# Ship Collision Risk for an Offshore Wind Farm

C.F.Christensen & L.W.Andersen
*RAMBØLL, Bredevej 2, DK-2830 Virum*

P.H.Pedersen
*SEAS Distribution A.m.b.A, Slagterrivej 25, DK-4690 Haslev*

ABSTRACT: The Danish government has presented extensive plans for reducing the $CO_2$ emissions by developing and improving renewable energy. Among these alternative energy sources wind energy is the most profitable. One of the problems with wind turbines is that they disfigure the landscape and the new trend is therefore towards large offshore wind farms. The present paper focuses on the ship collision risk analyses and the established model for calculation of the collision frequencies for the wind farms. In order to calculate the collision frequencies, issues as ship traffic, navigation routes, geometry of the wind farm and the bathymetry in the area are addressed. The ship collision frequencies forms the first step in an evaluation of whether the location is optimal from a ship collision point of view and moreover, the analysis forms the basis for marking the wind farm or the area around it in order to decrease the collision frequencies.

## 1 INTRODUCTION

The Danish government has presented activity plans stating that the $CO_2$ emission should be reduced with 20% by year 2005 as compared to 1988. In order to achieve this, the ratio of renewable energy should be increased and because wind energy is the most profitable the focus has been put here. The problem with wind turbines is that they disfigure the landscape and the new trend is therefore towards large offshore wind farms located more than 10 kilometres from the coastline. Besides the aesthetic benefit the offshore wind climate is better with larger mean wind velocity and less turbulence.

The Danish power supply company SEAS has been asked to carry out preliminary investigations for constructing wind farms at Rødsand south of Lolland in the Baltic Sea and at Omø Stålgrunde south of the Great Belt Link between Zealand and Funen. These wind farms comprise 72 turbines each with the size of approximately 2 MW giving a total capacity of 150 MW per wind farm. Besides the wind turbines the wind farm comprise internal cable connections, a trafo-module and cable connections to shore. The trafo module is the most vital part of the wind farm and a ship collision against the trafo module will stop the power supply from the whole park. Construction, installation and start of the wind farms are planned to take place in the period 2003 to 2005. The focus in the present paper is on the wind farm at Rødsand, but except from local conditions as the water depth and ship traffic, the described procedure is general.

The wind turbines at Rødsand will be constructed in a 9×8 grid with a distance between each of the wind turbines of 875 m x 475 m, which means that the entire wind farm will cover an offshore area of approximately 6.1 km × 3.8 km.

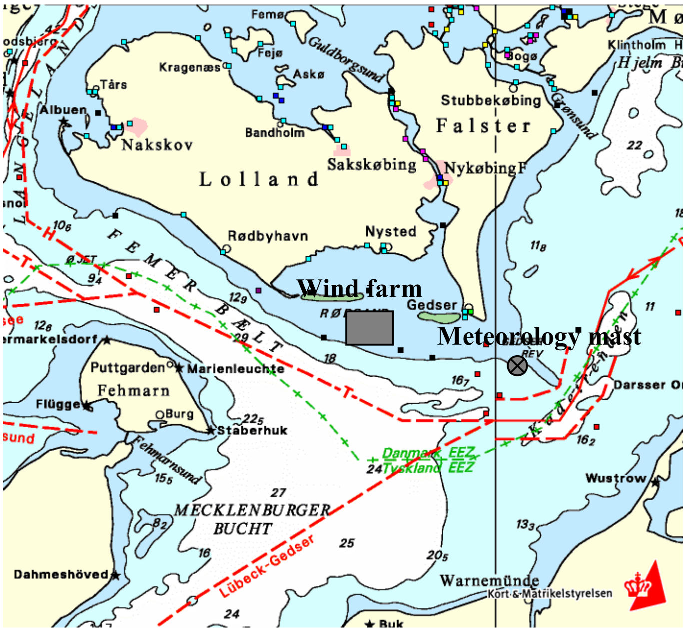

Figure 1. Location of the wind farm at Rødsand.

