TECHNICAL REPORT

ENERGI E2

Navigational Risk Assessment
Frequency analysis
Wind Farm Horns Rev 2

MARCH 2006

REPORT NO. 643233- REP – 01

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DET NORSKE VERITAS

TECHNICAL REPORT

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Summary:

This report contains an assessment of the navigational shipping risk related to the wind farm Horns Rev 2. The collision frequency is evaluated for the two locations "Nord" and "Syd" for the operation and construction phase

In the operation phase the total collision frequency for the "Nord" location is found to $4.3 \cdot 10^{-3}$ per year, corresponding to a return period of 230 years, whereas the total collision frequency for the "Syd" location is found to $1.2 \cdot 10^{-2}$ per year, corresponding to a return period of 84 years.

For the installation phase the frequency for a ship – ship collision between the construction vessels has been evaluated to $1.7 \bullet 10^{-2}$ corresponding to a return period of 60 years. This number is very uncertain and will very much depend on how the construction vessels are handled and controlled.

Moreover, as a comparison, the return period for a ship – ship collision in the area around Horns Rev with an approximate size of 80 km x 95 km has been found to equal 40 years. Compared to the obtained ship – turbine collision frequencies, it is seen that the risk for a ship – ship collision in the area is significantly higher then the risk contribution from the wind farm.

The present report does not deal with the consequences related to the ship collisions. The consequences will be more uncertain than the estimated frequencies and they will depend on whether the focus is on human safety or environmental impact. However, the consequences for the majority of the collisions be very limited; based on statistical data for ship collisions in Danish waters it is seen that oil spill occur in less than 1 in every 10 collision. The collision frequencies are therefore acceptable to our opinion.

Based on the present evaluation of the two possible wind farm locations, we will recommend that from a navigational safety aspect the "Nord" location should be chosen.

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Table of Content ***Page***

1 INTRODUCTION

The objective of this report is to provide a navigational risk assessment for the wind farm Horns Rev 2 located west of the already constructed wind farm Horns Rev 1.

A detailed frequency analysis is carried out for two possible wind farm locations “Nord” and “Syd” and covers the installation and operational situation. The frequency analysis is based on robust mathematical models where the model parameters are obtained from historical (statistical) data. The results of the analysis are therefore estimated average values of, for example, the time between two collisions. It should be noted that the frequency analysis cannot provide exact information such as the time and date for the next collision.

Due to the stochastic modelling, the uncertainties are quantified and focus can be put on the important issues. The risk analysis is thus a fine tool upon which to base a rational decision making process and in this case the decision is to determine the best location with respect to navigational safety.

The focus will be on the following subjects:

- Evaluation of ship –ship collision risk in the installation phase and ship – turbine collision risk in the operational phase.
- Identification of possible risk-reducing measures, which can be taken into account if required.

In order to evaluate the ship – ship and ship - turbine collision frequency (both due to human error (powered collision) and mechanical failure onboard ship (drifting collision)), the ship traffic in the area around Horns Rev has been mapped and the distribution of the ship sizes and types on the different shipping lanes has been obtained.

In the present report all leisure crafts are excluded. This is first of all because the number of leisure crafts in that part of the North Sea is very limited because the environmental conditions are not suitable for leisure crafts. Only larger ships covered by SOLAS[*] (Safety Of Life At Sea) or ships with AIS are included. Larger fishing vessels are assumed to follow prescribed routes, because the fishing areas for these ships are located further out in the North Sea. However, the number of fishing vessels in Esbjerg has decreased a lot in the recent years. The number of fishing vessels located in Esbjerg was 85 in 2002 and has decreased to 44 in 2005 and the fishing vessels are therefore of minor importance.

Based on the navigation routes, the ship traffic and other parameters, the ship – ship and ship-turbine collision frequencies are calculated. The collision frequencies are evaluated for the ship traffic situation as today.

Moreover, some possible risk-reducing measures related to the wind farm are identified. These can be taken into account if the risk is found to be too high.

The summary and conclusion of this work, including recommendations, is given in Chapter 2.

[*] International Convention for the Safety of Life at Sea

2 SUMMARY AND CONCLUSION

This chapter presents the summary and the conclusion for the risk analysis for the wind farm Horns Rev 2. The assessment covers the navigational safety in general.

The descriptions of the environmental conditions for the wind farm area are given in Chapter 3 and the two possible wind farm locations are described in Chapter 4.

Chapter 6 contains the ship traffic and the navigation routes and Chapter 8, including Appendix A, describes the collision model used for establishing the ship – ship and ship – turbine collision frequencies. The collision frequency results are given in Chapter 8. A rough evaluation of the frequency based on historical data is given in Chapter 9 and risk reduction measures are discussed in Chapter 10.

2.1 Conclusion

The evaluated collision frequencies for the two locations and the construction and operation phase have been evaluated. The results for the operation case is summarised in Table 2-1.

Annual frequency	Human failure	Drifting ships	Total collision
"Nord" location	$1.2 \cdot 10^{-3}$ / 820	$3.1 \cdot 10^{-3}$ / 320	$4.3 \cdot 10^{-3}$ / 230
"Syd" location	$7.1 \cdot 10^{-3}$ / 140	$4.9 \cdot 10^{-3}$ / 205	$1.2 \cdot 10^{-2}$ / 84

Table 2-1: Annual collision frequencies and corresponding return period for the two locations in the operation case.

From Table 2-1 it is seen that the north location has the lowest collision frequency. This is mainly because it is located further to the east than the tip of Horns Rev, which forces the ship traffic to the west.

For the installation phase the frequency for a ship – ship collision between the construction vessels has been evaluated. The annual collision frequency is found to equal $1.7 \cdot 10^{-2}$ corresponding to a return period of 60 years. This number is very uncertain and will very much depend on how the construction vessels are handled and controlled.

Moreover, as a comparison, the return period for a ship – ship collision in the area around Horns Rev with an approximate size of 80 km x 95 km has been evaluated. The return period for a ship – ship collision in the area is found to equal 40 years. Compared to the obtained ship – turbine collision frequencies, it is seen that the risk for a ship – ship collision in the area is significantly higher then the risk contribution from the wind farm. The wind farm will not effect the expected number of ship-ship collisions, because the ship traffic in the wind farm area that is forced out when the wind farm is constructed is insignificant.

The obtained results are of course uncertain and will depend on the assumptions and parameters used. From other studies it is seen that the main contribution to the uncertainty is from the drift duration and velocity and the transverse distribution of the ship. However, the used parameters are discussed and agreed with Germanisher Loyds and Marin in a working group under BSH "Bundesamt für Seeschiffahrt und Hydrographie" in Germany. Moreover, the navigation routes are identified from AIS plots where also the transverse distribution is indicated. The work is thus based on the best use of all available information and the obtained collision frequencies are therefore best estimates or slightly conservative.

It must be emphasised that the obtained collision frequencies cover all types of serious collisions where serious is defined as the ship must be repaired i.e. from dents to major damage to the ship and/or the turbine. Moreover the impact energy from a sideways collision (drifting ship scenario) will normally be lower than from a head on bow collision (human failure scenario) due to the lower impact velocity and the consequences will therefore usually be smaller. However, regarding environmental impact it can be argued that a head on bow collision rarely will lead to release of bunker or cargo oil, because oil tanks are never located in the bow of the ship.

The present report does not deal with the consequences related to a ship – turbine collision. The consequences will be more uncertain than the estimated frequencies and they will depend on whether the focus is on human safety or environmental impact. However, as noted previously the consequences will, for the majority of the collisions, be very limited; based on statistical data for ship collisions in Danish waters it is seen that oil spill occur in less than 1 in every 10 collisions. The collision frequencies are therefore acceptable to our opinion.

The impact from the wind farm on marine radar, communications and positioning systems has been evaluated. Due to the distance between the wind farm and navigational routes it is evaluated that the wind farm will not result in increased ship-ship risk due to radar shadow, echoes etc. from the wind farm. However, small vessels as lifeboats located inside the wind farm very close to a turbine can be difficult to detect by radar and it can thus have impact on SAR operations. However, the lifeboat will normally move and the effect is therefore in most cases not critical.

Moreover the influence from the wind farm Horns Rev 1 has been found to have an insignificant impact mainly because the reef is located between the two wind farms. The reef has therefore a large positive effect on both wind farms.

Based on the present evaluation of the two possible wind farm locations, we recommend that from a navigational safety aspect the "Nord" location should be chosen.

3 ENVIRONMENTAL CONDITIONS

This chapter provides a short description of the environmental conditions which may have an impact on the navigational safety and hence the collision risk. The parameters are ice, wind, waves, current (tide) and visibility.

3.1 Ice

The North Sea is heated by the Gulf Stream and therefore ice never forms, except very close to the coast where there can be stagnant water. Also glaciers do not release ice into the area under consideration.

Ice in the water therefore does not affect the ship traffic in this area of the North Sea and is therefore not included in the risk assessment.

3.2 Waves

Waves are created by the wind and the correlation between wind and waves is therefore strong as seen in Figure 3-1.

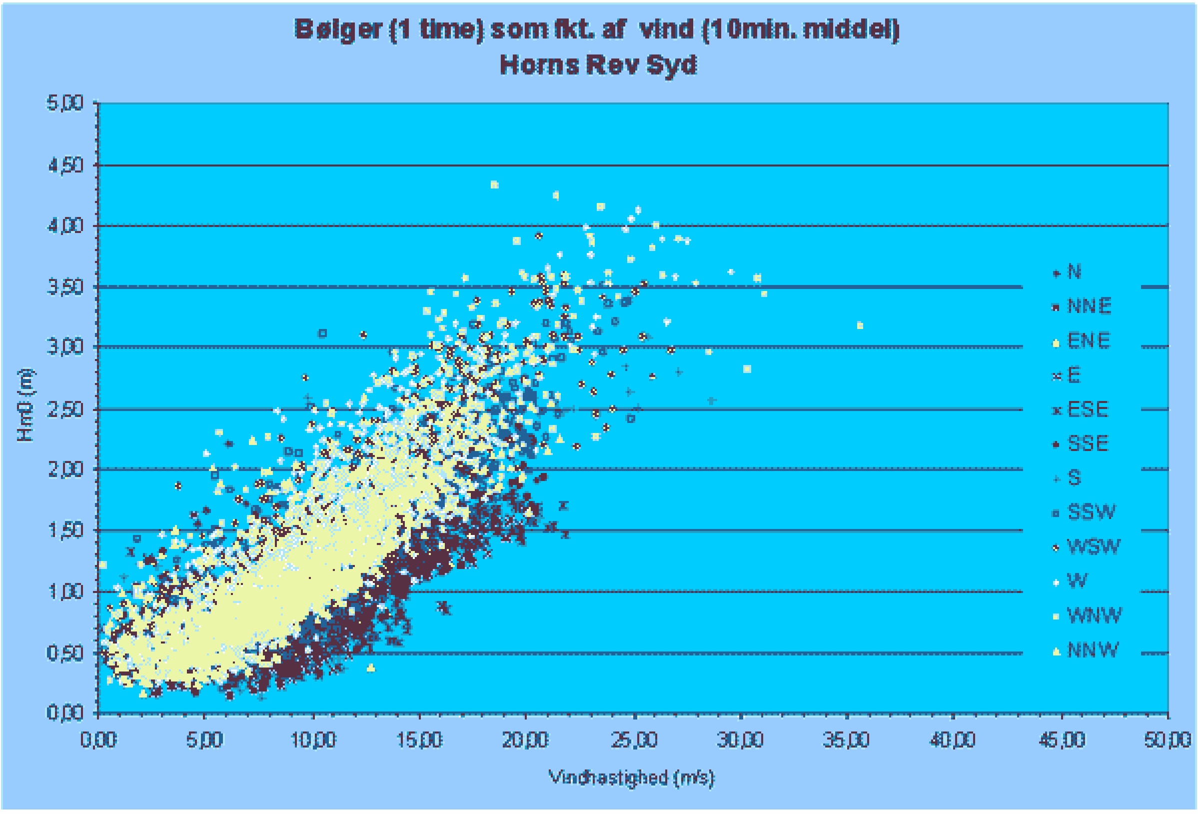

Figure 3-1: Correlation between wave height and wind velocity.

The typical significant wave height in the area is found to be around 1.5 to 2.0 meters. The wave height can however, be much larger for specific wind directions and large wind velocities.
From the report "Kortlægning af bølgeenergiforhold i den danske del af Nordsøen" made for the Danish Energy Authority, ref. /21/, it is seen that the significant wave height for the 1 year and 50 year return period is around 6 m and 8.4 m. However, due to the limited water depth in a part of the wind farm the waves will be limited by the water depth.

3.3 Wind

The typical wind direction in the North Sea is wind in the range from north-west to south-west. The wind velocity varies over the year with the lowest wind velocities during the summer. The storms occur typically during the fall and winter period.

Figure 3-2 and Figure 3-3 show the distribution for the wind direction and wind velocity respectively, which are used in the risk assessment to calculate drift direction and drift velocity.

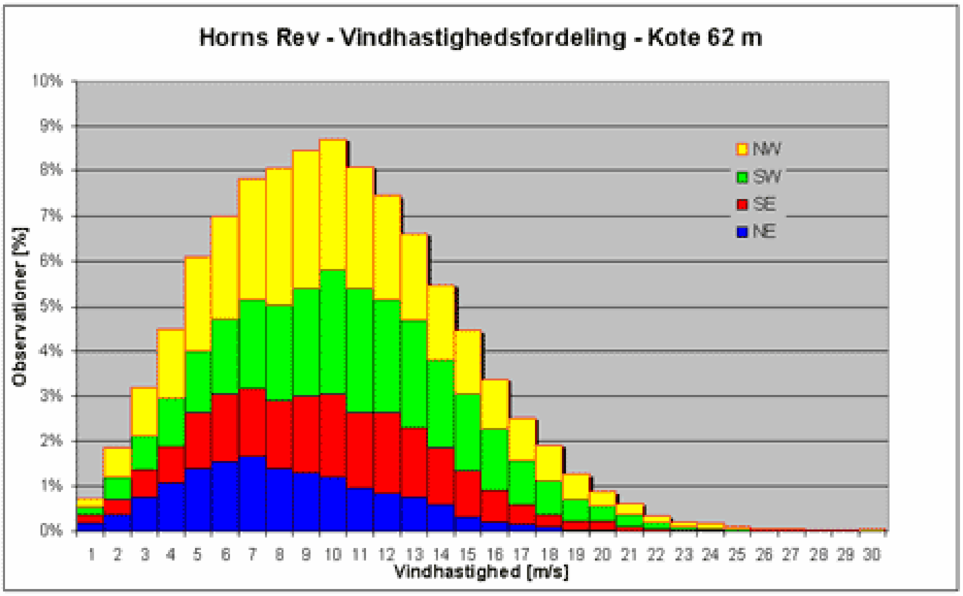

Figure 3-2: Distribution for the wind velocity.

The typical wind velocity at the wind farm location at the outer part of Horns Rev is around 8 to 10 m/s depending of the wind direction.

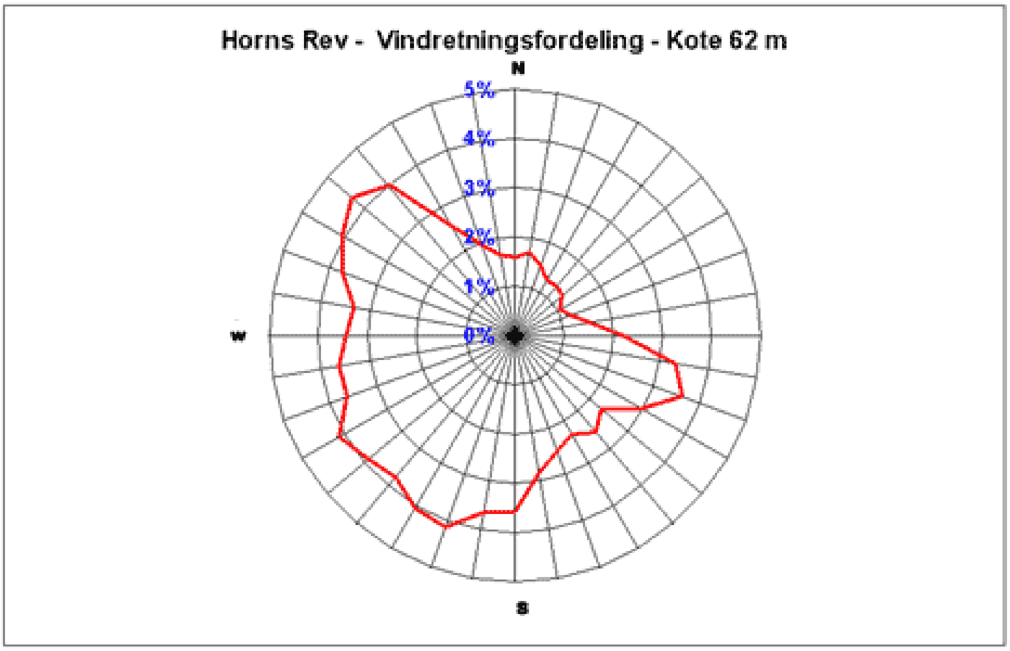

Figure 3-3: "Wind rose" – distribution for the wind direction (wind *from* the direction specified).

3.4 Current

The current in the area is governed by tide. The current is primarily in the directions north-south or north north–east south south-west.

When the current is governed by the tide the current direction changes every 12 hours and higher current speeds are only observed for about half of the time. Current in other directions are also rare. It is assumed that the current is west north-west – east-southeast in approximately 70% of the time and uniformly distributed between all other directions for the remaining 30% of the time.

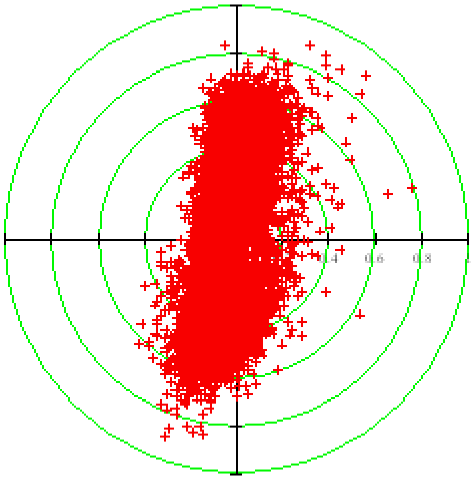

Figure 3-4: Measured current at Horns Rev 1, July 1999 to December 2000.

Based on information from Horns Rev 1 the typical maximum daily current is found to be below 0.5 m/s and the current velocities for a 50 year return period is approximately 0.8 m/s (about 1.6 knots).

From the measurements shown in Figure 3-4 it is seen that even though there are current most of the time the overall average current is very close to zero.

In the risk evaluation, the ship drift vector is calculated from the vector addition of ship drift due to the wind speed and direction added to a typical single current vector. For long drift durations the current governed by tide will average out due to directional change as seen in Figure 3-4. For short drift duration, it will depend on the current at that time. However, as stated above the overall average current is very close to zero.

If the current is included in the collision evaluation the collision risk will depend on the current direction. Current towards the wind farm will increase the collision risk for drifting ships and current away form the wind farm will decrease the risk and since the current is the same in both directions the contribution from the current will vanish. This current vector was therefore set to 0.0 knots for the calculations presented here.

Moreover, is should be noted that the drift velocity is mainly governed by the wind velocity and the approximation is therefore of minor importance.

3.5 Visibility

Fog can occur all year round, but foggy days are generally most frequent in the months January to March and in October, and are least frequent in the summer months of July and August. Fog is here defined as visibility less than one kilometre.

