the rotors and those with the turbine base; consequently, this will also be the case for the resulting number of collisions (c2) calculated for the farm of interest.

Furthermore, the observed collision probability should again correspond specifically to the species of interest.

p2 can be calculated from p1 by dividing it by the number of bird crossings per year (p1/b_ref).

- **non-avoidance coll. prob. per crossing** (p3)

The non-avoidance collision probability per crossing (p3) is the probability of a collision per bird crossing through the rotor area without avoiding the rotors. Note that the units of p3 are different from those of p1, and that p3 involves the collision probability per crossing of the rotor area, while p2 involves a crossing of the wind farm at turbine height.

The probability p3 should either be measured in the farm of interest itself, or it should be estimated by using an appropriate model, such as the model proposed by the SNH (Band 2000). A guidance document and spreadsheet for using this model can be found at http://www.snh.org.uk/pdfs/strategy/renewable/COLLIS.pdf. Note that the number of input parameters needed in such a model is substantial, including parameters such as wind speed and direction, and angle and speed of the bird flight. Furthermore, note that p3 as calculated with the above models only involves the collisions with the rotors and not those with the turbine-base; as a result, this will also be the case for the resulting number of collisions (c3) calculated for the farm of interest.

turbine size correction (p_cor)

The collision probability *per rotor surface area* decreases with an increase in rotor surface area. This is due to the fact that at the center of the rotor the collision probability is higher than at the rotor tips. Therefore, if the turbines in the farm of interest are of a different size than those in the reference farm, a correction is needed. With the model of Tucker or Band a theoretical correction can be estimated. Alternatively, a correction for rotor size can be based on an empirical relation between the number of collisions and rotor size.

The following empirical relationship is proposed in various Environmental Impact Assessments (e.g. WEOM, Airtricity, etc.):

p_cor = 0.902631 + 0.000138*O

where O is the rotor-area of an individual wind turbine in the wind farm of interest.

Note that for relationships with a low explanatory power, a predictive uncertainty-interval should be taken into account. In case the collision probability per year (p1) itself is based on an empirical relationship between number of collisions and rotor size, a separate correction for turbine size is no longer needed! Also, the correction is not needed for route 3, as the rotor size is already incorporated in the collision probability (p3).

- **micro-avoidance** (a_micro)

Micro-avoidance is the fraction of birds flying at rotor collision course that do not collide due to last-minute avoiding manoeuvres.

In route 1 and 2, micro-avoidance is not needed, as it is already included in the observed collision probabilities (p1 and p2).

4.3 Scaling up

- **no. of turbines encountered** (e and e_ref)

This is the average number of turbines encountered per bird-crossing. This number can be based on empirical data (e.g. radar data) or estimated with use of models. These models can range from complex geometrical models involving the specific wind farm configuration (e.g. Bolker et al. 2007), to more simple estimations. An often used estimate is the square root of no. of turbines; this approximation is reasonable if the wind farm is more or less square in shape, or if the birds approach the wind farm equally often from all angels (i.e. random flight directions).

In some cases alternative estimations may be preferred. For instance, if the flight direction is at right angles to the turbine rows, the no. of rows can be used.

5 Probability analysis

The models described in chapter 2 are deterministic models. This means that they calculate a single and fixed collision probability per set of parameter values. In using these models, however, several uncertainties play a role; these include uncertainties due to a lack of knowledge as well as uncertainties due to the natural variation of the parameter values. These uncertainties can be dealt with by choosing ‘safe’ parameter values at the upper or lower boundaries of their uncertainty margins, such that the resulting collision probability will correspond to a worst-case scenario. This will provide information on the expected upper limit to the collision probability, but not about the probability that such a collision probability will actually occur.

To study the probability of the results, an uncertainty or probability analysis can be done using bootstrapping or Monte Carlo methods (Manly 2006). Such an analysis uses not one value per parameter, but includes the whole uncertainty range around it. For each parameter, this uncertainty range is based on all observed values and the frequency with which they occur. A random generator will then pick one value per parameter from their frequency distributions, thus leading to a large number of sets of random parameter values. For all these of these sets the collision probability is then calculated by one of the deterministic models described above. Together, the collision probabilities resulting from all these randomly combined sets will lead to a probability density function, which shows the probability that a certain collision probability will occur. This function thus provides insight in the range of potential outcomes, but also shows which uncertainties contribute most to the variability of the final result. If these uncertainties are caused by a lack of knowledge, further research to these subjects would be useful to improve the accuracy of the final result. A probability analysis is specifically useful in case many parameters are involved (such as in route 3) and their uncertainty ranges ‘accumulate’, such that the worst-case scenario will always result in a relatively large collision probability.

An example of a probability density graph is shown in figure 51. It shows four probability density curves (black, red, green, blue) corresponding to four different bootstrap-simulations each based on for instance a different frequency distribution for a certain parameter. The black arrow indicates that for the blue simulation a collision probability larger than 0.1 will occur in 3% of all results. The figure also makes clear that in the blue simulation, higher collision probabilities (up to 0.3) occur than in the other simulations. A probability analysis in the context of bird collisions has been carried out by Hatch and Brault (2007).

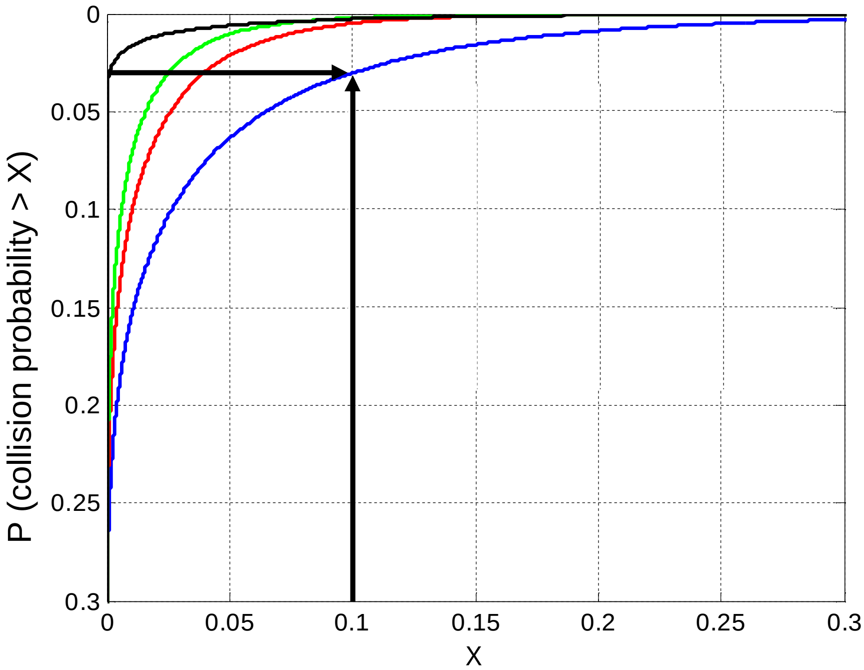


Figure 5.1 Example of a probability density curve.

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