The wind farm is located 12 kilometres south of Nysted on Lolland and the distance from the border of the wind farm to an international navigation route (the T-route) is 8 kilometres. This international route is one of the most trafficked seaways in the Danish waters with approximately 46000 ship passages per year. The location of the wind farm and the T-route is shown in Figure 1.

The T-route is a typical center marked navigation route, but 6 kilometers east of the wind farm there is traffic separation where ships from north through Øresund meats with the east – west going traffic. At the traffic separation the navigation route is both side-marked and center-marked. The way of marking influences the position of the ship traffic.

In Figure 2 the actual position of the wind turbines is shown together with the position of the trafo-module and the power cable between the trafo-module and the shore.

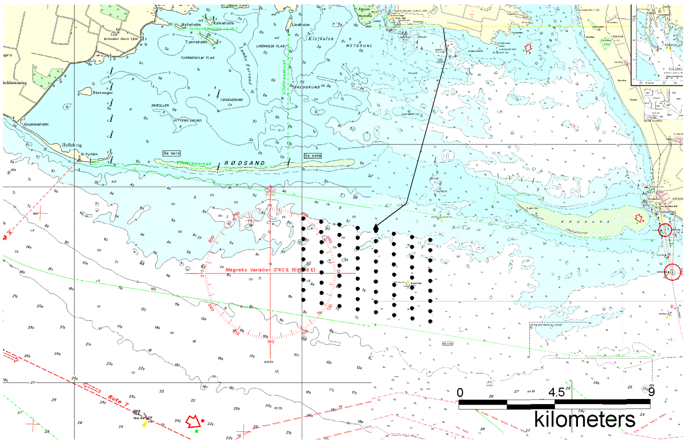

Figure 2. Illustration of the individual wind turbines together with the power cable to shore for the wind farm at Rødsand.

The construction cost for an offshore farm is much higher than a wind farm constructed on land and it is therefore important to evaluate whether the location is optimal. The optimal position is here seen from a ship collision's point of view. The present paper is focused on the ship collision risk analyses and the established model for calculation of the collision frequencies for the wind farms. The analyses therefore deal with:

- Ship traffic, the number of ships and the distribution of the position of the ship traffic in the area near the wind farm.
- Navigational routes in the vicinity of the wind farm.
- Wind, waves and current conditions in the area, which are important for drifting ships.
- Geometry of the wind farm and the bathymetry in the area.

The present ship traffic will be described in terms of quantity, ship class distributions and probability distributions for their position in the sailing route.

The procedure for the calculation and the decision strategy is shown in the flow diagram given in Figure 3.

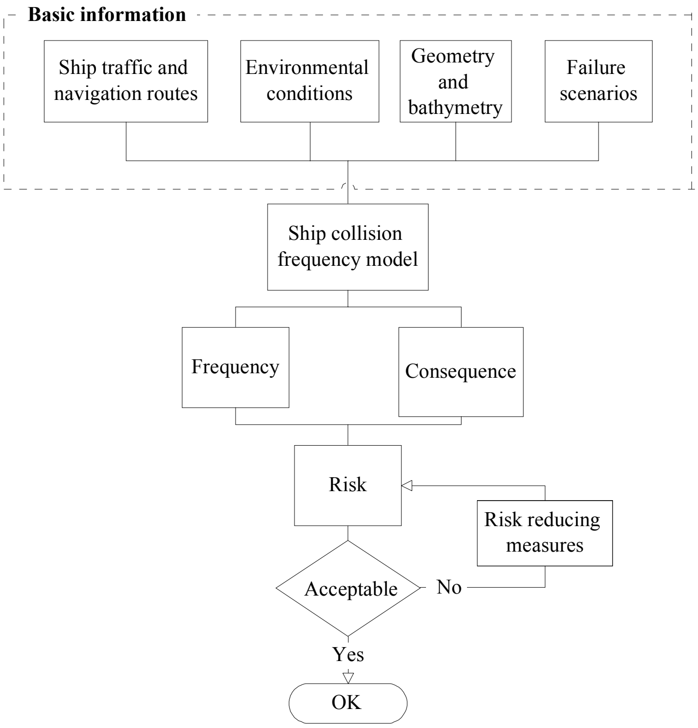

Figure 3. Flow diagram of the calculation procedure.