DMI (Danish Metrological Institute) has estimated the average number of days with fog in Denmark to be 74, based on 30 years of data.

Fog usually occurs at the coast and the number of days with fog out on the open waters is much lower than at the coast. In the SAFECO I project, ref. /2/ it was estimated that pour visibility occurs in 5% of the time. Since the two considered areas are located far from the coast the 5% seems reasonable. This corresponds to the average number of days with fog in the specific area in the North Sea is approximately 20 days per year.

3.6 Water depths

The water depth in the considered areas “Nord” and “Syd” location varies between 3.5 m and 20 m. The water depths are largest for “Syd” location where the water depth varies between 3.5 and 20 m, whereas the water depth in “Nord” location is slightly smaller, between 4 and 17 meters.

The water depth decreases towards the reef located in the southern part of both of the considered locations. As seen from the water depth, grounding is very likely at the reef and the reef will therefore yield protection to some extend.

The change in water level due to tide in the North Sea is not large. The water level for a 50 year return period is estimated to 1.8 m above LAT (Lowest Astronomical Tide).

4 DESCRIPTION OF WIND FARM ASSUMPTIONS

Two possible wind farm locations are evaluated in this report. Both locations are at the outer part of Horns Reef, but the "Syd" location have the largest extension in the same direction as the reef whereas the "Nord" location is stretch in the north-south direction from the reef and towards the north. The distance from the area to the Danish coast at Blåvand is around 31 km.

The coordinates for the corners in the two considered areas are given below.

Nord		Syd	
x	y	x	Y
410075	6167683	403776	6164037
412612	6169255	411246	6159954
414697	6166122	414308	6156524
411421	6156898	405750	6155030
406618	6155795	400062	6161704

The location of the considered areas is given in Figure 4-1.

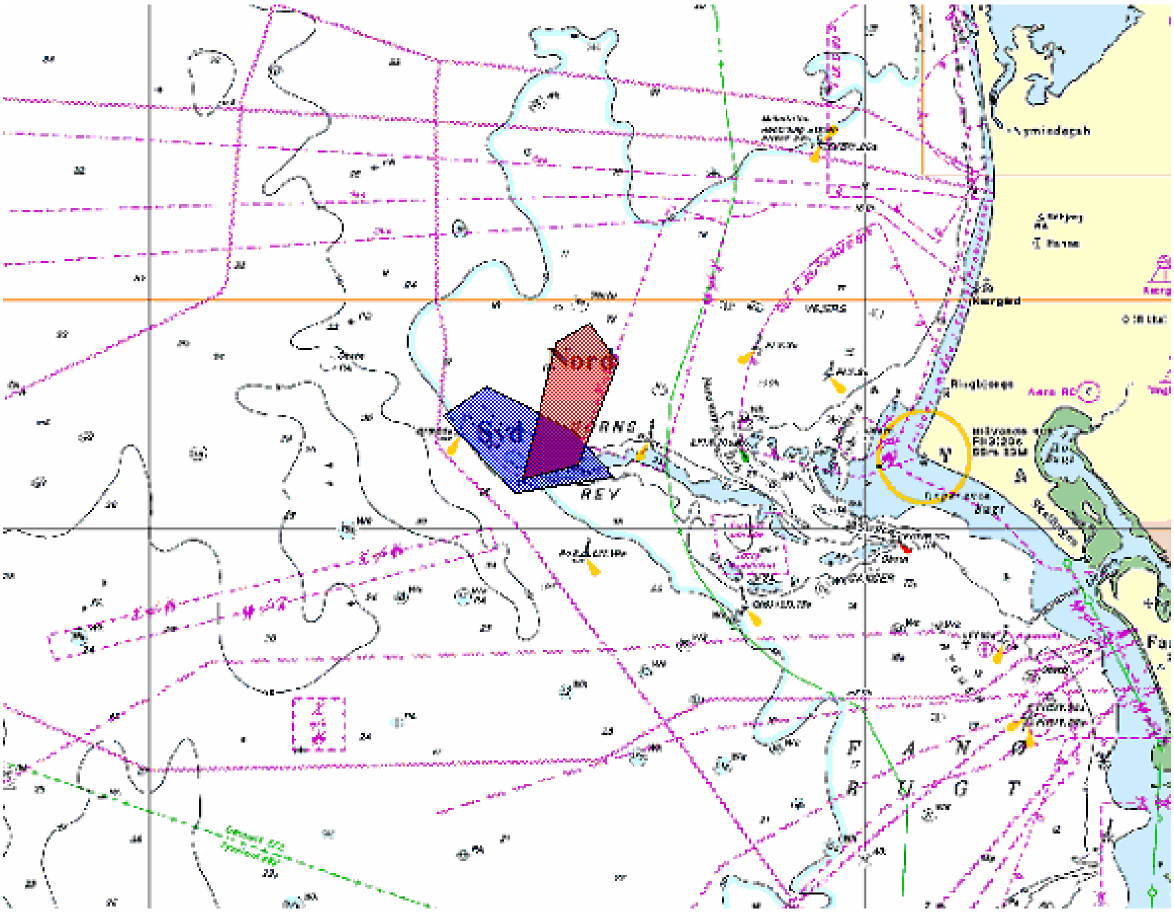

Figure 4-1: The location of the considered areas including planned wind farms in the area.

4.1 The wind farm

The wind farm consists of 92 turbines plus 3 extra test turbines in total 95 turbines and one transformer station. The wind turbines are assumed to be large, each capable of generating around 3-5 MW. The hub height for such a turbine will be approximately 75 meters and the total height to blade tip will be around 120 meters. The diameter of the tower at the water surface, which is relevant for the ship - turbine collision is assumed to be 10 meters. The analysis assumes that all ships will not contact the turbine blades (that is, the ship's superstructure is less than 75 – (120-75) = 30 m above the water line).
Depending on the chosen type of wind turbine the distance from blade tip to sea surface may be down to 23 m. In rare cases it may be possible for a ship to collide only with the blade, but since the foundation usually has a larger diameter than the tower and most ships have a superstructure with less width then the hull and because the ship will have to pass right by the front of the turbine the event would be extremely rare. Moreover, the foundation diameter at sea surface in the calculation is assumed to be around 10 m. This value is slightly conservative and thus covers the possible ship blade impact. The exact diameter of the turbines has though minor importance because it is small compared to 2 times the ship width.
The transformer station is assumed to have a size corresponding to a cross section area of 25m times 25m.

The assumed turbine configuration in the two areas "Nord" and "Syd" is shown in Figure 4-2.

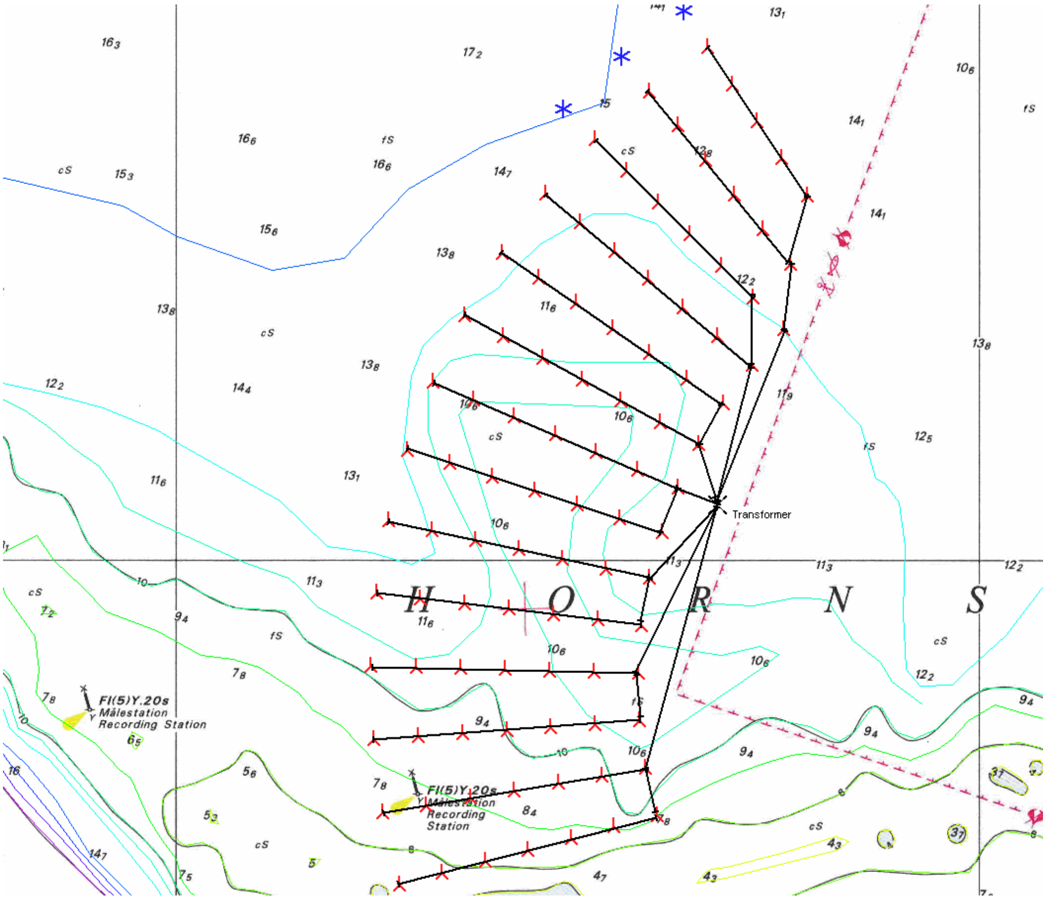

Figure 4-2: Wind turbine configuration for the "Nord" location.

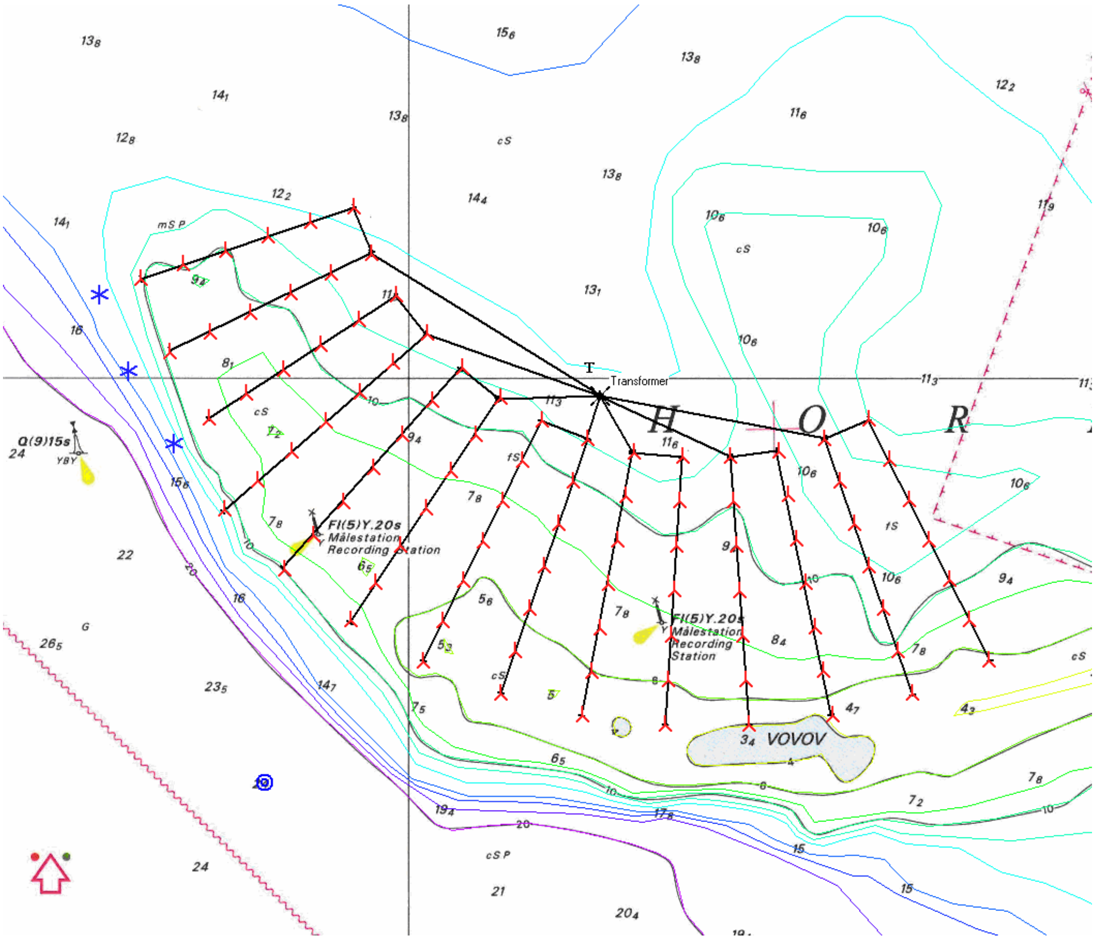

Figure 4-3: Wind turbine configuration for the "Syd" location.

The turbine layout as shown in the figures above is implemented in the risk model.

5 PROCEDURE FOR CALCULATION OF THE COLLISION RISK

This section provides a short description of the procedure for evaluating the collision frequencies for the different scenarios. In an overall risk analysis the starting point would be to identify all possible hazards, rank them and evaluate the most critical ones. However, navigational risk assessments have been carried out for a long period and therefore by experience the risk analysis considers only the following two main hazards, which covers all relevant hazards. These are ship – ship collision related to the construction phase and ship - turbine collision for the scenarios drifting ship and powered collision (human failure) when it is navigating normally.

In order to evaluate the risk the following steps are performed:

- Identification of the annual ship traffic in the area, including shipping lanes, ship types and ship sizes
- Evaluation of the ship collision frequency for the considered scenarios and cases
- Evaluation for a base case where no turbines are erected and the two considered wind farm locations in order to evaluate the additional risk that results from the erection of the wind farm
- Evaluation of whether the risk is acceptable and to identify possible risk reduction measures

The most important basic information in the risk analysis is, of course, the ship traffic in the area. This covers mapping of the shipping lanes in the vicinity of the wind farm, estimation of the annual number of ships for each lane as a function of the relevant ship types and ship sizes.

When the mapping of the ship traffic is obtained together with the environmental parameters it forms the input to the model and the collision frequencies can be obtained.

The following three broad mechanisms are considered:

- Collision resulting from navigational error whilst the ship is fully operational. This scenario could lead to a head on bow collision with the wind turbine, possibly at full speed. (Human error)
- Collision resulting from a mechanically disabled ship drifting into the turbine through the action of wind, wave and current. This could lead to a side way collision, probably at no more than a few knots. (Drifting ship)
- Collision between two ships. The crossing frequency is calculated from the traffic image data and the collision frequency is then calculated by taking the location and visibility into account. (Ship – ship collision)

A detailed description of these scenarios is given in Appendix A in this report. It is generally accepted that failure of the ship, including human failure on the bridge, will lead to one of the above scenarios and thus no formal hazard identification task is needed to derive the above scenarios. An example of a hazard that will lead to one of the above scenarios is given very briefly in Figure 5-1.

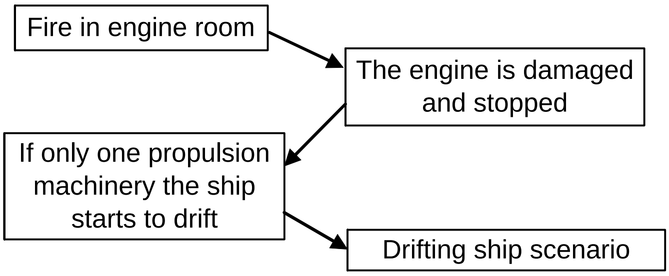

Figure 5-1: Example of an event leading to the drifting ship scenario.

Finally different risk reduction measures are suggested. The implementation of these should be based on a cost - benefit analysis and decisions can therefore not be made before an actual project is developed.

6 SHIP TRAFFIC AND NAVIGATION ROUTES

In this chapter the ship traffic and navigation routes in the waters around Horns Rev in the North Sea is established and described. The number of ships corresponds to the ship traffic today (approximately year 2005).

In the present report all leisure crafts are excluded, but the number of leisure crafts around Horns Rev is insignificant. Only larger ships (>500 grt) covered by SOLAS or ships with AIS are included. Larger fishing vessels are assumed to follow prescribed routes, because the fishing areas for these ships are located further out in the North Sea. However, the number of fishing vessels in Esbjerg have decreased a lot in recent years and the fishing vessels are therefore of minor importance.

In the following the overall ship traffic in the area around Horns Rev will be described and then broken down to navigation routes which are relevant for the ship traffic around the evaluated wind farm locations.

6.1 Ship traffic information

The main part of the commercial vessels which enters the North Sea are either passing through the Dover Strait, through Skagerrak or are local traffic in the North Sea. A small number of vessels will of course pass north of Scotland and together with coastal traffic from the Norwegian west coast head on south depended on there final destination.

The obtained ship traffic is based on VTS (Vessel Traffic System) registrations in the German Bay, statistical reports and information from the Port authorities regarding number of annual arrivals, goods handling etc. The local traffic routes around the wind farm are based on AIS data. The sources are given below.

- Mail from Gordon Wise, Maritime and Coastguard Agency [Gordon_Wise@mcga.gov.uk] with information about the ship traffic in the Dover Strait
- Information received from Esbjerg Port (Jens Juul Poulsen [JJP@portesbjerg.dk] and Karl Johan Madsen)
- Fiskeridirektoratet (Inger Lise Wolff-Jensen from statistical department)
- Esbjerg Fiskeriforening
- Information received form Oslo Port (Tommy Svendsen [tommy.svendsen@ohv.oslo.no])
- ELSAM Background report no. 23 “*Ship Collision at Horns Rev*”, May 2000.
- VTS data from Øresund and Great Belt used for obtaining the traffic in Skagerak
- Information received from WSD Nord
- WSD statistic 2001 from WSD Nordwest
- AIS plots from Farvandsvæsnet for the area around Horns Rev.

Besides the above information, the sea map Horns Rev from the British Admirality Charts 1405 and 2182B has been used to determine the exact way-point coordinates for the obtained navigation routes.

6.1.1 Ships through Skagerrak

As the only deep sea entrance to the Baltic Sea, Skagerrak is passed by approximately 42700 commercial vessels each year.

Through Skagerrak two routes are predominant. These routes are an east-west bound route south of Norway (Kristiansand) and a route along the north-west coast of Jutland. The traffic passing south of Norway towards/from the Atlantic Ocean is of no importance for the present study.

It is assumed that approximately 85% of shipping, corresponding to 36000 ships, that cross Skagerrak follow the coast of Jutland towards the south. The traffic that follows the northern and western coast of Jutland separates out on several routes after it has passed Hanstholm, but the main part of these routes will pass far to the west of Horns Rev. Only a small part of this traffic will follow the coast towards the south. Examples for this traffic are traffic between Skagerrak and Die Ems or Die Elbe, Weser and Jade.

The remaining part is traffic towards the Strait or the large harbours in this area. The annual traffic between Skagerrak and the Dover Strait area is estimated to be approximately 32000. The navigation route follows the waypoint west of Hanstholm and the entrance point north of Off Botney - West Friesland - or Off Vlieland T.S.S.

Ship traffic from the Norwegian west coast will be similar to the description above. This traffic is though much lower frequency or smaller in ship size and will follow a route in the north-northwest – south-southeast going direction.

6.1.2 Esbjerg

Based upon information received from the port authorities in Esbjerg a detailed analysis of the commercial traffic to and from this port has been possible. From Esbjerg six main routes are identified and reflect 98% of the total traffic. The routes are described in the following bullet points and shown in Figure 6-1.