## 2 SHIP TRAFFIC AND NAVIGATION ROUTES

The ship traffic at Rødsand consists mainly of ships passing through the Femern Belt and from the Baltic Sea. In order to describe the ship traffic in the area around the wind farm, the annual ship movements on different navigational routes have been estimated on basis of data for the ship traffic. These data have been collected from the ports in the Baltic Sea, VTS (Vessel Traffic Service) registrations in the Great Belt and in Øresund and the traffic through the Kieler Canal. A number of navigational routes have been defined and the yearly number of ship movements on each of these routes has been estimated on basis of the collected data. The navigational routes considered are sketched in Figure 4.

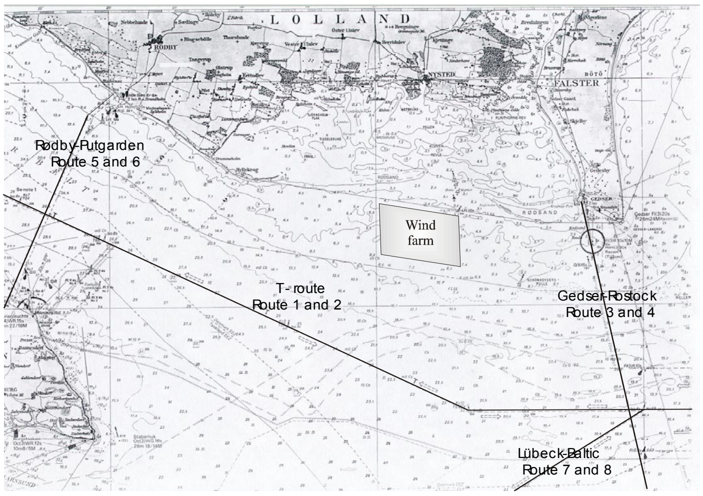

Figure 4. Navigation routes around the wind farm at Rødsand.

There are 4 main waterways in the vicinity of the wind farm, which corresponds to 8 navigational routes when the sailing direction is taken into account. The most important route (denoted 1 and 2) is the international navigation route called the T-route. The guaranteed water depth in the T-route is 19 metres. The other routes (3-4 and 5-6) are ferry routes between Denmark and Germany located on each side of the wind farm with the distance 10 and 21 kilometres. The last route (7-8) is between Lübeck in Germany and the Baltic Sea. The ship traffic is described with respect to the number of yearly movements and the ship size distribution in GRT and is based on the information from the pilots and port authorities, the Kieler Canal and the VTS registrations.

In Table 1 and Table 2 is shown the navigational route and corresponding number of yearly ship movements distributed on ship classes. The relations between ship class and GRT, ship length, draft and width of ship are based on statistical data from Lloyds Register of Ships and this statistical base are used in the frequency calculation.

| Ship class | *GRT* | *Femern-Baltic* | *Baltic-Femern* | *Gedser-Rostock* |
|---|---|---|---|---|
| Route | - | 1 | 2 | 3 |
| 1 | 0-250 | 1904 | 1904 | 0 |
| 2 | 251-500 | 1577 | 1577 | 0 |
| 3 | 501-1000 | 1767 | 1767 | 0 |
| 4 | 1001-1500 | 1679 | 1679 | 0 |
| 5 | 1501-2000 | 1657 | 1657 | 0 |
| 6 | 2001-3000 | 2282 | 2282 | 0 |
| 7 | 3001-4000 | 4331 | 4331 | 995 |
| 8 | 4001-6000 | 4882 | 4882 | 236 |
| 9 | 6001-10000 | 2882 | 2882 | 1169 |
| 10 | 10001-25000 | 806 | 806 | 927 |
| Total | - | 23773 | 23773 | 3327 |

Table 1. Annual traffic distribution on the first three routes and the relation between ship class and GRT.

| Ship class | *Rostock-Gedser* | *Rødby-Putg.* | *Putg.-Rødby* | *Lübeck-Baltic* | *Baltic-Lübeck* |
|---|---|---|---|---|---|
| Route | 4 | 5 | 6 | 7 | 8 |
| 1 | 0 | 0 | 0 | 22 | 22 |
| 2 | 0 | 0 | 0 | 22 | 22 |
| 3 | 0 | 0 | 0 | 78 | 78 |
| 4 | 0 | 0 | 0 | 243 | 243 |
| 5 | 0 | 0 | 0 | 243 | 243 |
| 6 | 0 | 1144 | 1144 | 415 | 415 |
| 7 | 995 | 0 | 0 | 620 | 620 |
| 8 | 236 | 0 | 0 | 982 | 982 |
| 9 | 1169 | 17520 | 17520 | 2517 | 2517 |
| 10 | 927 | 0 | 0 | 1685 | 1685 |
| Total | 3327 | 18664 | 18664 | 6827 | 6827 |

Table 2. Annual traffic distribution on the last five routes.

The number of fishing vessels in the area is very modest and the size of these fishing vessels is also limited, and it is hence assumed that the fishing vessels are too small to cause major damage on a wind turbine. The fishing vessels are therefore not included in Table 1 and Table 2.

## 3 MODEL FOR SHIP COLLISION

In order to determine yearly collision frequencies for the wind farm and the trafo-module, a model has been constructed taking into account the variability of the exact ship location along the considered routes, human errors, failure on propulsion machinery and steering failure, (Fujii 1983, Larsen 1993).

For the determination of the collision frequencies for the wind farm, it is assumed that any ship that due to one of the above-mentioned failure modes will be located within the area of the wind farm will collide with one of the turbines in the park area. The frequency is thus determined as the frequency that the ship will be within the wind farm area due to one of the failure modes. All types of collisions whether it will be a direct collision on a turbine or a glancing off when touching the turbine are considered as a collision.

The geometry of the wind farm and the trafo-station is modelled together with the bathymetry in the vicinity of the wind farm. The water depth in the wind farm varies between 5.0 and 8.6 metres.

The ship traffic is assumed to sail parallel to the ideal navigation routes. The ship location perpendicular to the navigation route is assumed to follow a distribution given as a uniform plus a Gaussian distribution. The ration between the to distributions is taken to be 2% uniform and 98% Gaussian, (Pyman 1983).

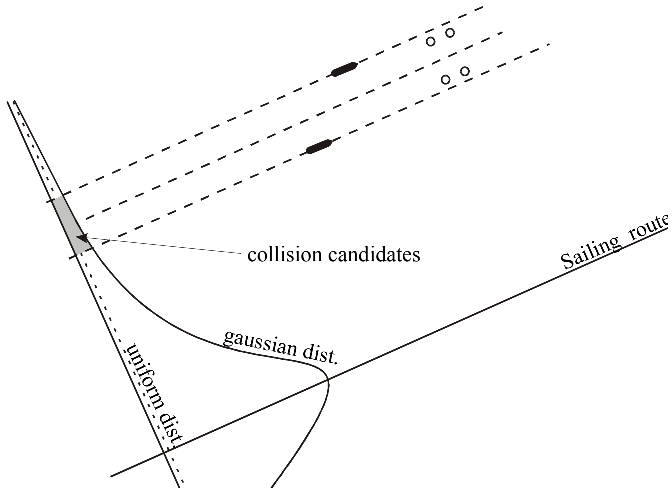

Figure 5. Illustration of the geometrical ship distribution.