- Traffic bound for Skagerrak, Norwegian ports and north of Scotland will all head out on a westerly course keeping south of Horns Rev. When clear of the western buoy of Horns Rev vessels will turn north.
- A significant number of supply vessels are operating between Esbjerg and the Danish oil and gas fields in the North Sea. They are more or less heading out due west when passing Grådyb buoy with minor course alterations dependent upon the position of the oil field. It is registered that around 1300 vessels are operating on this route every year.

- Vessels bound for Newcastle and Teesport all head out on a west south-westerly course. Close to 600 vessels follow these routes every year.
- Traffic bound for the Humber will follow a south westerly course. Around 800 vessels are estimated to follow this route annually.
- The traffic Bound for Harwich, the Thames Estuary and Dover Strait will follow a south westerly route towards Off Botney - and West Friesland T.S.S. It is estimated that 800 vessels follow this route annually.
- Traffic bound for Die Elbe, Weser and Jade will follow a southern course passing clear of Røde Klit Sand to the east. At Amrum Bank course alteration will be made for passing east or west of Helgoland before entering the rivers. From Esbjerg to Amrum Bank around 350 vessels per year will follow this route.

From the above it is seen that most of the ship traffic from Esbjerg passes south of the reef and towards the west – southwest. Based on the above the main routes in the lower part of the North Sea are given in Figure 6-1. This pattern must then be broken down in minor routes around the considered wind farm locations.

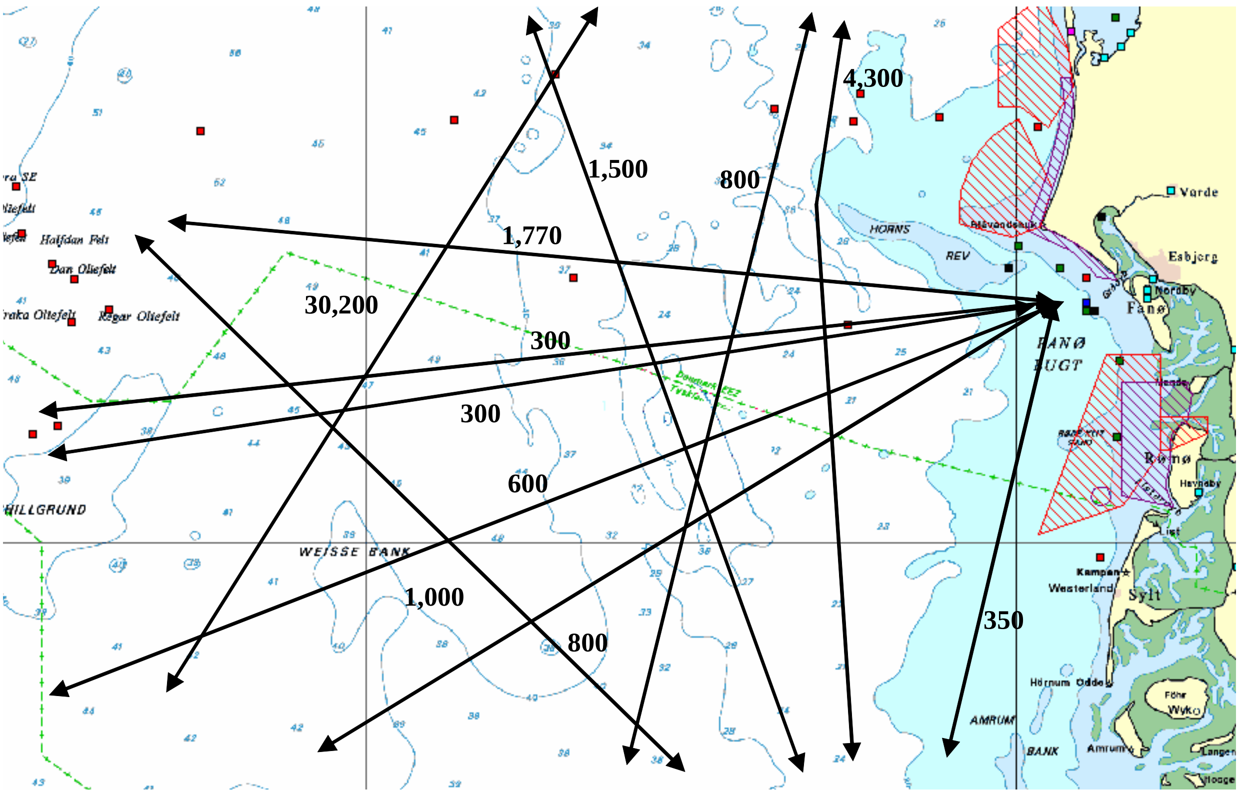

Figure 6-1: Main traffic routes in the southern part of the North Sea.

6.1.3 AIS data and local routes around the wind farm location

The above traffic pattern must be broken down to more local routes around the Horns Rev and the two possible wind farm locations. Derivation of the local routes is based on the AIS data plots received from Farvandsvæsnet.

The AIS data is shown in Figure 6-2 and covers the period 27/9 2005 to 7/11 2005. The red lines in the figure are north going ships and the blue are south going ships. It is seen that north and south going traffic are in the same order of magnitude.

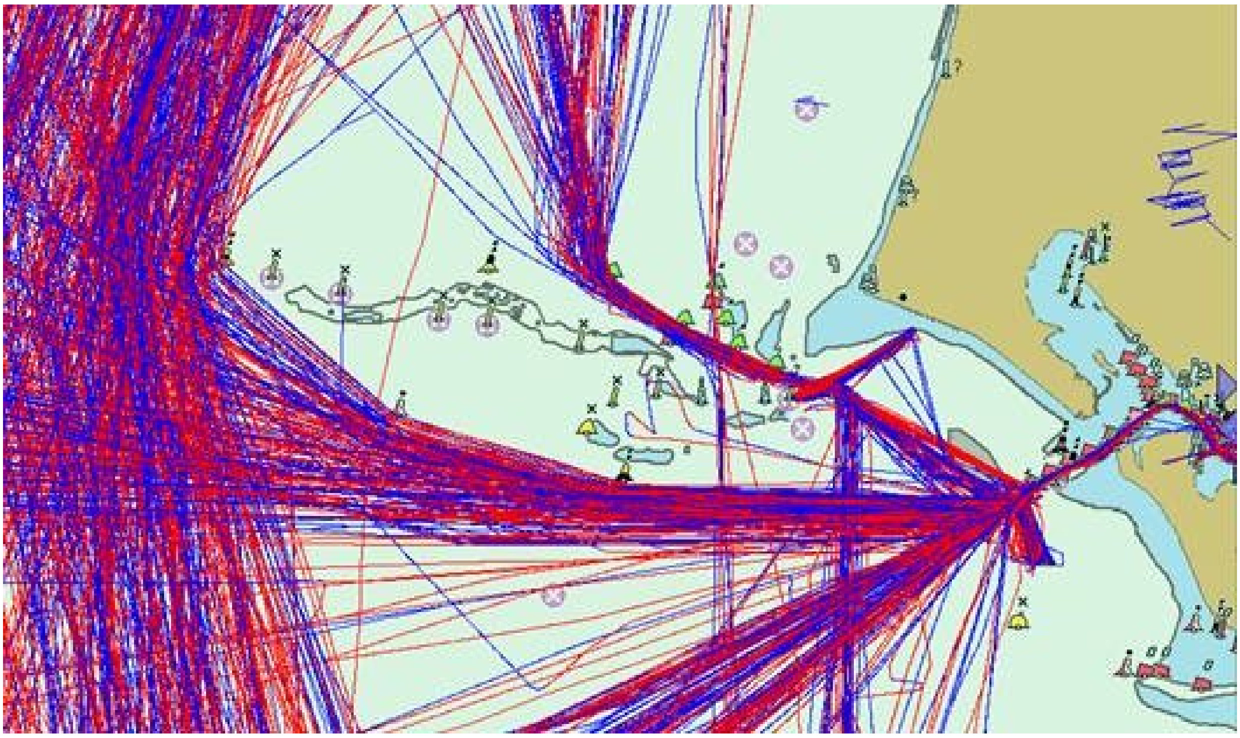

Figure 6-2: AIS plot of the area around Horns Rev.

From Figure 6-2 it is seen that most of the ships are avoiding the area around the reef. Moreover, it is seen that the main part of the ships passes south of the Horns Rev and that the reef forces all north and south going ships to pass far from the coast.

6.2 Fishing vessels

The fishing vessels will in many cases travel much more randomly than commercial ship traffic so they are more difficult to represent with route structures. However, in order to get an idea of the possible influence from the fishing vessels, the fishing intensity is examined. The catch per day is reported for the different squares shown in Figure 6-3.

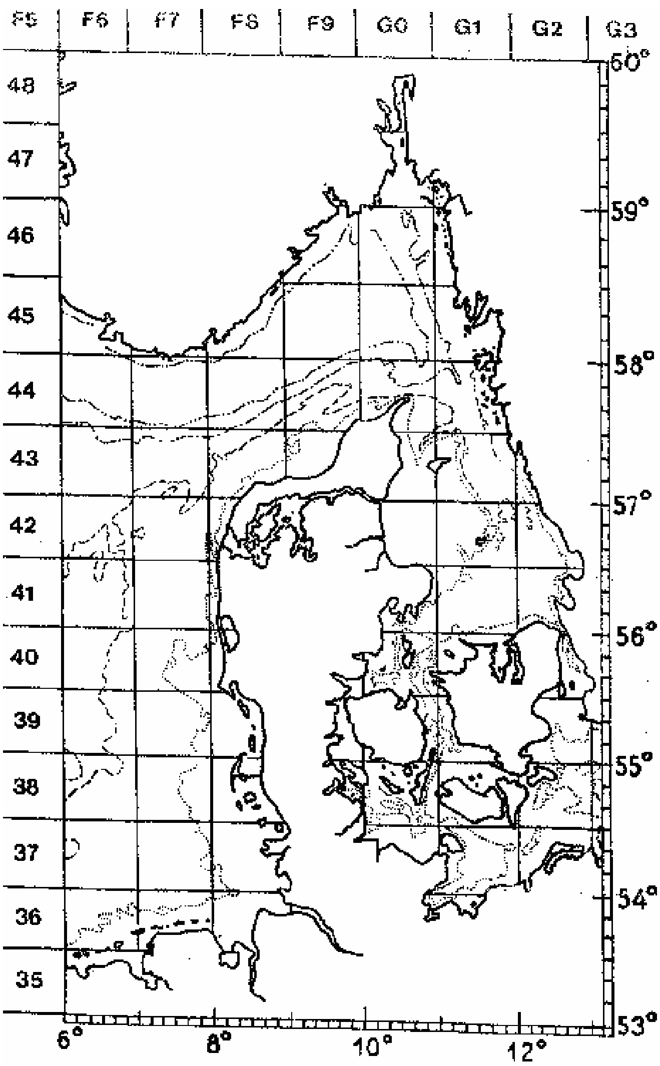

Figure 6-3: Squares used for reporting the fishing location and catch.

The considered wind farm locations lie in the square F7 39 and F7 40. From the AIS plot it was seen that the ship traffic in the area was very limited and it shows that the number of large fishing vessels operating in the area is very limited.

The information given in Table 6-1 about the number of different fishing vessels per square, catching days and landed catch is obtained from Niels Thorup in the Danish Directorate of Fisheries for the year 2002.

Fishing square	Number of different vessels in the area	Catching day trips	Total catch [kg]	Average catch [kg/day trip]
F7 39	167	1602	9.275.978	5790

Table 6-1: Fishing activities in section F7 39 for year 2002.

It should also be kept in mind that one square as given in Table 6-1 covers approximately 3500 km^2, which is large compared to the considered wind farm areas.

From Table 6-1 it is seen that the number of different fishing vessels in the area was limited already in 2002 and the activity has been decreasing over the last decade. Esbjerg Fiskerriforening have informed DNV that the number of fishing vessels located in Esbjerg was 85 in 2002 and has decreased to 44 in 2005; it is still decreasing.

Moreover numbers from Inger Lise Wolff-Jensen in Fiskeridirektoratet show that the landings have decreased with more than 32% from 2004 to 2005, which indicate that the fishing vessels are fishing in areas further away and therefore landing the catch in other harbours.

Finally, the numbers received from the statistical department in Fiskeridirektoratet show that the number of landings in the first 11 month in 2005 is approximately 1400 and extrapolating this to a full year the number becomes around 1550 landings. However, more than 23 % of the landings are with vessels smaller than 5 grt[*]. These small vessels have been included in the analysis. The annual number of fishing vessels in and out of Esbjerg used in the risk evaluation has therefore been estimated to 1100.

As a conservative approach the 1100 fishing vessels are assumed to follow the prescribed routes north and south of Horns Rev.

6.3 Summary of the ship traffic

Having established the most frequently used navigational routes in the southern part of the North Sea and the more local traffic around the Horns Rev, an evaluation of which routes that can have impact on the two evaluated wind farm areas can be made.

A number of the previously described routes are considered to be insignificant for the present evaluation due to the distance to the wind farm areas. In Figure 6-4 the navigation routes and the corresponding number of ship movements is shown. It is seen that the wind farm Horns Rev 1 will have no impact on the wind farm Horns Rev 2 because the distance is large between the farms and because the reef is located between them.

[*] Measure of the size or cargo capacity of a ship. Represents the total internal volume of a vessel, with some exemptions for non-productive spaces such as crew quarters; 1 gross register ton is equal to a volume of 2.83 m³.

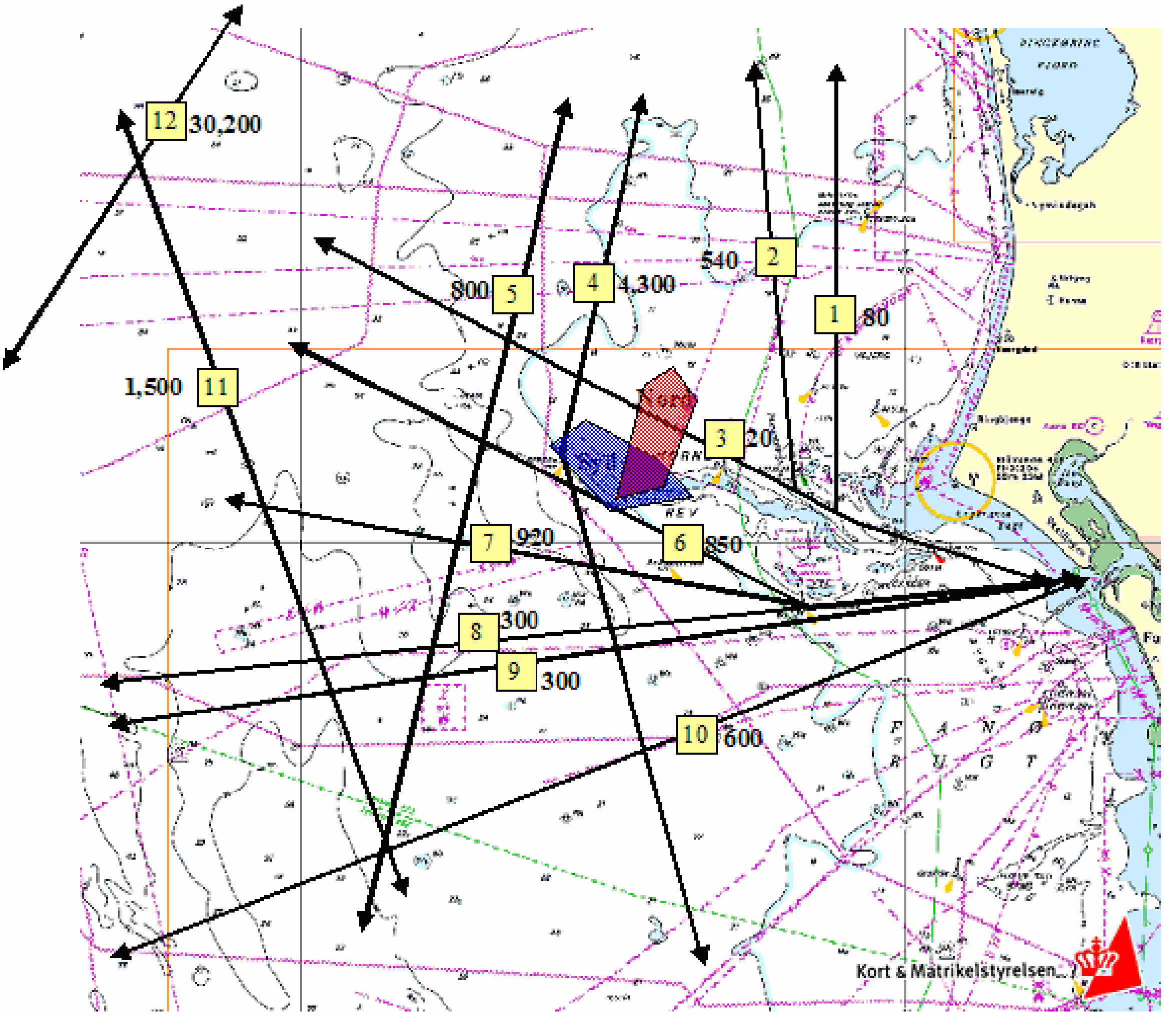

Figure 6-4: Shipping routes with potential impact on the two considered wind farm areas.

From Figure 6-4 it is seen that the wind farms will have a small impact on the navigation routes. The impacts for the two locations are described below.

North location:
Route number 3 passes through the area. However, only 20 ships per year (supply or fishing vessels) are estimated to follow the route. If the north location is chosen it is assumed that the route will vanish and the ships will instead follow the route south of the reef.

South location:
Route 6 and Route 4 will be slightly affected by the southern location. If the location is chosen it is assumed that these routes will be shifted west and south so they will pass the wind farm area by a distance of 1 nautical mile.