The 3 parameters in the combined distribution for the 8 navigation routes are given in Table 3. The standard deviation in the Gaussian distribution will in general depend on whether the navigation route is center-marked or side-marked, where a center-marked navigation route as in this case yields the largest deviation.

| Navigation | Gaussian | | Uniform |
|---|---|---|---|
| Route | Mean | Std. deviation | Length |
| 1 | 0 m | 1200 m | 13000 m |
| 2 | 0 m | 1200 m | 13000 m |
| 3 | 0 m | 500 m | 8000 m |
| 4 | 0 m | 500 m | 8000 m |
| 5 | 0 m | 500 m | 6000 m |
| 6 | 0 m | 500 m | 6000 m |
| 7 | 0 m | 1200 m | 14000 m |
| 8 | 0 m | 1200 m | 14000 m |

Table 3. Parameters in the geometrical model for the ship distribution transversely to the navigation routes.

The three collision scenarios: human errors, failure on propulsion machinery and steering failure are considered. A short description of the three scenarios is given in the following.

*Human failure*

If a human failure shall result in a ship collision the following two restrictions must be fulfilled. The ship has to be on collision course, i.e. have direction towards the wind farm or the trafo module, and the ship will have to maintain this course until collision, thus no actions are taken in order to prevent the collision. The probability that the collision course is maintained is denoted “the probability of human failure”.

*Steering failure*

When the steering system of a ship fails, the rudder will be locked and the ship will start sailing into a circular path. The diameter of the circle depends on the locked position of the rudder and the underkeel clearance. According to general experience, a full deflection of the rudder is the most typical result of a failure of the steering system and this scenario is considered in the present study.

*Failure on propulsion machinery*

A failure on propulsion machinery will cause the ship to start drifting. The drift direction is as a first case assumed to be likely in any direction. The drift direction will though depend on the distribution of the current and wind direction. If the drifting direction is towards the considered wind farm, a sideways collision will occur, i.e. a ship without steering velocity will start to drift sideways. The two other scenarios will result in a head on bow collision.

In modelling the collision frequencies for the drifting ships it has been taken into account that the reaction time from being a drifting ship to information of the relevant authorities and arrival of a tugboat in order to stop the drifting ship will take a minimum of 10 hours. This assumption limits the maximum drift distance at Rødsand to approximately 18 kilometres.

The probabilities and other parameters used in the three scenarios are given in Table 4, (Fujii 1983, Macduff 1974, Pedersen 1995) and verified in (Karlsson 1998).

| Scenarios | Parameter | Value |
|---|---|---|
| Human error | Probability for human error<br>Duration of error | $2\times10^{-4}$ per passage<br>20 minutes |
| Steering failure | Probability for steering failure<br>Sail radius | $6{,}3\times10^{-5}$ per hour<br>2,5×ship length |
| Failure in propulsion machinery | Probability for drifting ship<br>Anchoring probability | $1{,}5\times10^{-4}$ per hour<br>0,7 |

Table 4. Used probabilities and parameters in the three collision scenarios.

## 4 SHIP COLLISION FREQUENCIES

Combining the stated failure modes and the traffic description the collision frequencies can be obtained.

It is found that drifting ships, i.e. ships having failure on propulsion machinery drifting towards the wind farm, are the largest contributors to the collision frequencies. A ship with failure on its propulsion machinery will drift sideways in a direction that depends on current and wind direction. The ship collision frequencies related to human failures, i.e. navigational errors, absence of navigator etc. are very modest due to the large distance (around 8 kilometres) between the wind farm and the navigation routes. Moreover, it is found that by and large all the ship collision frequencies are related to ship movements on the routes nearest to the wind farm with most traffic, i.e. route 1 and 2 (the T-route). The collision frequencies and the corresponding return periods are given in Table 5. There is no contribution from steering failure due to the large distance and the two scenarios thus also correspond to the two collision types “head on bow” collision and “sideways” collision (drifting ship).

| Collision scenarios | Frequency | Return period |
|---|---|---|
| Drifting ships | $1.8 \times 10^{-1}$ | 6 year |
| Human failure | $7.1\times10^{-9}$ | $1.4 \times 10^{-8}$ year |
| Total frequency | $1.8 \times 10^{-1}$ | 6 year |

Table 5. Collision frequencies and return periods for the wind farm at Rødsand.