Including the above modifications the traffic routes and traffic intensity used in the analysis of the two wind farm locations for the wind farm in operation are shown in Figure 6-5

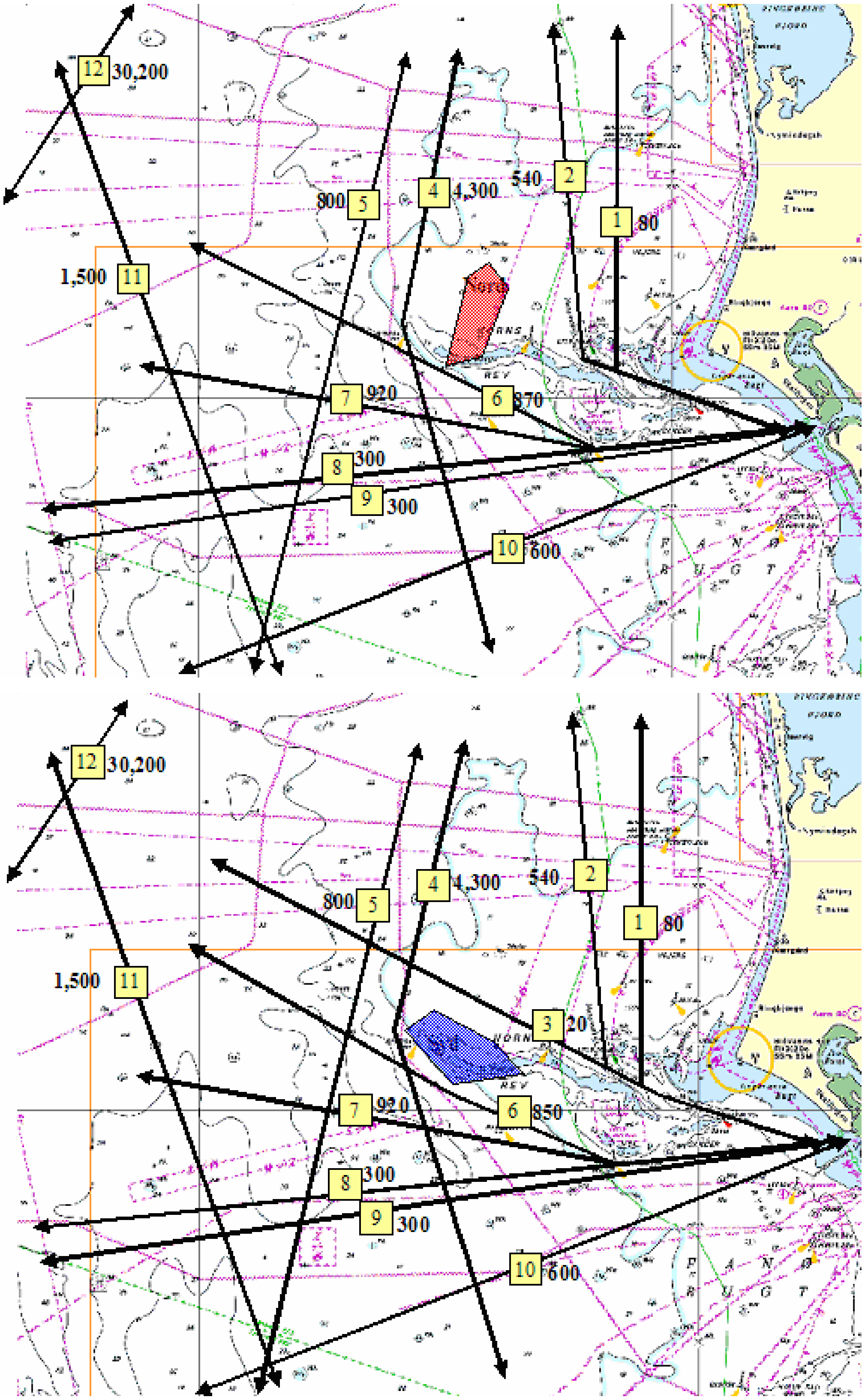

Figure 6-5: Shipping routes used for the two considered wind farm areas. Top "Nord", bottom "Syd".

For all the routes the distribution of the ships perpendicular to the ideal route is assumed to follow a Gaussian distribution with a mean value corresponding to the ideal route and a standard deviation depending on the ship type and sea location combined with a uniform distribution with a width of six times the standard deviation. It is assumed that 2% follows the uniform distribution and 98% follows the Gausian distribution. The distribution corresponds very well to what was measured in Øresund during construction of the Øresund Link and the distribution is also the one agreed with the German authorities (BSH Bundesamt für Seeschiffahrt und Hydrographie).

The standard deviation for the routes together with the used way-points for each route is given below in Table 6-2 for “Nord” location and Table 6-3 for “Syd” location. The standard deviation applied between waypoints varies linearly between the values given at the way-points. A more detailed description is given in Appendix A.

	Longitude		**Latitude**		**Transverse ship traffic**
Route no	**Grad**	**Min**	**Grad**	**Min**	**Standard deviation [nm]**
1	55	32.1	7	53	0.25
1	55	57	7	52	1.5
2	55	33	7	49	0.25
2	55	57	7	44	1.5
4	55	8	7	38	1.5
4	55	35	7	25.5	1
4	55	57	7	33.5	1.5
5	55	10.5	7	6	2
5	55	55	7	25.6	2
6	55	24.6	8	11.5	0.5
6	55	26	7	50	1
6	55	42.6	6	53	2
7	55	24.6	8	11.5	0.5
7	55	26	7	50	1
7	55	33	6	47	2
8	55	24.6	8	11.5	0.5
8	55	22.3	6	45	2
9	55	24.6	8	11.5	0.5
9	55	20	6	44	2
10	55	24.6	8	11.5	0.5
10	55	9	6	51	2
11	55	58	6	40	3
11	55	11	7	8.5	2
12	56	6	6	52.8	3
12	55	21	6	0	3

Table 6-2: North location: Way-points for the shipping routes and the related standard deviation for the transverse distribution Gaussian function.

	Longitude		Latitude		Transverse ship traffic
Route no	Grad	Min	Grad	Min	Standard deviation [nm]
1	55	32.1	7	53	0.25
1	55	57	7	52	1.5
2	55	33	7	49	0.25
2	55	57	7	44	1.5
3	55	32.1	7	53	0.25
3	55	48	6	57	1.5
4	55	8	7	38	1.5
4	55	35.4	7	22	1
4	55	57	7	33.5	1.5
5	55	10.5	7	6	2
5	55	55	7	25.6	2
6	55	24.6	8	11.5	0.5
6	55	26	7	49	0.5
6	55	42.6	6	53	1
7	55	24.6	8	11.5	0.5
7	55	26	7	49	1
7	55	33	6	47	2
8	55	24.6	8	11.5	0.5
8	55	22.3	6	45	2
9	55	24.6	8	11.5	0.5
9	55	20	6	44	2
10	55	24.6	8	11.5	0.5
10	55	9	6	51	2
11	55	58	6	40	3
11	55	11	7	8.5	2
12	56	6	6	52.8	3
12	55	21	6	0	3

Table 6-3: South location: Way-points for the shipping routes and the related standard deviation for the transverse distribution Gaussian function.

From Table 6-2 and Table 6-3 it is seen that the navigation routes are assumed to pass about 1 nm away from the wind farm area at the closest approach and that the standard deviation for the transverse ship traffic at these way-points close to the area are assumed to be small, about 1.0 to 0.5 nm.

6.4 Influence on the ship traffic from the wind farm

Depending on its location the wind farm may have influence on the ship traffic in the area. Moreover, when more than one wind farm is constructed in the same area there may be a shadow effect. The shadow effect arises due to the assumption that the ships are sailing or drifting in straight lines. In addition, it is assumed that a ship will collide with only one wind turbine. For this reason, the frequencies of ship-turbine collisions for turbines within an array of turbines will be lower than for a turbine at the edge of the array that is closer to ship traffic. A turbine or a wind farm may therefore shield, or shadow, others and thus have a positive effect with respect to ship – turbine collisions. However, wind farm Horns Rev 1 is located far from Horns Rev 2 so the effect is negligible. Moreover the wind farms are located almost on each side of the reef and the reef will therefore have a positive effect with respect to ship – turbine collisions on both wind farms.

Another possible effect on the ship traffic could be an increased ship – ship collision, if the wind farm forces the ship traffic out of the area and hereby increase the ship density at the wind farm borders. If the increase is in areas with high traffic density the frequency of meeting situations will be increased and hence results in a higher frequency of ship-ship collision. However, from Figure 6-2 it is seen that the ship traffic in the considered areas are very limited and the effect is therefore negligible.

6.5 Ship type distributions on the routes

The data sources described in the previous sections do, in most cases, also contain information about ship type and ship sizes, which can be used for the local routes.

For the large routes west of Horns Rev the ship traffic distribution on ship types are based on information received from Dover VTS. The distribution is given in Table 6-4 for the ships through the English Channel and it is seen that the majority of ships (70%) are of the type general cargo ships, container vessels and others.

Ship types	Number of ships	Relative distribution [%]
Chemical Tankers	3140	3.2
Chemical/Oil	6410	6.4
Container Vessels	10546	10.6
Crude Oil Tanker	3046	3.1
General Cargo	26628	26.7
LPG Tanker	3404	3.4
Products Tanker	3264	3.3
Ore/Oil Carrier	212	0.2
Passenger Ships	772	0.8
Reefer Vessels	3450	3.5
RoRo Cargo (not Ferries)	2180	2.2
Vehicle Carriers	3930	3.9
Others	32670	32.8
Total	99652	100.0

Table 6-4: Ship types and annual frequencies through the Strait in 2003

In the risk analysis the ship traffic is divided into the following six groups of ship types:

- Tankers
- Chemical tankers
- Ferries and Ro/Ro vessels
- Supply ships
- Fishing vessels
- All others (this is mainly general cargo, bulk carriers and container vessels)

The reasons for using these groups are as follows. The first two groups are chosen due to the consequences in case of a collision. The ferries and ro/ro vessels are combined in one group because they travel a bit faster and they generally have more than one set of propulsion machinery and hence the failure frequency is lower. Supply ships and fishing vessels are ships passing very close to the wind farm and the only ships that will use Slugen through Horns Rev once in a while. The last group contains the rest of the ships and the consequence in case of a collision for these ships is assumed to be release of bunker oil.

Moreover, due to the different dimension of the ships, the ships are divided into different size classes. The calculation is then made for the average ship in each ship class. In the tables below the assumed relations between ship size, length and breadth for the different ship types and ship class are given.

Tankers				
Ship class DWT	DWT*	GRT	L [m]	B [m]
0 – 1.000	800	560	53	9
1.000 – 3.000	2400	1680	77	13
3.000 – 5.000	4000	2800	91	15
5.000 – 10.000	8000	5600	115	19
10.000 – 20.000	16000	11200	145	24
20.000 – 40.000	32000	22400	183	30
40.000 – 80.000	64000	44800	230	38
>80.000	96000	67200	263	44

Table 6-5: Relation between ship classes and size length and breadth for tankers

Cargo ships				
Ship class DWT	DWT	GRT	L [m]	B [m]
0 – 1.000	800	560	53	9
1.000 – 3.000	2400	1680	77	13
3.000 – 5.000	4000	2800	91	15
5.000 – 10.000	8000	5600	115	19
10.000 – 20.000	16000	11200	145	24
20.000 – 40.000	32000	22400	183	30
40.000 – 80.000	64000	44800	230	38
>80.000	96000	67200	263	44

Table 6-6: Relation between ship classes and size length and breadth for cargo ships

* The amount of cargo, fuels, water, stores and crew that the ship can carry when fully loaded.

Ferries				
Ship class DWT	DWT	GRT	L [m]	B [m]
0 – 1.000	800	4000	103	17
1.000 – 3.000	2400	12000	148	25
3.000 – 5.000	4000	20000	176	29
5.000 - 10.000	8000	40000	222	37
10.000 – 20.000	16000	80000	279	47
20.000 – 40.000	32000	160000	351	59
40.000 – 80.000	64000	320000	443	74
>80.000	96000	480000	507	84

Table 6-7: Relation between ship classes and size length and breadth for ferries

6.6 Annual number of ship movements on the navigation routes

Using the ship classes described in the previous section the annual ship traffic on the different routes given in Figure 6-5 can be obtained. The annual ship traffic for the navigation routes with mixed ship traffic divided into ship classes and size is given in the following tables.

DWT in 1000	Route 1 Total number of ships 80	Route 2 Total number of ships 540	Route 3 Total number of ships 20		Route 4 Total number of ships 4300			
	Fishing vessel	Fishing vessel	Supply ship	Fishing vessel	Chemical Tanker	Tanker	Ro/Ro	All others
0-1	70	469	0	9	4	41	65	450
1-3	10	71	2	1	19	104	165	1149
3-5	0	0	8	0	78	25	40	277
5-10	0	0	0	10	96	63	100	694
10-20	0	0	0	0	56	25	39	273
20-40	0	0	0	0	38	20	31	217
40-80	0	0	0	0	13	13	20	138
>80	0	0	0	0	3	3	5	35
Sum:	80	540	10	10	308	294	465	3233

Table 6-8: Estimated annual ship traffic for the navigation routes 1, 2, 3 and 4.

DWT in 1000	Route 5 Total number of ships 800				Route 6 Total number of ships 850		Route 7 Total number of ships 920		Route 8 Total number of ships 300			
	Chemical Tanker	Tanker	Ro/Ro	All others	Supply ship	Fishing vessel	Supply ship	Fishing vessel	Chemical Tanker	Tanker	Ro/Ro	All others
0-1	1	8	124	141	0	217	0	191	0	10	4	56
1-3	5	11	177	201	142	33	165	29	0	4	16	82
3-5	10	1	10	11	458	0	535	0	1	4	8	60
5-10	10	1	25	28	0	0	0	0	1	0	16	24
10-20	3	0	4	4	0	0	0	0	0	0	5	5
20-40	1	0	8	9	0	0	0	0	0	0	0	3
40-80	0	0	3	4	0	0	0	0	0	0	0	1
>80	0	0	0	0	0	0	0	0	0	0	0	0
Sum:	29	21	351	399	600	250	700	220	2	18	48	231

Table 6-9: Estimated annual ship traffic for the navigation routes 5, 6, 7 and 8.

DWT in 1000	Route 9 Total number of ships 300 Chemical Tanker	Tanker	Ro/Ro	All others	Route 10 Total number of ships 600 Chemical Tanker	Tanker	Ro/Ro	All others	Route 11 Total number of ships 1500 Chemical Tanker	Tanker	Ro/Ro	All others
0-1	0	10	4	56	0	19	7	112	1	14	23	157
1-3	0	4	16	82	0	9	32	164	7	36	58	401
3-5	1	4	8	60	2	7	17	119	27	9	14	97
5-10	1	0	16	24	2	0	32	49	34	22	35	242
10-20	0	0	5	5	1	0	9	10	20	9	14	95
20-40	0	0	0	3	0	0	0	6	13	7	11	76
40-80	0	0	0	1	0	0	0	3	5	4	7	48
>80	0	0	0	0	0	0	0	0	1	1	2	12
Sum:	2	18	48	231	5	36	96	463	107	102	162	1128

Table 6-10: Estimated annual ship traffic for the navigation routes 9, 10 and 11.

DWT in 1000	Route 12 Total number of ships 30200 Chemical Tanker	Tanker	Ro/Ro	All others
0-1	70	327	553	4331
1-3	127	638	1074	5429
3-5	166	563	1074	3964
5-10	273	820	1436	2996
10-20	102	457	378	1104
20-40	69	411	244	1042
40-80	64	233	237	844
>80	63	220	236	655
Sum:	933	3669	5232	20366

Table 6-11: Estimated annual ship traffic for the navigation route 12.

6.6.1 Annual number of ship movements during construction

The ship traffic during construction is uncertain. However, it is assumed that the construction of the wind farm will take approximately two years. In Table 6-12 is given the assumed number of vessels in the year with most activity. The evaluated annual frequency is thus conservative.

Period	Number of ships
Marts – May	7
June – August	15
September – November	7
December - February	3

Table 6-12: Estimated annual ship traffic for the construction phase.

Some of the vessels will be located at the construction site for long period, whereas other vessels may travel back and forth every day. It is therefore assumed that all vessels in average will travel to and from Esbjerg every second day. Moreover, it is assumed that there will be a restricted navigation channel and a construction area only for the construction vessels. The assumed route is given in Figure 6-6.

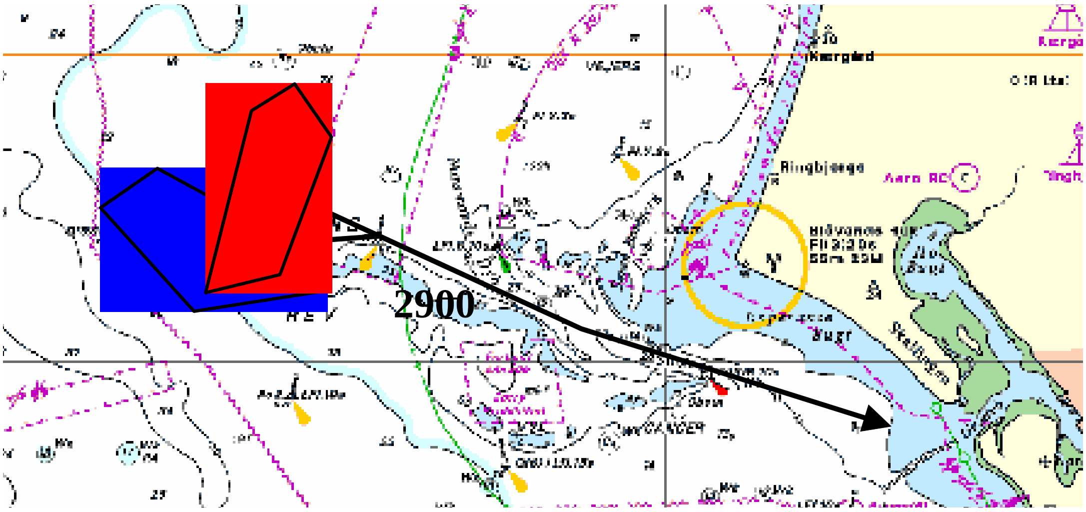

Figure 6-6: Shipping route for construction of the wind farm.

Due to the shallow water area in a part of the wind farm it is assumed that the construction vessels will be limited in size. The assumed size distribution for the construction vessels are given in Table 6-13.

DWT in 1000	Construction phase Total number of ships 2800 Construction vessels
0-1	0
1-3	685
3-5	2215
5-10	0
10-20	0
20-40	0
40-80	0
>80	0
Sum:	2900

Table 6-13: Estimated annual ship traffic for the construction phase.

7 SHIP COLLISION MODEL

Transportation by sea using conventional shipping operations results in both economic benefits and associated ship accident risks, which can result in safety and environmental impacts.

In the present risk analysis the focus is on ship to wind turbine collision for the wind farm in operation and the ship – ship collision scenario for the construction phase. The ship to turbine collision is covered by the following two broad mechanisms:

- Collision resulting from navigational error whilst the ship is fully operational. This scenario is caused by a radar or human failure and could lead to a head on bow collision, probably at close to full sea speed.
- Collision resulting from a mechanically disabled ship drifting into the turbine through the action of wind and/or current. This scenario is caused by failure of propulsion machinery and could lead to a side-way collision, generally at much reduced drift speeds.

The ship – ship collision scenario is governed by the ship intensity and the local conditions such as visibility and sailing direction. The crossing frequency is calculated from the traffic image data and the collision frequency is then calculated by using the collision per crossing probabilities which take account of the location and visibility.

Accidents due to steering failure are assumed to be insignificant due to the distance from the navigation routes to the wind farm. To be conservative, steering failure frequencies are included within the mechanical breakdown frequencies discussed below. In practice a ship with disabled steering may be able to avoid collision by the use of forward and reverse thrust.

Risk assessment of these accident modes can be performed by assessing the accident frequency, followed by an assessment of the accident consequences, typically in terms of cargo spill, lives lost or in financial terms. DNV has developed the MARCS model to perform such marine transport risk assessments in a structured manner. The frequency model in MARCS is similar to those used extensively by DNV to assess ship to offshore platform collision. This model is also described by proffesor Pedersen in ref. /20/. A description of MARCS and the relevant input parameters is given in Appendix A.

7.1 Assumptions and input parameters

In this section some of the most important basic assumptions and input parameters to the MARCS program are given.

7.1.1 Human failure

For the human failure scenario (named as powered collision in MARCS), which will lead to a head on bow collision. The probability of collision given that the ship is on collision course is equal to the probability of a human failure.

In the present calculation one value is used for the probability of human failure. The value covers the combination of visibility, radar failure and the human failure (drunk, ill, absent, distracted etc). Note that the designation "Human failure" is not completely correct because radar failure is also included. However, a radar failure e.g. will lead to the same collision scenario and it is therefore only a matter of name (human failure or causation probability). In the following the term human failure is used for the top event.