From Table 5 it is seen that the collision frequency is governed by the contribution from drifting ships.

In Figure 6 is the collision frequencies shown as a function of ship class. The largest parts of the ship collision frequencies are related to rather large ships (between 3000 to 25000 GRT). The contribution from ships larger than 25000 GRT vanishes due to the limited water depth. For ships in this range of GRT it is not practically possible and economically reasonable to design the wind turbine to resist a ship collision.

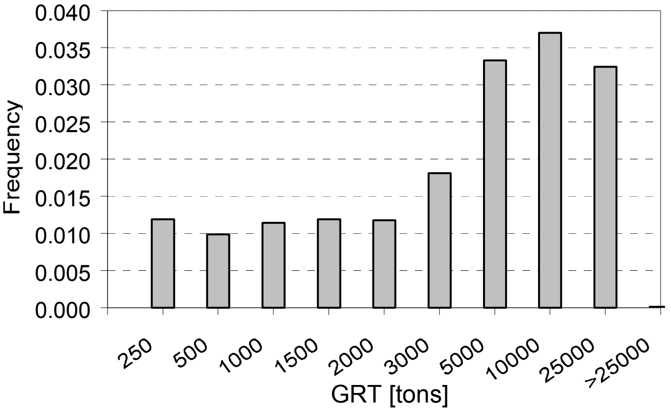

Figure 6. Collision frequencies as a function of ship size (GRT) for the wind farm at Rødsand.

Moreover it is seen that ships with GRT less than 3000 contributes significantly to the collision frequencies with approximately 40%. For ships of this size it is possible to design the turbine to resist a collision, but the additional expenditures should of cause be considered.

The colliding ships corresponding to the size distribution are typically different types of cargo ships (tankers, container vessels, bulk carriers, etc.).

### 4.1 *Sensitivity study*

As seen from Table 5 the contribution from human errors is very close to zero. This is due to the assumption that all ships will follow the T-route with a given deviation. This may not necessarily be true because by sailing closer to the cost a significant shortcut can be made. Such a route is possible for all ships with a draught less than 4 metres. A sensitivity study, where one fifth of the traffic with a draught less than 4 metres is assumed to follow a parallel shifted route 6 kilometres further north closer to the wind farm, is being carried out.

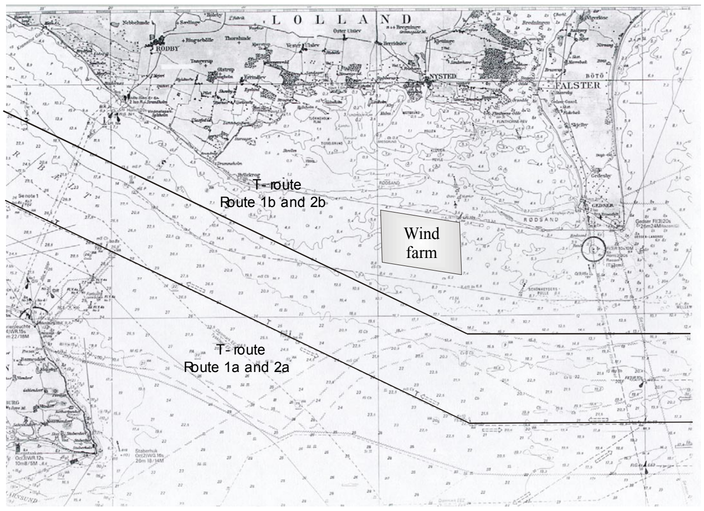

Figure 7. Navigation route in the sensitivity study.

The parallel shifted route is shown in Figure 7. For this parallel shifted route the standard deviation in the Gaussian distribution has been decreased from 1200 metres to 800 metres and also the width of the uniform distribution is decreased from 13000 meters to 8000 meters due to the shorter distance to the shore.

The ship traffic on the new route and the reduced traffic on the original route are shown in Table 6.

| Ship class | *Femern-Baltic* | *Baltic-Femern* | *Femern-Baltic* | *Baltic-Femern* |
|---|---|---|---|---|
| Route | 1a | 2a | 1b | 2b |
| 1 | 629 | 629 | 1275 | 1275 |
| 2 | 460 | 460 | 1117 | 1117 |
| 3 | 998 | 998 | 769 | 769 |
| 4 | 1493 | 1493 | 186 | 186 |
| 5 | 1494 | 1494 | 163 | 163 |
| 6 | 2246 | 2246 | 36 | 36 |
| 7 | 4313 | 4313 | 18 | 18 |
| 8 | 4886 | 4886 | 2 | 2 |
| 9 | 2882 | 2882 | 0 | 0 |
| 10 | 806 | 806 | 0 | 0 |
| Total | 20207 | 20207 | 3566 | 3566 |

Table 6. Annual traffic distribution on the route 1a and 2a, and the shifted route 1b and 2b used in the sensitivity study.

Based on the new traffic distribution the collision frequencies can be obtained. The results are given in Table 7.

| Collision scenarios | Frequency | Return period |
|---|---|---|
| Drifting ships | $2.1\ x10^{-1}$ | 5 year |
| Human failure | $3.6x10^{-3}$ | 300 year |
| Steering failure | $1.6x10^{-5}$ | 60000 year |
| Total frequency | $2.1\ x10^{-1}$ | 5 year |

Table 7. Collision frequencies and return periods for the sensitivity study for the wind farm at Rødsand.

From Table 7 it appears that if some of the ships have a tendency to make a shortcut and sail closer to shore instead of following the international T-route, the contribution from "human failure" can become significant.

SEAS have therefore carried out some measurements of the traffic in the area in order to identify a better estimate of the different ships' navigation routes. This is described in Section 7.

## 5 VERIFICATION OF THE OBTAINED SHIP COLLISION FREQUENCIES

As part of the risk analysis a registration of known actual ships' accidents was performed. The information was obtained for "Søværnets Operative Kommando" (the Navy) in Denmark and covered a period of 10 years from 1990 to 2000. In Figure 8 is given a map showing the registered accidents.

Figure 8. Registered grounding in the vicinity of the wind farm.

It follows from Figure 8 that two groundings have occurred in the vicinity of the wind farm during the investigated period of 10 years. Comparing this to the obtained return period of approximately 6 years for the wind farm indicates that the obtained frequencies for the wind farm seams reasonably.

## 6 SHIP COLLISION AGAINST METEOROLOGY MAST

In 1996 SEAS established a measuring mast on Gedser Reef approximately 21 km east south east for the new wind farm at Rødsand. The water depth at the location, which is in between the T-route and Gedser, is approximately 6.5 metres. Just north of the mast the reefs can be passed by ships with a draught of less that 6 metres, and at every location on the reef the water depths is deeper than 4 metres.

The measuring mast is a 48 metre high steel mast founded on a steel system rammed into the seabed. The mast is marked with light and is visible both visually and on the radar.

A ship has collided with the mast twice in 1998 and 2000. The first time resulted in minor damage only. The second time the mast was severely damaged and it was necessary to remove the mast and foundation completely. In 1998 the ship, a coaster of approx. 1500 DWT, collided with the mast at night in rough weather conditions and bad visibility. It has not been possible to identify the ship, which was involved in the second collision, hence it has not been possible to clarify the special conditions relating to this accident.

During the investigation of the accidents it was observed that a large number of ships both east and west bound, with a DWT up to 2000-3000 DWT, passes Gedser Reef north of the T-route.

## 7 MEASURING PROGRAMME OF SHIP TRAFFIC CLOSE TO THE WIND FARM

The sensitivity analysis carried out as part of frequency analysis shows that the risk of a ship collision with the wind farm will increase significantly if the ships pass north of the T-route. Based on the results of the frequency analysis and the registration of the collisions with the measuring mast, it was decided to carry out a detailed measuring programme for the ship traffic.