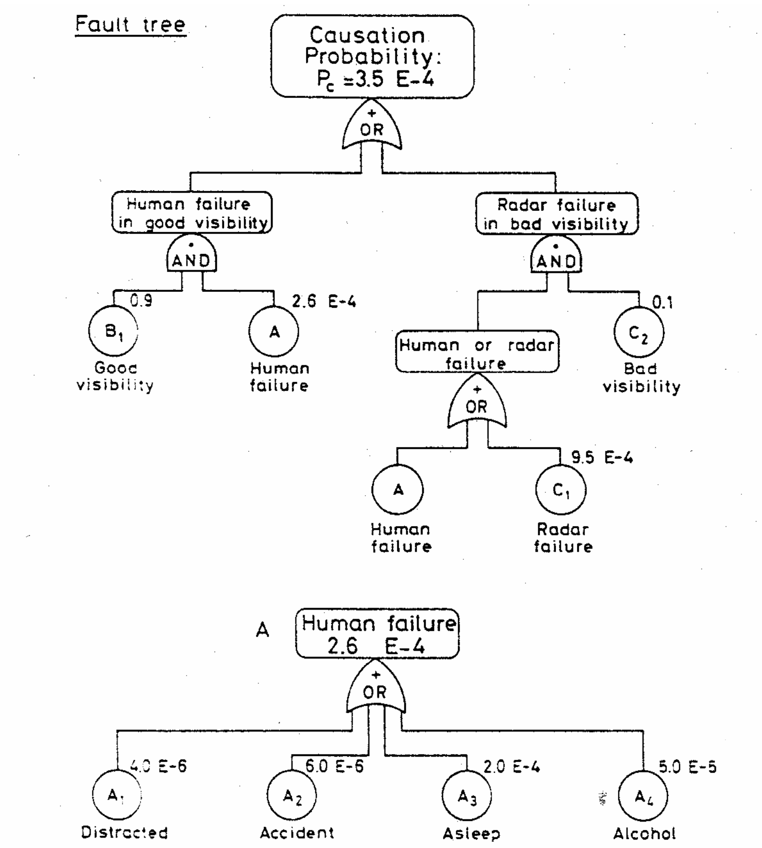

Figure 7-1: Fault tree for causation (human failure) probability.

The probability of human failure is here taken as $3.0 \cdot 10^{-4}$ slightly larger than stated in Preben Terndrup Pedersen ref. /20/ shown Figure 7-1. The value is based on the observations given in "Integrated Study on Marine Traffic Accidents", Yahei Fujii, ref. /11/, and "The Probability of Vessel Collisions", T Macduff, ref. /12/, and supported by Ole Damgaard Larsen ref. /19/.

The conclusion made by Fujii is based on traffic and accidents from four straits in Japan. Fujii estimates the probability of human failure to be in the interval $0.8 \cdot 10^{-4}$ to $5.0 \cdot 10^{-4}$ with a best estimate of $2.0 \cdot 10^{-4}$.

Macduff has based his analysis on data from the English Channel and estimates the probability of a human failure to be in the interval $1.4 \cdot 10^{-4}$ to $1.6 \cdot 10^{-4}$.

In the SAFECO project ref. /2/ and ref. /3/ the probability of human failure was estimated to be $2.9 \cdot 10^{-4}$. Thus the value used here, $3.0 \cdot 10^{-4}$, seems reasonable or maybe slightly conservative.

Moreover, due to wind and current the ship will not be completely parallel to the sailing direction and the ship width is therefore increased by a factor of 1.2.

In the following a short description of the calculation of the collision frequency for the human failure scenario is given. The scenario is illustrated in Figure 7-2.

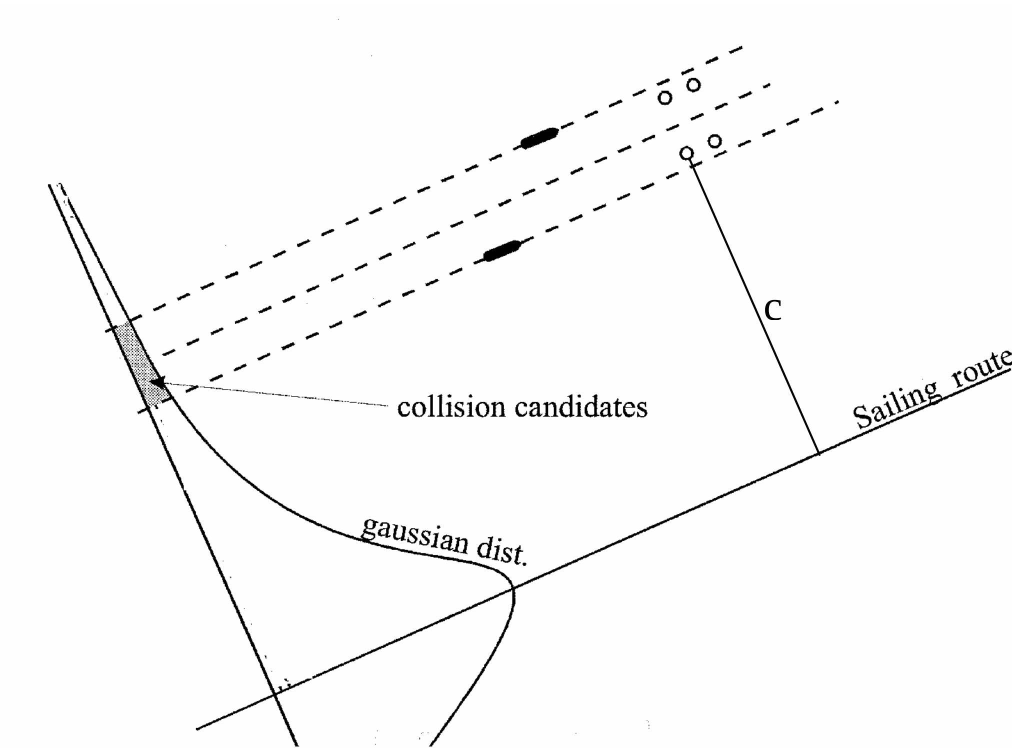

Figure 7-2: Illustration of the human failure scenario.

For the navigation lanes given in Figure 6-4, where there are no major bends, the formula for the ship-turbine collision frequency can be simplified to:

$$F_{Human} = N \cdot P_{Human} \cdot \int_{c-0.5(D+W_{ship})}^{c+0.5(D+W_{ship})} f(y)dy \qquad \text{where}$$

N is the number of ships on the lane for the specific ship class per year.
P_{Human} is the probability for a human failure ($3.0 \cdot 10^{-4}$).
f(y) is the transverse distribution of the ships on the navigation lane. This is assumed to be Gaussian with a mean value corresponding to the navigation lane centre-line and a standard deviation depending on the ship type and distance to shore, shallow water or a wind farm.
c is the distance from the turbine perpendicular to the navigation lane.
D is the turbine foundation diameter.
W_{ship} is the width of the ship, increased by a factor of 1.2 as stated above, for the ship class under evaluation.

From the formula it is seen that the calculation is performed for each lane, ship type and ship size class because the width of the ships vary with type and size class. For further details see the description given in Appendix A.

For the navigation lanes containing bends an extra contribution occurs. At the bend there is a probability ($3.0 \cdot 10^{-4}$) that the ship will not turn but keep sailing in the same direction. In case the ship does not turn at the bend it is assumed that the error is detected after 20 minutes. This means that if an obstacle is located more than 20 minutes away from the bend the probability for a collision is zero. See also the description given in Appendix A.

7.1.2 Drifting ships

Failure of the propulsion system will make the ship start to drift. A ship with no steering speed will start drifting side ways and can cause a side-way collision with a turbine. The drift angle with the wind may deviate from 90 degrees for ships with large super structures at one end, such as tankers, but as a conservative assumption 90 degrees is used.

The probability of collision due to failure of the propulsion machinery will depend on the number of propulsion machinery units in the ship. In general one propulsion machinery is assumed, but for the ferries and ro/ro vessels, which have between 2 and 4 sets of propulsion machineries, the failure rate is different. The failure rate for the ferries and ro/ro vessels is estimated to be $1.34 \cdot 10^{-5}$ failure per hour whereas the failure rate for the other ships is around $2.5 \cdot 10^{-4}$. These failure estimates are based on previous work performed by DNV, see ref. /2/ and ref. /3/.

Any ship included in the calculation may drift to the considered wind farm areas. Failure of propulsion machinery can occur at all points along the navigation lane and the calculation must therefore be carried out by integration over the whole length of the navigation lane. In practice this is done by dividing the length into pieces and adding the different contributions together.

The contribution for a piece of length d_i of the navigation lane is given by the formula

$$F_{Drift} = N \cdot f_{fop} \cdot \frac{d_i}{v_{ship}} \cdot \frac{\theta_i}{360} \cdot W_{drift} \cdot \sum_{Wind\ class} P_{wind\ class,i} (1 - P_{repair,i}) \cdot (1 - P_{anchor,i}) \quad \text{where}$$

- N is the number of ships on the lane for the specific ship class per year.
- P_{Anchor} is the probability that the ship will drop anchor and stop the ship. This probability depends on the weather conditions and the seabed conditions.
- f_{fop} is the frequency for failure of the propulsion machinery per hour. This frequency depends on the ship type.
- d is the length of the considered part of the navigation lane.
- v_{ship} is the velocity of the cruising ship.

- θ is the angle space (sector) where the sideways drifting ship will collide with the turbine. At the turbine this corresponds to a length equal to the ship length plus the turbine foundation diameter. This is conservative as ships do not generally drift completely sideways.
- W_{drift} is the probability for the specific drift direction relative to a uniform drift direction.
- P_{wind_class} is the probability for the given wind class.
- P_{repair} is the probability that the ship will repair the propulsion machinery and stop drifting. This is a function of the drift duration (distance and drift velocity). The drift velocity is assumed to be between 0.9 to 3.6 knot depending on the wind conditions.

Control of a drifting ship can also be re-gained through the use of one or more tugs of sufficient performance. The effect of possibly available sea-going tugs within the calculation has not yet been included in the risk analysis, though MARCS is capable of modelling the effect of tugs on drifting collisions. However, due to the environmental conditions in the North Sea, rescue activities with tugs are very difficult and this is therefore neglected as a conservative approach.

The drift duration is here governed by the self repair time. The drift duration is assumed to follow the formula

$$f(t) = \frac{1}{1.5(t-0.25)+1} \quad \text{for } t > 0.25 \text{ and for } t < 0.25 \; f(t) = 1$$

Below the wind classes are given together with the probability of anchoring. The sea bed is assumed to correspond to the type mud, which yields large probabilities for anchoring. These probabilities are derived from DNV rules regarding the performance of anchoring systems onboard ship, coupled with expert judgement, which indicates that the probability of a save in wind force 10 should be 95% and 5% for soft and rocky sea bottom, respectively.

The weather conditions can be quite severe in the North Sea, but on the other hand the water depth and sea bottom conditions are ideal for anchoring.

	Wind Class			
	Calm	Fresh	Gale	Storm
Probability of wind class	0.815	0.139	0.040	0.006
Probability of anchoring for mud sea bottom	0.99	0.93	0.79	0.37

Table 7-1: Probability for the different wind classes (see also Section 3.3) and probability for successful anchoring.

Table 7-2 gives the values used for mechanical breakdown frequencies and the assumed cruising speed for the different ship types. The values are taken from the SAFECO research project, ref. /2/ and /3/.

Ship type	Break down frequencies			Cruising speed
	0 – 10000 DWT	10000 – 50000 DWT	> 50000 DWT	
Tankers	$2.5\cdot10^{-4}$	$2.5\cdot10^{-4}$	$2.5\cdot10^{-4}$	12 knots
Chemical Tankers	$2.5\cdot10^{-4}$	$2.5\cdot10^{-4}$	$2.5\cdot10^{-4}$	12 knots
Others	$2.5\cdot10^{-4}$	$2.5\cdot10^{-4}$	$2.5\cdot10^{-4}$	12 knots
Ferries / ro-ro	$1.34\cdot10^{-5}$	$1.34\cdot10^{-5}$	$1.34\cdot10^{-5}$	16 knots

Table 7-2: Mechanical breakdown frequencies per hour and cruising speeds.

For further details for the drifting ship scenario see the description given in Appendix A.

7.1.3 Ship – ship collision

The collision frequency is calculated by first determining the encounter (meeting) frequency and then applying a probability of collision given an encounter. The encounter frequency at a location is calculated as

$$F(\text{encounter}) = d_1\, d_2\, U\, A\, \Delta$$

where d_i are the ships densities for lane 1 and 2 (in ships per square nautical mile), U is the relative velocity between the lanes (in knots), A is the area of the location (in nautical miles^2) and Δ is ship interaction distance (how close must the ships be to register as an encounter in nautical miles).

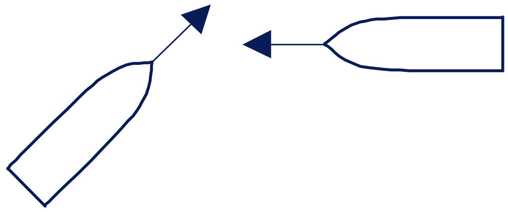

Figure 7-3: Encounter situation that may lead to ship – ship collision.

The probability of a collision given an encounter between lanes 1 and 2 for defined local conditions is obtained from fault tree analysis similar to the fault tree given in Figure 7-1. This probability takes the visibility and degree of internal vigilance into account. The collision frequency is then calculated as:

$$F(\text{ship-ship collision}) = P(\text{collision} \mid \text{encounter}) \cdot F(\text{encounter})$$

The above collision frequency is then calculated for all areas in the evaluated area and for all combinations of all the navigation routes.

8 CALCULATED COLLISION FREQUENCIES

In the present chapter the calculated collision frequencies for the considered wind farm areas are given. The frequencies cover all serious accident consequences, where a serious accident is one that requires that the ship has to be repaired before it can continue to trade. Hence the consequences that result from a portion of the calculated collision frequencies are minor.

Moreover, both the construction and operation phase are considered for both locations.

8.1 Installation phase

The evaluated results for the installation phase are more uncertain than the results from the operation phase. This is due to the fact that the traffic pattern during installation will be more random. However, based on the estimated annual amount of ship traffic related to the installation phase and the assumption that a restricted navigation channel from Esbjerg to the wind farm location will be used the ship – ship collision frequency is evaluated.

Moreover, it is assumed that ship – turbine collisions are not possible because no wind turbines are erected yet. This is not completely true, but it is evaluated that the ship – ship collision frequency is much larger and the contribution from ship – turbine collisions can therefore be ignored. The ship – ship collisions are calculated for the navigation route shown in Figure 6-6.

Since the sailing distance to the two wind farm locations are almost the same and the number of installation vessels will be independent of the locations the risk related to the construction phase will be very similar for the two locations. The results are given in Table 8-1.

Location	**“Syd”**	**“Nord”**
Annual frequency	$1.72 \cdot 10^{-2}$	$1.58 \cdot 10^{-2}$
Return period	58	63

Table 8-1: Ship –ship collision frequency for the two considered locations related to the installation phase.

The reasonably large frequencies are mainly due to the fact that the route through Slugen that “crosses” the reef is very narrow and the ships in meeting situations will therefore have limited space to operate in.

Because it is assumed that other vessels will be kept out of the navigation channel to the construction site, all ship - ship collisions will be between installation vessels.

8.2 Operation phase - North location

In the case the wind farm is erected in the north location, the total collision frequency is evaluated to be $4.3 \cdot 10^{-3}$ per year corresponding to a return period of 232 years. The table below gives the collision frequency for the different scenarios.

Scenario	Human failure	Drifting ships	Total collision
Annual frequency	$1.2 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$4.3 \cdot 10^{-3}$
Return period	820	320	230

Table 8-2: Total annual collision frequencies for the North location.

In the following sections the above results are given in more details.

8.2.1 Human failure scenario – North location

The annual collision frequency for the human failure scenario ($1.2 \cdot 10^{-3}$) is shown below for the different ship types and navigation routes.

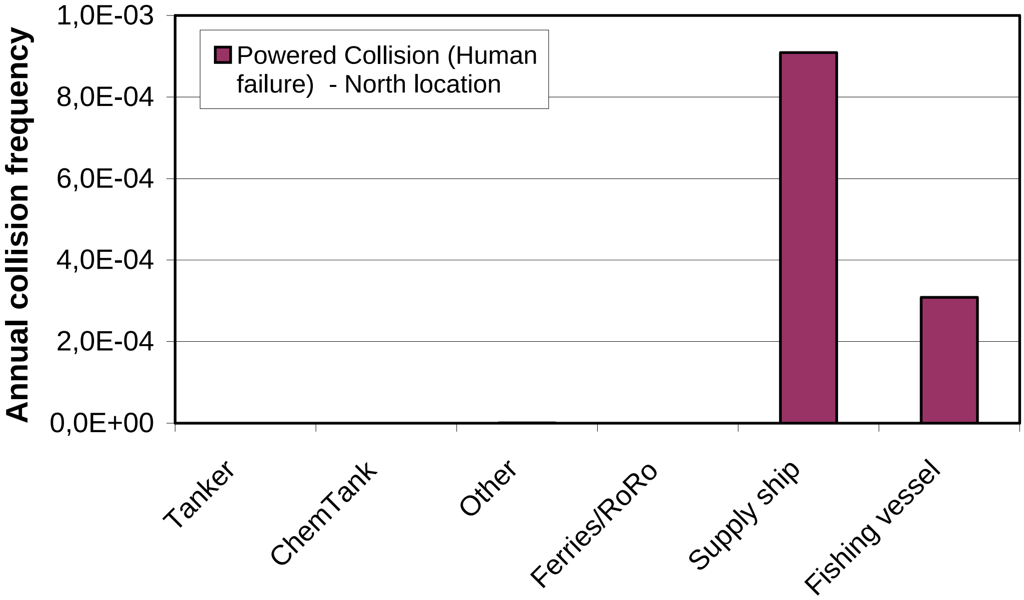

Figure 8-1: Annual collision frequency for human failure scenario divided on ship types.

From Figure 8-1 it is seen that the main risk contribution is from supply and fishing vessels, and the traffic type “Other” also gives a small but noticeable contribution. This is because the north – south going traffic is located so far to the west of the wind farm area that the contribution from other traffic types (tankers, chemical tankers and roro/ ferries) becomes very limited.

The main contribution is from route 6 because this is the only route that passes very close to the wind farm. The route is assumed to have a way-points 1 nm south of the wind farm.

8.2.2 Drifting ships scenario – North location

The drifting ship scenario is evaluated to be $3.1 \cdot 10^{-3}$ accidents per year, corresponding to a return period of about 320 years. Figure 8-2 shows the collision frequency for drifting ships divided on ship type. The largest contributions is from the ship type “Other” (which contains general cargo, bulk and container vessels etc.) with about 74%, while the contribution from “Tanker” and “Chemical tanker” is about 8% and 7%, respectively.

The drifting ships are mainly governed by ships travelling west of the wind farm because the governing wind direction is in the range southwest to northwest. Moreover the main part of the ship traffic is located in this area.

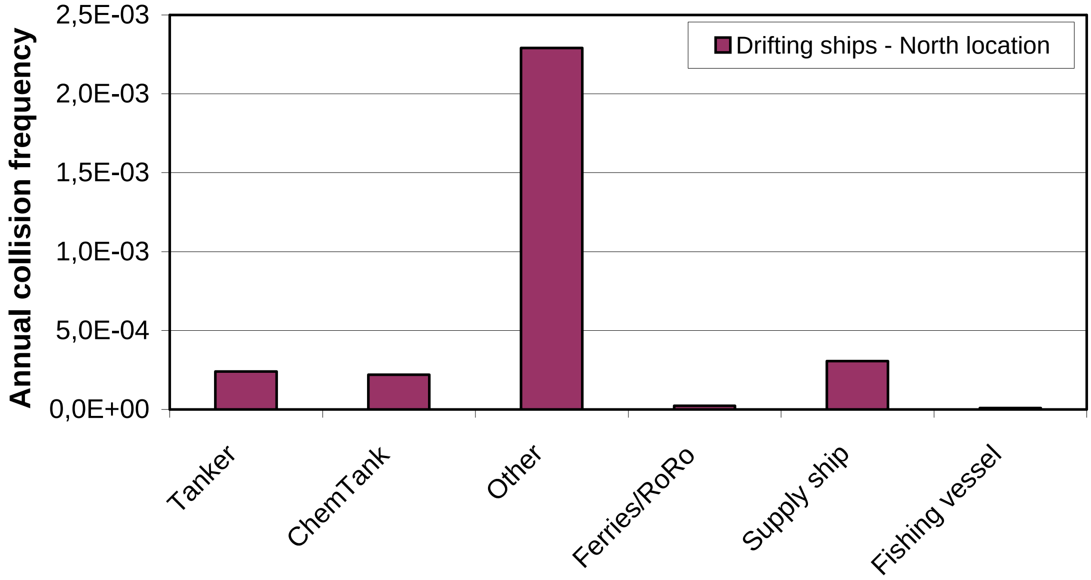

Figure 8-2: North location: Annual ship – turbine collision frequency divided on ship types, drifting ship scenario.

Figure 8-3 shows the collision frequency for drifting ships divided on navigation routes. From the figure it is seen that the largest contributions is from route 4 passing just west of the wind farm. The large contribution is due to the large traffic intensity and the short distance to the wind farm.

The second largest contribution is seen from route 12. This is mainly due to the large traffic intensity on this route. The drift duration for this route will often be large and in many cases risk reduction actions such as tugs can be initiated if the weather permits it.

Possible risk reduction actions as tugs are not included and the collision frequency is therefore conservative.

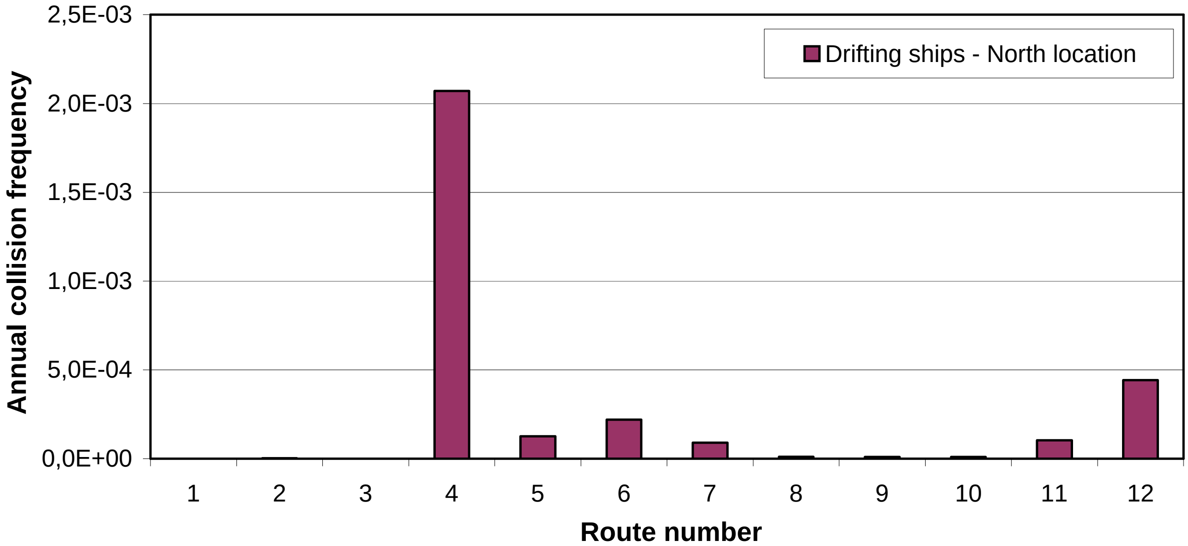

Figure 8-3: North location: Annual ship – turbine collision frequency divided on navigation routes, drifting ship scenario.

It must be emphasised that the calculated collision frequencies presented cover all types of collisions from minor scratches or dents to major damage to the ship and/or the turbine. Moreover the impact energy from a sideways collision (drifting ship scenario) will normally be lower than from a head on bow collision (human failure scenario) due to the lower impact velocity and the consequences will therefore usually be smaller. However, regarding environmental impact it can be argued that a head on bow collision rarely will lead to release of bunker oil or cargo, because bunker oil or cargo tanks never are located in the front of the ship.

8.3 Operation phase - South location

For the case where the wind farm is erected in the south location the total collision frequency is evaluated to be $1.2 \cdot 10^{-2}$ per year corresponding to a return period of 84 years. The table below gives the collision frequency for the different scenarios.

Scenario	Human failure	Drifting ships	Total collision
Annual frequency	$7.1 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$
Return period	140	205	84

Table 8-3: Total annual collision frequencies for the south location.

In the following sections the above results are given in more details.

8.3.1 Human failure scenario – South location

The annual collision frequency for the human failure scenario ($7.1 \cdot 10^{-3}$) is shown below for the different ship types and navigation routes.

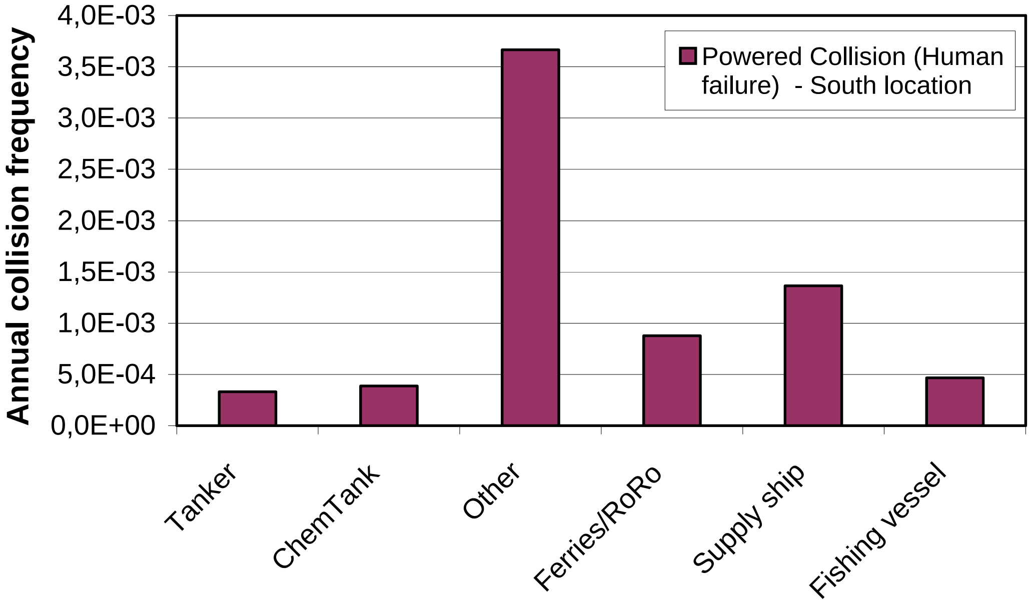

Figure 8-4: South location: Annual collision frequency for human failure scenario divided on ship types.

From Figure 8-4 it is seen that largest frequency contribution is again from the traffic type "Other", which contains general cargo, bulk and container vessels etc. but contributions are also seen from the other traffic types. This is because the south location is located further to the west than the north location and is therefore closer to the main traffic routes.

In Figure 8-5 the collision frequency divided on navigation routes is shown.

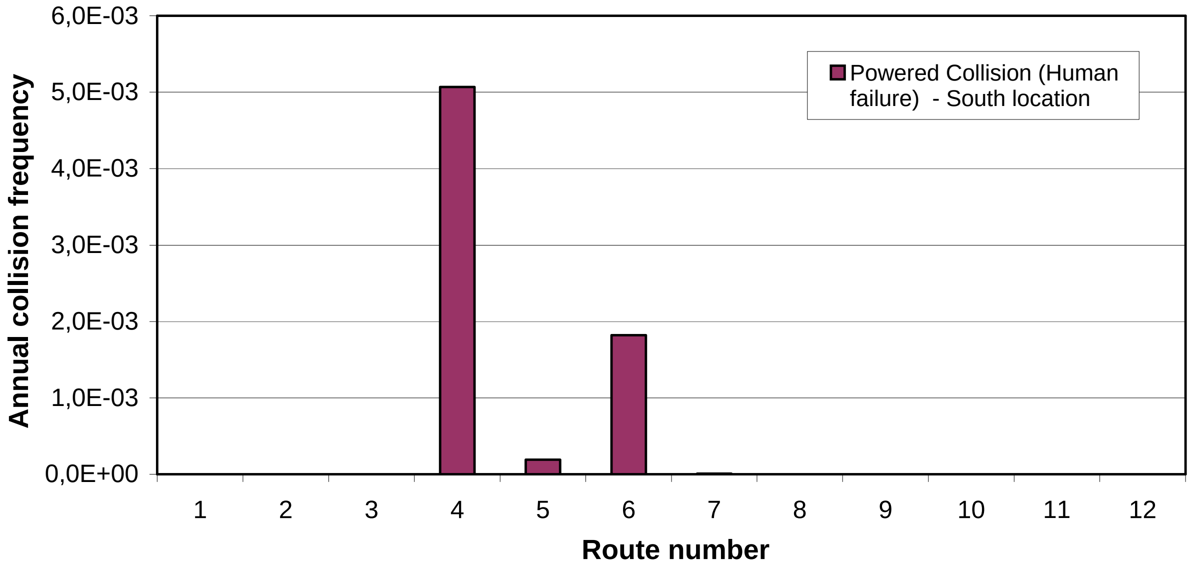

Figure 8-5: South location: Annual collision frequency for human failure scenario divided on routes.

The main contribution is from route 4 due to the large traffic intensity on this route, but also route 6 has a significant contribution because it has a way-point 1 nm south of the wind farm.

8.3.2 Drifting ships scenario – South location

The drifting ship scenario is evaluated to be $4.9 \cdot 10^{-3}$ accidents per year, corresponding to a return period of about 205 years. Figure 8-6 shows the collision frequency for drifting ships divided on ship type. The largest contributions is from the ship type “Other” with about 69%, while the contribution from “Supply ships” is about 16% and “Tanker” and “Chemical tanker” is about 8% and 7%, respectively.

The drifting ships are mainly governed by ships travelling west of the wind farm because the governing wind direction is westerly. Moreover the main part of the ship traffic is located west of the wind farm.

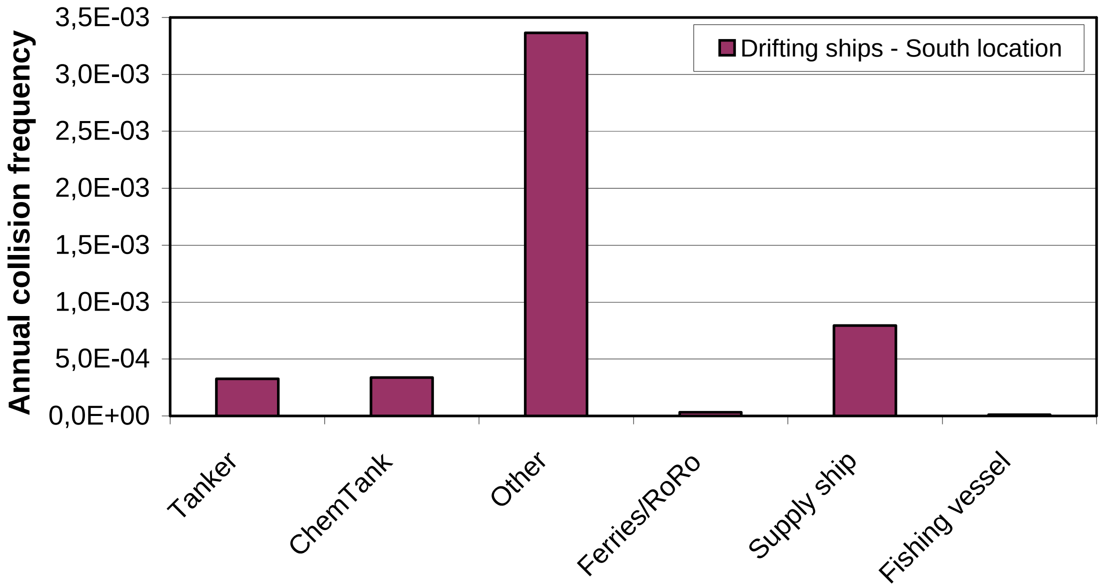

Figure 8-6: South location: Annual ship – turbine collision frequency divided on ship types, drifting ship scenario.

Figure 8-7 shows the collision frequency for drifting ships divided on navigation routes. From the figure it is seen that the largest contributions is from route 4 passing just west of the wind farm. The large contribution is due to the large traffic intensity and because the shortest distance is 1 nm to the wind farm.

The second largest contribution is seen from route 6. This is mainly due to the short distance and because the wind farm has the largest dimension in the direction parallel to the route. Finally a large contribution is seen from route 12, which is due to the large traffic intensity. However, as mentioned earlier the drift duration for this route will be large and in many cases risk reduction actions such as tugs can be initiated if the weather permits it.

The obtained frequencies are therefore conservative because possible risk reduction from tugs is not included.

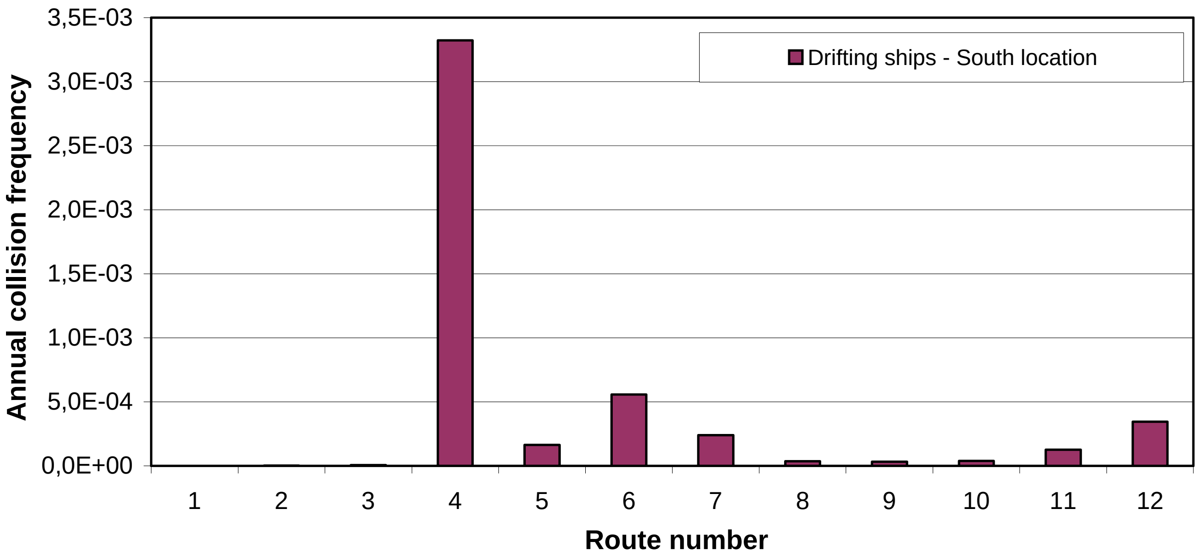

Figure 8-7: South location: Annual ship – turbine collision frequency divided on navigation routes, drifting ship scenario.

It must again be emphasised that the calculated collision frequencies presented cover serious collisions, were the ship must be repaired. However the consequences can still be modest.

8.3.3 Ship – ship collision

In order to evaluate the obtained collision frequencies the total ship – ship collision frequency for the ships in the area is estimated so they can be compared. Route 12 is excluded in the calculation because it is located far from the considered area.

The total ship –ship collision frequency for all ships in the area covering approximately 80×95 km around Horns Rev is evaluated to $2.5 \cdot 10^{-2}$ per year, corresponding to a return period of 40 years.

Compared to the obtained ship – turbine collision frequencies, it is seen that the risk for a ship – ship collision in the area is significantly higher. However, this is of course also due to the fact that ship – ship collisions can occur all over the considered area included in the model where as ship – turbine collisions only can occur in the wind farm area.

8.4 Summary of collision frequencies

The evaluated collision frequencies for the two locations and the construction and operation phase is summarised in the following. Table 8-4 gives the collision frequencies and the corresponding return period for the operation phase.

Annual frequency	Human failure	Drifting ships	Total collision
"Nord" location	$1.2 \cdot 10^{-3}$ / 820	$3.1 \cdot 10^{-3}$ / 320	$4.3 \cdot 10^{-3}$ / 230
"Syd" location	$7.1 \cdot 10^{-3}$ / 140	$4.9 \cdot 10^{-3}$ / 205	$1.2 \cdot 10^{-2}$ / 84

Table 8-4: Annual collision frequencies and corresponding return period for the two locations in the operation case.

From the found return periods given in Table 8-4 for a ship – turbine collision for the two considered wind farm locations it is seen that the north location is the best with respect to navigational safety. This is mainly because it is located more east than the tip of Horns Rev, which forces the ship traffic to the west.

For the installation phase the frequency for a ship – ship collision between the construction vessels have been evaluated. It is found that annual collision frequency is around $1.7 \bullet 10^{-2}$ corresponding to a return period of 60 years. This number is very uncertain and will very much depend on how the construction vessels are handled and controlled.

Moreover, as a comparison the return period for a ship – ship collision in the area around Horns Rev with an approximately size of 80 km x 95 km is evaluated. The return period for a ship – ship collision in the area is found to 40 years. Compared to the obtained ship – turbine collision frequencies, it is seen that the risk for a ship – ship collision in the area is significant higher then the risk contribution from the wind farm.

It should be noted that the present report does not deal with the consequences related to a ship – turbine collision. The consequences will be more uncertain than the estimated frequencies and they will depend on whether the focus is on human safety or environmental impact. However, as noted previously, the consequences of the collisions will in the main part be very limited; based on statistical data for ship collisions in Danish waters it is seen that oil spill occur in less than 1 in every 10 collisions. The collision frequencies are therefore acceptable to our opinion.

9 VERIFICATION OF COLLISION FREQUENCIES

In the present chapter a rough verification of the obtained collision frequencies is made based on data about ship collisions in the period 1993 to 2002 (10 years). The data is based an extract from a database handled by the Danish Maritime Authority and information given in "Accidents at Sea" from the Danish Maritime Authority, ref. /4/.

The ship accidents for commercial ships close to the considered area in the North Sea are given in Table 9-1. Note that groundings are excluded.

Date	Ship type	Tonnage	Location	Accident and cause
6/12-1994	Bulkcarrier	778	55°44N, 06°45E	Shifted cargo / Extreme weather
19/10-1994	Bulkcarrier	997	55°26N, 06°55E	Capsizing / Unknown
13/12-1996	Container vessel	7676	55°07N, 05°09E	Engine breakdown / Error in ship construction
27/7-1997	Bulkcarrier	1655	55°55N, 07°50E	List / Cargo not secured
27/4-1998	Bulkcarrier	491	55°24N, 07°10E	Engine breakdown / Technical failure
5/2-1999	Bulkcarrier	415	55°10N, 07°40E	Capsizing / Extreme weather
6/5-2000	Ro-Ro	17068	55°25N, 08°10E	Collision / Human error
2/3-2001	Dredger	473	55°23N, 08°04E	Collision / Human error

Table 9-1: Ship accidents in the North Sea.