Radar observations were performed along two lines as shown in Figure 9, and the number and locations of ships passing the lines were registered in the autumn of 2000.

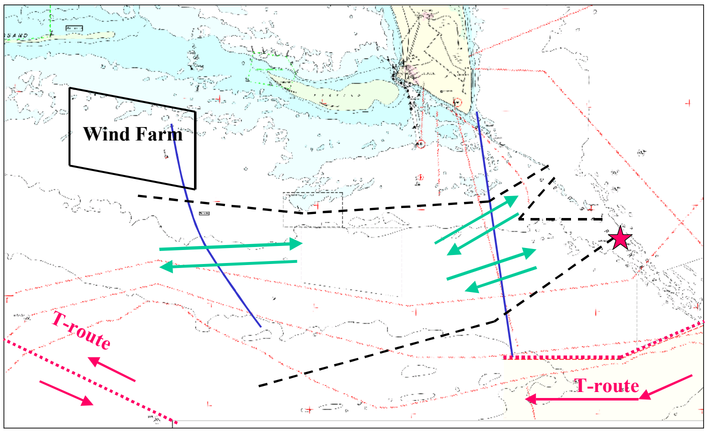

Figure 9. The two full lines indicate where the radar observations were carried out. The dashed lines indicates the deviation of the traffic and the arrows indicates where the central part of the traffic is located on these lines (preliminary results).

In the period from October to November 2000, a total number of 516 passages were observed, this corresponds to 6 to 7 per cent of the total traffic through Femern Belt. Preliminary evaluations of the data show that a significant part of the ships pass very close south of the new wind farm, and it is the intention to perform a more detailed analysis of the data at the beginning of 2001. The results of this analysis will form a basis for an update of the risk analysis for ship collisions against the wind turbines and the trafo-module.

## 8 RISK REDUCING MEASURES

The results of the updated risk analysis may lead to proposals for introduction of risk reducing measures. Such measures could be:

- Different types and markings
- Protective arrangements (especially for the trafo-module)
- VST monitoring or guard vessels

The marking is the most economical manageable but the effect of marking is not known. There is a risk for the ships would uses the markings as way-points and hereby actually increase the risk of a collision because the ships will pass closer to the wind farm. The use of way-points will be examined through interviews with captains on minor ships.

The protective arrangements could be consider for the very vital trafo-module.

## 9 CONCLUSION

As a first step the resulting yearly collision frequencies for the wind farm and trafo module is calculated and different risk reducing strategies are considered. Based on the first analysis a measuring program is established and an analysis of the use of way-points are initiated. Based on these results the risk of a ship collision should be reevaluated and the need of further risk reducing measures considered.

The overall conclusion from the present study, is that it is of great importance to initiate risk analysis activities at an early stage of a project, to ensure that proper action can been taken in the detailed design phase if any needs are identified.

The analysis shows that ”thinking risk” from the start makes it possible to identify problem areas and areas with importance for the design of the project. Such areas could be actual ship traffic distribution, location of trafo-module etc.

## REFERENCES

Fujii, Y. 1983. Integrated Study on Marine Traffic Accidents, IABSE Colloquium Copenhagen.

Karlsson, M, Rasmussen,,F.M,,& Frisk,L, 1998. Verification of ship collision frequency model. *Proceedings of the international symposium on advances in ship collision analysis,* p. 117 – 121.

Larsen, O.D. 1993. Ship Collision With Bridges, The Interaction between Vessel Traffic and Bridge Structures. Switzerland: IABSE-AIPC-IVBH

Macduff. T. 1974. The Probability of Vessel Collisions, *Ocean Industry* p. 144 - 148.

Pedersen, P.T. 1995. Probability of Grounding and Collision Events. *Risk and Response, 22nd WEGEMT Graduate School.*

Pyman, M.A.F, Austin, J.S. & Lyon, P.R. 1983. Ship/Platform Collision Risk in the U.K. Sector, IABSE Colloquium Copenhagen.