Is should be noted that more than 80% of the accidents in the North Sea are related to fishing vessels. The typical cause for fishing vessels are collision or grounding, but fire and leakage are also common causes. This indicates than the maintenance of fishing vessels is not always as good as it should be. However, the fishing activity has decreased and is decreasing so the influence from fishing vessels are of limited importance.

The locations of the accidents shown in Table 9-1 are illustrated in Figure 9-1. It is seen that most of the incidents are related to ships passing in and out of the approach to Esbjerg harbour or ships travelling west of Horns Rev.

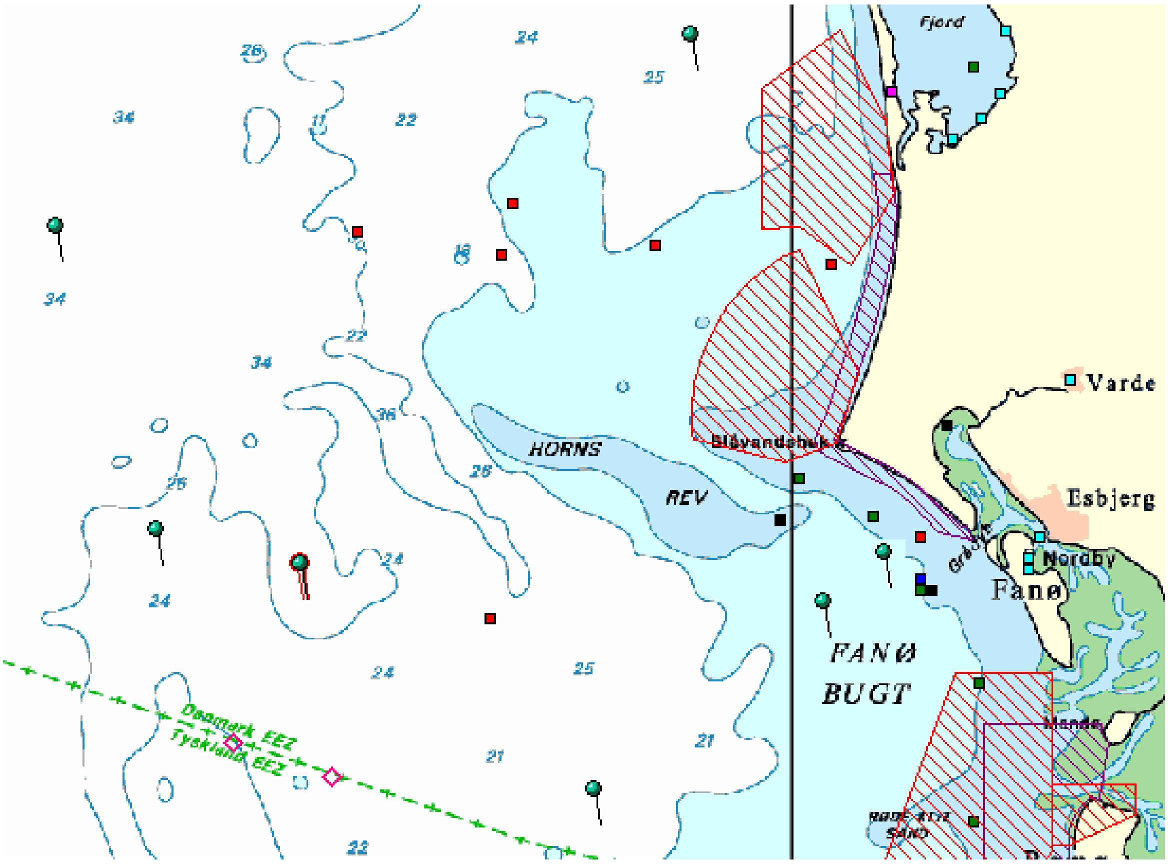

Figure 9-1: Accidents shown in Table 9-1 are marked with green pins except for accident no. 3 which is located further to the west.

A general comparison between the above events seen in the North Sea and the estimated ship – turbine collision frequency is difficult. However, it is seen that the events occur and in most case where the navigational routes are assumed to be. Further more it is seen that no events have occurred in the considered wind farm area in the 10 years period the data covers. Based on this a return period around 100 to 200 years seems reasonable.

10 WIND FARM EFFECT ON RADAR AND COMMUNICATION SYSTEMS

The influence from a wind farm on marine radar and navigation and communication systems have been investigated in connection with the North Hoyle wind farm in UK on behalf of Maritime and Coastguard Agency (MCA), ref. /23/. The main conclusions of the study is given below and based on the results of the study the impact from Horns Rev 2 on ship radar and communication systems is evaluated.

The conclusion in the study is that GPS (Global Positioning System) and Magnetic compasses are not affected by the wind turbines. Moreover, it is concluded that the wind farm structures has no noticeable effects on any voice communications systems, vessel to vessel or vessel to shore station. These include shipborne, shorebased and hand held VHF transceivers and mobile telephones.

Regarding radar coverage two main cases has been studied. The first case is small vessel radar performance, where small vessel is a lifeboat within the wind farm close to a turbine and the observing ship is up to 1.5 nm from the wind farm. The conclusion is here that the wind turbines produce blind and shadow areas in which other turbines and vessels cannot be detected unless the observing vessel is moving. However, in normal situations the ships will be moving and the problem is therefore reduced.

A larger vessel was easily detected within and beyond the wind farm. However, while it was broadside on to the direction of the shore radar, reflections from the turbines produced strong multiple echoes.

The overall conclusion with respect to radar is that for ships travelling close to and on several sides of the wind farm there is a concern about the use of radar as an effective aid to both vessel and mark detection and, consequently, for ship-to-ship collision avoidance.

10.1 Effect from Horns Rev 2 on radar

The Horns Rev 2 wind farm are located north of Horns Rev. No ships will cross the reef due to the limited water depth and no ships passes therefore close by on the east side of the wind farm, see Figure 10-1.

Moreover, the “Nord” location of the wind farm is located more to the East than the tip of the reef and the north-south going traffic is thus forced away from the wind farm. A meeting situation between ships on route 4 and 6 will in this case take place more than 5 nm from the wind farm and it is therefore evaluated that radar interference from the turbines will be negligible.

The “Syd” location is located more to the west than the “Nord” location and both north-south and east-west going traffic will pass close to the wind farm (route 4 and 6 in Figure 10-1). According to the study carried out on behalf of MCA there is a possibility of blind areas or false echoes in this case. However, as seen from Figure 4-3 the turbines are placed in a curved pattern so the visibility and effect on radar is probably minor compared to the study at the North Hoyle wind farm where the turbines are placed in a square with 90 degree corners. Moreover, the ship traffic intensity south of the Horns Rev 2 wind farm (route 6) is low and the probability for a critical meeting situation is thus limited. Finally the ships on route 6 are mainly minor ships, which will be more manoeuvrable than e.g. large oil tankers where long response time is necessary.

However, if the “Syd” location is chosen it might be considered to study the radar interference from the turbines in more detail in order to clarify whether there is an increased ship-ship collision risk or not.

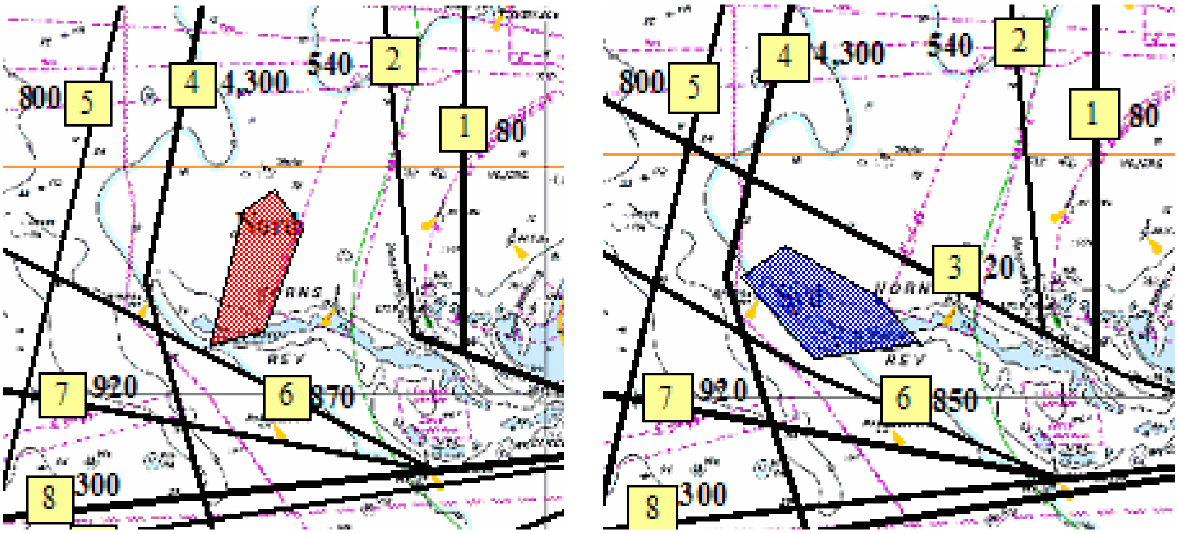

Figure 10-1: Navigation route in the proximity of Horns Rev 2 “Nord” and “Syd” location.

11 RISK REDUCTION MEASURES

Different construction and operational measures that can decrease the estimated risk are provided in this section. A discussion of whether or not the different risk reduction measures should be implemented must be based on an ALARP (As Low As Reasonable Practical) approach, for example based on a cost – benefit analysis.

Only risk reduction measures related to the wind farm is included. It should be noted that other measures through e.g. IMO, the national authorities etc. continuously is implemented in order to increase the navigational safety. This is measures as Electronic Chart Display System (ECDIS), out phasing of single hull tankers and ensuring of emergency capacity and special emergency locations. Such risk reduction measures are not included here.

11.1 Risk reduction measures for wind farms

Below is given some possible risk reductions measures that can be carried out for the wind farm:

1. Establishment of an international shipping exclusion zone covering 500 m outside the wind farm clearly marked on sea maps and in navigational handbooks.
2. Lights to mark the presence of the wind farm, as required by the different authorities covering sea and air traffic.
3. Establishment of a radio channel to the control centre of the wind farm, which is permanently manned and located on land.
4. Marking the wind farm by buoys that indicate the international shipping exclusion zone.
5. Installation of racon beacons or AIS on some of the wind turbines located at the corner of the wind farms to enhance the radar image on the ship's bridge.
6. Installation of an automatic system to alert the wind farm control centre is an unidentified ship is approaching the wind farm.
7. Establishing a manned vessel traffic service, which will contact all ships approaching the wind farm area.
8. Establishing a standby vessel, this also will be able to handle minor oil spill in case of a collision.
9. Establishing of emergency tug(s) of sufficient power to recover drifting ships before they collide with the wind turbines.

Points 9 are a measure which also is handled on a governmental and international level. This is for example through the HELCOM Copenhagen Declaration from 10 September 2001, where the governments of the contracting parties are obliged to give high priority to their national capacity building for oil and chemical accidents at sea and their emergency towing capabilities.

A detailed ALARP evaluation has not been carried out for the above risk reducing measures. However, based on previous knowledge and engineering judgement a rough estimate is that bullet numbers 1 to 3 should be carried out, bullets 4 to 6 might be carried out, whereas bullets 7 to 10 are too expensive compared to the benefit they supply.

It could be argued the item 6 is of no use because you can only see e.g. a drifting ship on collision course, but cannot stop it anyway. However, the information will assure that the turbine can be stopped. This will decrease the wind load and thus increase the probability for absorbing the collision load in case of a minor collision.

In the report "Risk Analysis of Navigational Safety in Danish Waters", ref. /22/ the risk reduction related to some of the measures is given. The given risk reduction factors are uncertain, but it is certain that the effect is positive.

The risk reduction factors given in ref. /22/ and shown in Table 11-1 are estimated for year 2008.

Risk reduction measure	Risk reduction factor
VTS system without guard vessel	0.45
AIS	0.82

Table 11-1: Effect of the risk reduction measures taken from ref. /22/, Table 7.13.

It should be noted that the above risk reduction factors are not included in the present analysis. Moreover, the factors are valid only if the existing traffic pattern (annual frequency, ship type, ship size and route locations) does not change. However, due to increased economic growth the ship traffic will increases in the future probably both in number and in ship size. The size is though mainly governed by the harbour sizes and capacity and since the life time of the wind farm is only 25 years and the increase will not be significant.

The effect of the above risk reduction measures on the total risk level will therefore depend on the amount of risk reduction introduced compared to the traffic increase.

12 REFERENCES

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13 APPENDIX A: INTRODUCTION TO MARCS

13.1 Overview

The Marine Accident Risk Calculation System (MARCS) was developed by DNV to support our marine risk management consultancy business. The MARCS model provides a general framework for the performance of marine risk calculations. A block diagram of the model is shown in Figure 13-1.

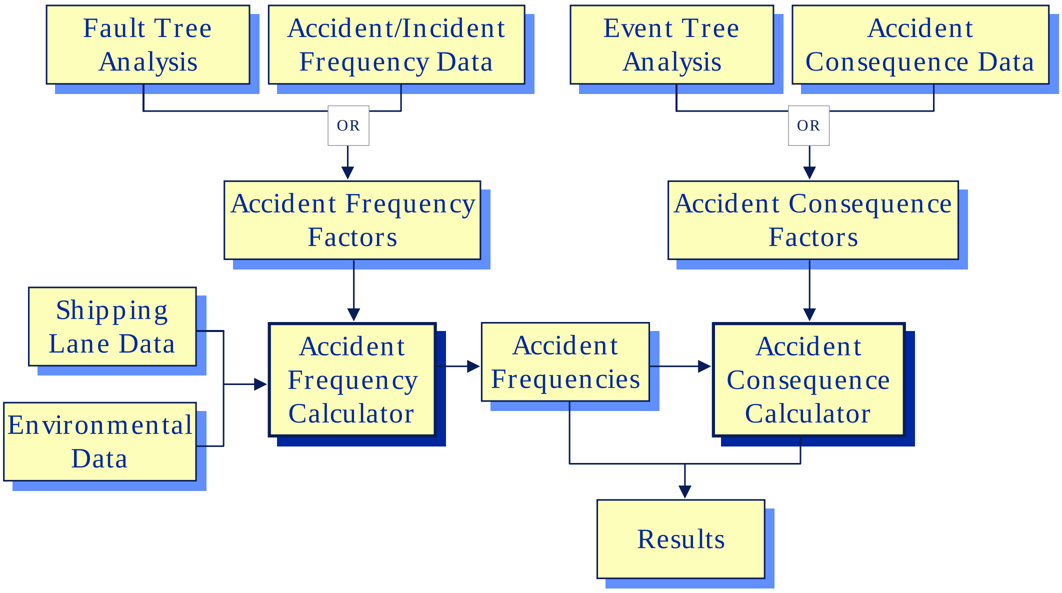

Figure 13-1: Block Diagram of MARCS

The MARCS model classifies data into 4 main types:

- Shipping lane data describes the movements of different marine traffic types within the study area;
- Environment data describes the conditions within the calculation area, including the location of geographical features (land, offshore structures etc) and meteorological data (visibility, wind rose, currents and sea state);
- Internal operational data describes operational procedures and equipment installed onboard ship – such data can affect both accident frequency and accident consequence factors;
- External operational data describes factors external to the ship that can affect ship safety, such as VTMS (Vessel Traffic Management Systems), TSS (Traffic Separation Schemes), and the location and performance of emergency tugs – such data can affect both accident frequency and accident consequence factors.

As indicated in Figure 13-1, accident frequency and consequence factors can be derived in two ways. If a coarse assessment of accident risk is required, the factors may be taken from worldwide historical accident data. Alternatively, if a more detailed study is required, these factors may be derived from generic fault trees or event trees which have been modified to take account of specific local factors.

13.2 Critical Situations

MARCS calculates the accident risk in stages. It first calculates the location dependent frequency of critical situations (the number of situations which could result in an accident –"potential accidents" – at a location per year; a location is defined as a small part of the study area, in this case about 1/8 nautical mile square, but depending on the chosen calculation resolution). The definition of a critical situation varies with the accident mode. MARCS then assesses the location dependent frequency of serious accidents for each accident mode via "probability of an accident given a critical situation" parameters. A "serious accident" is defined by Lloyds as any accident where repairs must be made before the ship can continue to trade. Finally, the location dependent accident consequence, and hence risk, is assessed.

13.3 Data used by MARCS

13.3.1 Traffic Image Data

The marine traffic image data used by MARCS is a representation of the actual flows of traffic within the calculation area. Marine traffic data is represented using lane data structures. Different traffic types are divided into separate marine databases in order to facilitate data verification and the computation of different types of risk (for example, crude oil spill risk versus human safety). A typical traffic lane is shown in Figure 13-2. The following data items are defined for all lanes:

1. The lane number (a unique identifier used as a label for the lane);
2. The lane width distribution function (Gaussian, truncated Gaussian or uniform);
3. The lane directionality (one-way or two-way);
4. The annual frequency of ship movements along the lane;
5. A list of waypoints, and an associated lane width parameter at each waypoint;
6. The vessel size distribution on the lane.

Additional data may be attached to the lane, such as: the hull type distribution (single hull, double hull, etc) for tankers; the loading type (full loading, hydrostatic loading) for tankers; ship type etc.

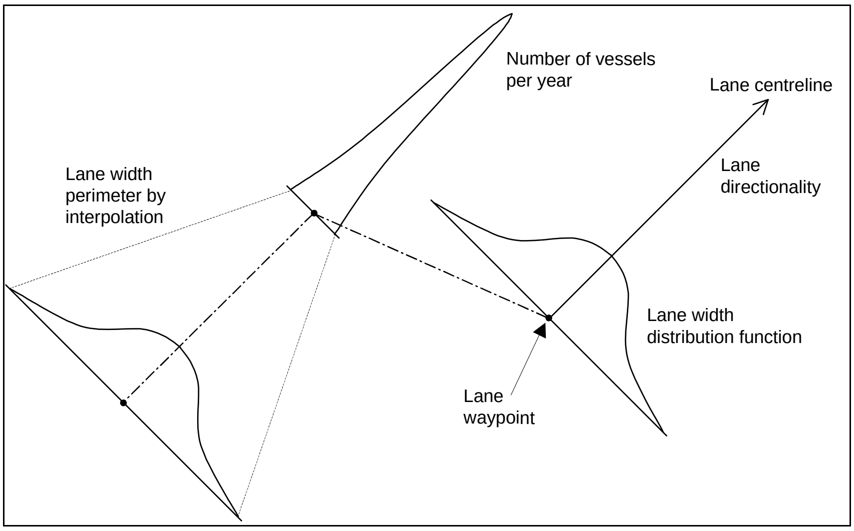

Figure 13-2: Shipping Lane representation used in MARCS

Detailed surveys of marine traffic in UK waters in the mid 1980s (e.g. HMSO, 1985, ref /7/) concluded that commercial shipping follows fairly well defined shipping lanes, as opposed to mainly random tracks of individual ships. Further detailed analysis of the lanes showed that the lateral distribution across the lane width was approximately Gaussian, or truncated Gaussian plus a small part uniform distributed for traffic arriving in coastal waters from long haul voyages (e.g. from the US or Canada). The transverse ship distribution is also investigated in Øresund where the analysis is based on registrations carried out by VTS Drogden, ref. /10/.

The shipping lane distributions used in MARCS are shown in Figure 13-3.

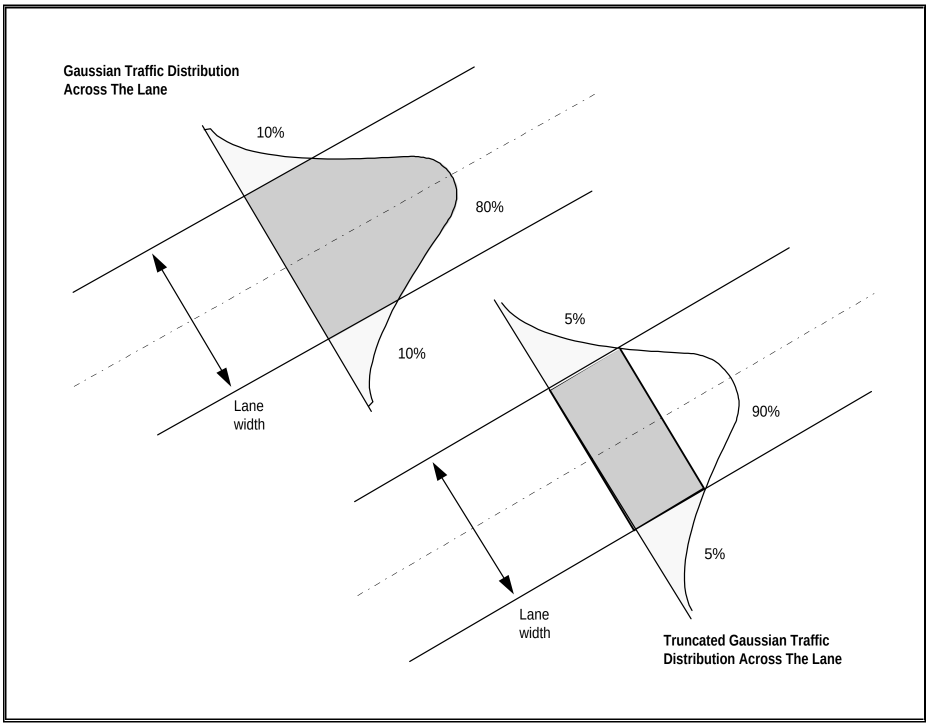

Figure 13-3: Shipping Lane Width Distribution Functions used in MARCS

The marine traffic description used by MARCS is completed by the definition of four additional parameters for each type of traffic:

- Average vessel speed (generally 8 to 18 knots);
- Speed fraction applied to faster and slower than average vessels (generally plus/minus 20%);
- Fraction of vessels travelling faster and slower than the average speed (generally plus/minus 20%);
- Fraction of vessels that exhibit "rogue" behaviour (generally set to 0%, though historical accident data in many geographical areas shows a small proportion of (usually) smaller vessels undergo accidents through lack of watch keeping (bridge personal absent or incapacitated)).

A rogue vessel is defined as one that fails to adhere (fully or partially) to the Collision Avoidance Rules (Cockcroft, 1982, ref. /5/). Such vessels are assumed to represent an enhanced collision hazard. These four parameters can be specified as a function of location within the study area for each traffic type.

The marine traffic image is made up by the superposition of the defined traffic for each contributing traffic type.

13.3.2 Internal Operational Data

Internal operational data is represented within MARCS using either worldwide data or frequency factors obtained from fault tree analysis or location specific survey data. Fault tree parameters take into consideration factors such as crew watch-keeping competence and internal vigilance (where a second crew member, or a monitoring device, checks that the navigating officer is not incapacitated by, for example, a heart attack). Examples of internal operational data include:

- The probability of a collision given an encounter;
- The probability of a powered grounding given a ship’s course is close to the shoreline;
- The frequency (per hour at risk) of fires or explosions.

Internal operational data may be defined for different traffic types and/or the same traffic type on a location specific basis.

13.3.3 External Operational Data

External operational data generally represents controls external to the traffic image, which affect marine risk. In MARCS it relates mainly to the location of VTS zones (which influence the collision and powered grounding frequencies by external vigilance, where external vigilance means that an observer external to the ship may alert the ship to prevent an accident) and the presence and performance of emergency towing vessels (tugs) which can save a ship from drift grounding.

13.3.4 Environment Data

The environment data describes the location of geographical features (land, offshore structures etc.) and meteorological data (visibility, wind rose, sea currents and sea state).

Poor visibility arises when fog, snow, rain or other phenomena restricts visibility to less than 2 nautical miles. It should be noted that night-time is categorised as good visibility unless fog, for example, is present.

Wind rose data is defined within 8 compass points (north, north-east, east etc) in 4 wind speed categories denoted: calm (0 – 20 knots); fresh (20 to 30 knots); gale (30 to 45 knots); and storm (greater than 45 knots). Sea state (wave height) within MARCS is inferred from the wind speed and the nature of the sea area (classified as sheltered, semi-sheltered or open water).

Sea currents are represented as maximum speeds in a defined direction within an area.

13.4 Description of Accident Frequency Models

The section describes how MARCS uses the input data (traffic image, internal operational data, external operational data and environment data) to calculate the frequency of serious accidents in the study area.

13.4.1 The ship – ship Collision Model

The collision model calculates the frequency of serious inter-ship powered collisions at a given geographical location in two stages. The model first estimates the frequency of encounters (critical situations for collision - when two vessels pass within 0.5 nautical miles of each other) from the traffic image data using a pair-wise summation technique, assuming no collision avoiding actions are taken. This enables the calculation of either total encounter frequencies, or encounter frequencies involving specific vessel types.

The model then applies a probability of a collision for each encounter, obtained from fault tree analysis, to give the collision frequency. The collision probability value depends on a number of factors including, for example, the visibility or the presence of a pilot. Figure 13-4 shows a graphical representation of the way in which the collision model operates.

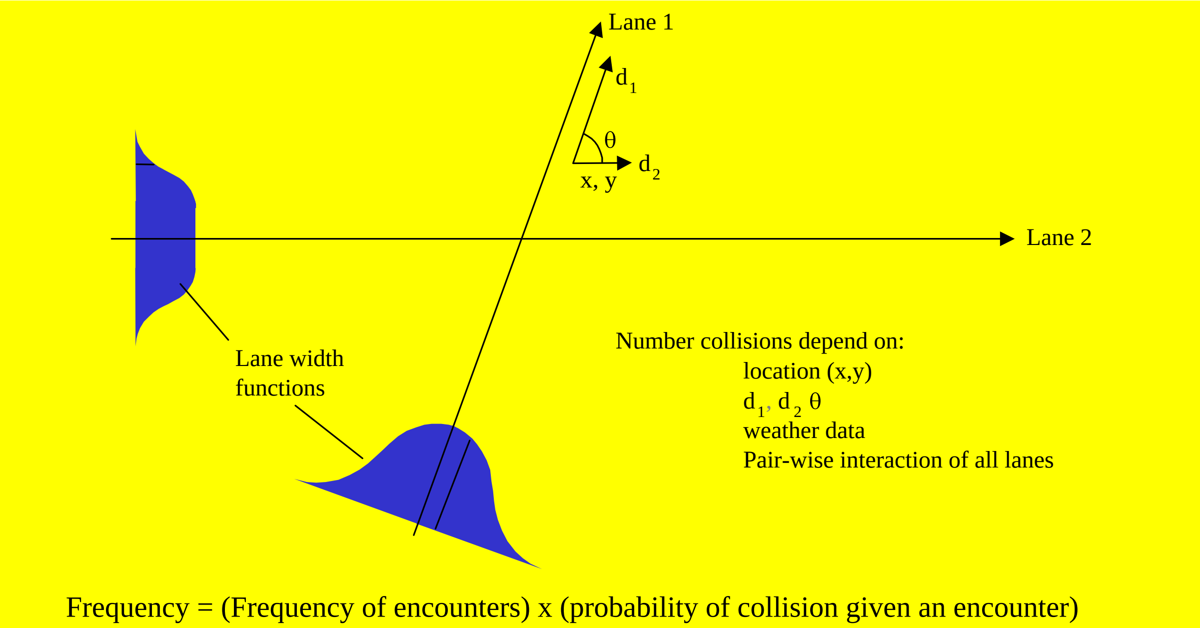

Figure 13-4: Graphical representation of the collision model

In Figure 13-4, d_1 refers to the density of traffic associated with lane 1 at the location x, y. The frequency of encounters at location x, y through the interaction of lanes 1 and 2 is proportional to the product of d_1, d_2 and the relative velocity between the lane densities.

13.4.2 The Powered Grounding Model

The powered grounding frequency model calculates the frequency of serious powered grounding accidents in two stages. The model first calculates the frequency of critical situations (sometimes called "dangerous courses" for powered grounding accidents). A critical situation is defined as a planned course change point (waypoint) located such that failure to make the course change would result in grounding within 20 minutes navigation from the planned course change point if the course change is not made successfully.

The frequency of serious powered groundings is calculated as the frequency of critical course changes multiplied by the probability of failure to make the course change correctly. Figure 13-5 shows a graphical representation of the way in which the powered grounding model operates.

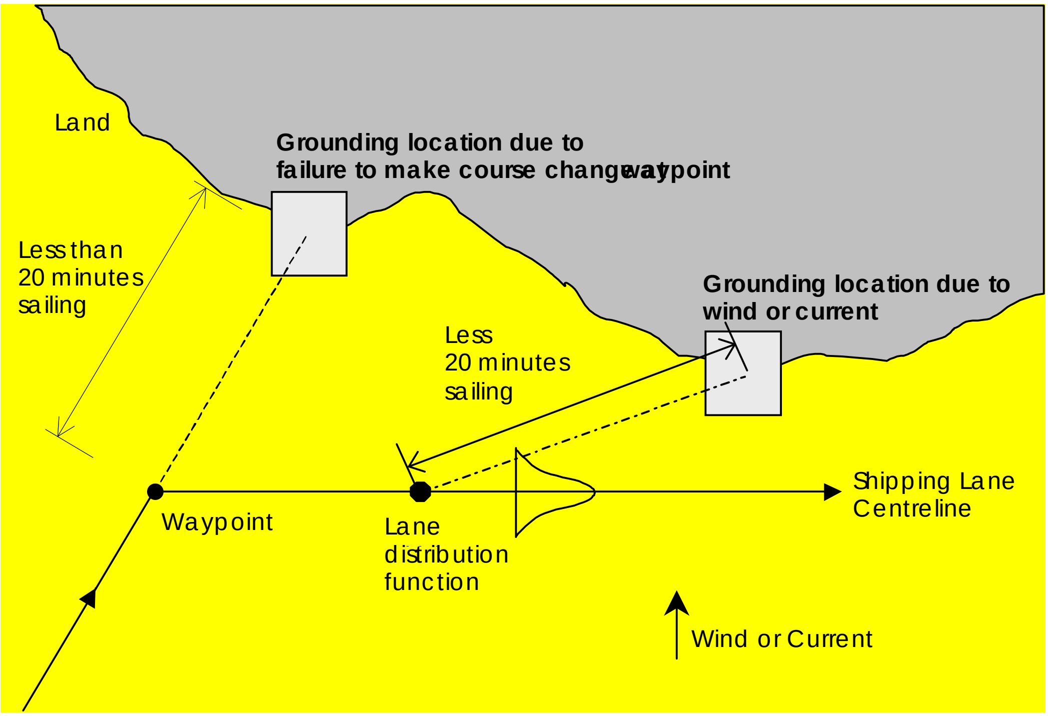

Figure 13-5: Graphical representation of the powered grounding model

The powered grounding parameters are derived from the fault tree analysis of powered grounding. The powered grounding fault tree contains 2 main branches:

- Powered grounding through failure to make a course change whilst on a dangerous course. A dangerous course is defined as one that would ground the vessel within 20 minutes if the course change were not made.
- Powered grounding caused by crew inattention and wind or current from the side when the ship lane runs parallel to a shore within 20 minutes sailing (the frequency of this hazard mode is not assessed in this project).

Both these branches are illustrated in Figure 13-5. The powered grounding frequency model takes account of internal and external vigilance, visibility and the presence of navigational aids (radar) in deducing failure parameters.

13.4.3 The Drift Grounding Model

The drift grounding frequency model consists of two main elements as follows: first, the ship traffic image is combined with the ship breakdown frequency factor to generate the location and frequency of vessel breakdowns; second, the recovery of control of drifting ships can be regained by one of 3 mechanisms: a) repair, b) emergency tow assistance, or c) anchoring. Those drifting ships that are not saved by one of these three mechanisms (and do not drift out into the open sea) contribute to the serious drift grounding accident frequency results.

The number and size distribution of ships which start to drift is determined from the ship breakdown frequency, the annual number of transits along the lane and the size distribution of vessels using the lane. The proportion of drifting vessels which are saved (fail to ground) is determined from the vessel recovery models. The drift grounding frequency model is illustrated in Figure 13-6.

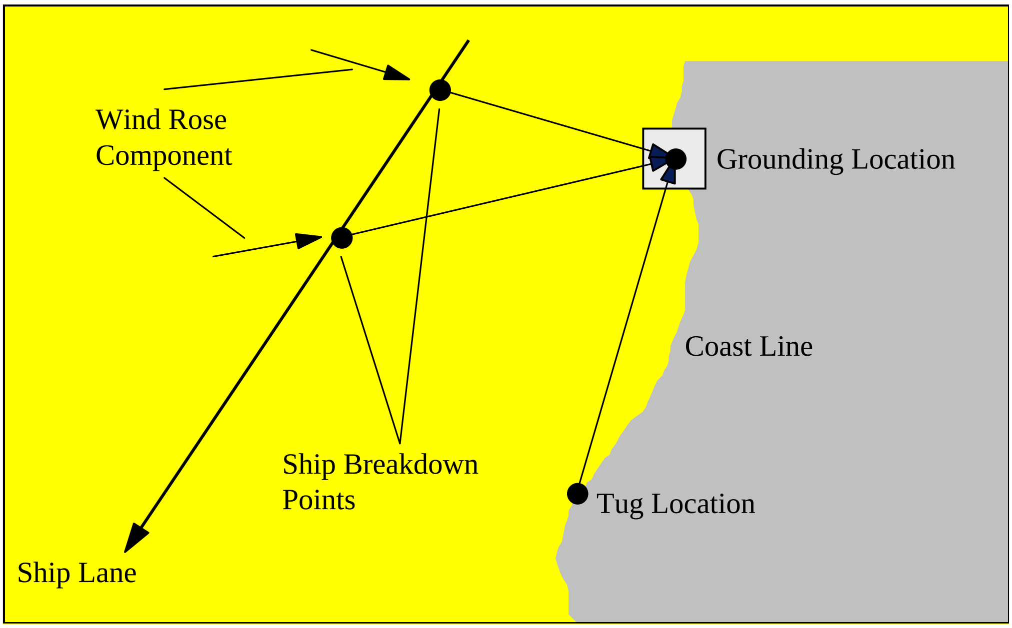

Figure 13-6: Graphical representation of the drift grounding model

Implicit in Figure 13-6 is the importance of the time taken for the ship to drift aground. When this time is large (because the distance to the shore is large and/or because the drift velocity is small) then the probability that the ship will recover control before grounding (via repair or tug assistance) will be increased.

13.5 Repair Recovery Model

Vessels which start to drift may recover control by effecting repairs. For a given vessel breakdown location, grounding location and drift speed there is a characteristic drift time to the grounding point. The proportion of drifting vessels which have recovered control by self-repair is determined from this characteristic drift time and the distribution of repair times.

The graph given in Figure 13-7 is the values agreed in the risk harmonisation group under BSH.

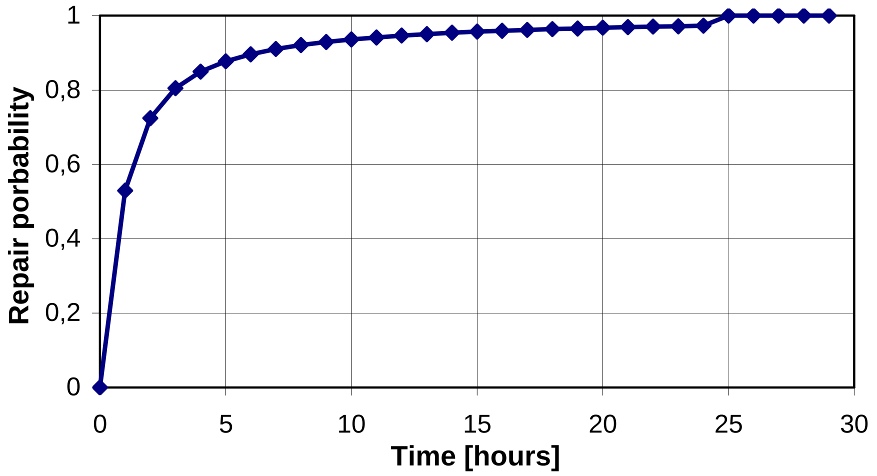

Figure 13-7: Graphical representation of the self repair save mechanism

13.6 Recovery of Control by Emergency Tow

Drifting vessels may be brought under control (saved from grounding or collision) by being taken in tow by an appropriate tug. It should be noted that the tug save model assumes a save is made when the ship is prevented from drifting further towards the shoreline by the attachment of a suitable tug. In practice, two or more tugs would be required to complete the ship save, by towing the vessel to a safe location, but this aspect of the save is not modelled in MARCS.

Two types of tug can be represented within MARCS. Close escort tugs move with ships through their transit, thus their time to reach a drifting ship is always small. Pre-positioned tugs are located at strategic points around the study area. The model works by calculating for each tug:

- If the tug can reach the drifting vessel in time to prevent it grounding. This time consists of the time to reach the ship (almost zero when close escorting) and the time to connect and take control of the ship (which is a function of sea state);
- If the tug can reach the ship before it grounds, then the adequacy of the tug with regard to control of the ship is evaluated. (The presence of several tugs of differing power is assumed to be represented by the presence of one tug of the largest power. This is because only one tug is usually used to exert the main "saving" pull. Other tugs present are used to control the heading of the disabled ship, and to bring the ship to a safe location.)
- When several tugs of various capabilities can reach the drifting ship in time, then the tug with the best performance is assumed to be connected to the ship and takes control of the largest proportion of the drifting vessels.

The tug model contains parameters to take explicit account of:

- The availability of the tug (some tugs have other duties);
- The tugs response time (delay before assistance is summoned);

- The tug speed (as a function of sea state);
- The time to connect a line and exert a controlling influence on the ship (as a function of sea state);
- The performance of the tug (identified as the maximum control tonnage for the tug) as a function of wind speed and location (since the wind speed and the fetch control the sea state).

Tug performance parameters can take account of ship wind and wave resistance, tug wind and wave resistance and tug length and propulsion arrangement (open versus nozzle) which influences the propulsion efficiency.

13.7 Recovery of Control by Anchoring

The anchor save model is derived with reference to the following reasoning:

1. Anchoring is only possible if there is a sufficient length of suitable water to prevent the ship running aground. Suitable water is defined as a depth of between 30 fathoms (about 60m - maximum for deployment of anchor) and 10 fathoms (about 20m - minimum for ship to avoid grounding). Sufficient length is calculated as 100m for anchor to take firm hold of the seabed + 300m to stop ship + 300m for length of ship + 100m for clearance = 800m, or 0.5 nautical miles (to be slightly conservative).
2. If such a track exists, then the probability that the anchor holds is calculated as a function of the wind speed and the sea bottom type (soft sea beds consist predominantly of sands, silts and muds). If the anchor hold, then an anchor save is made.

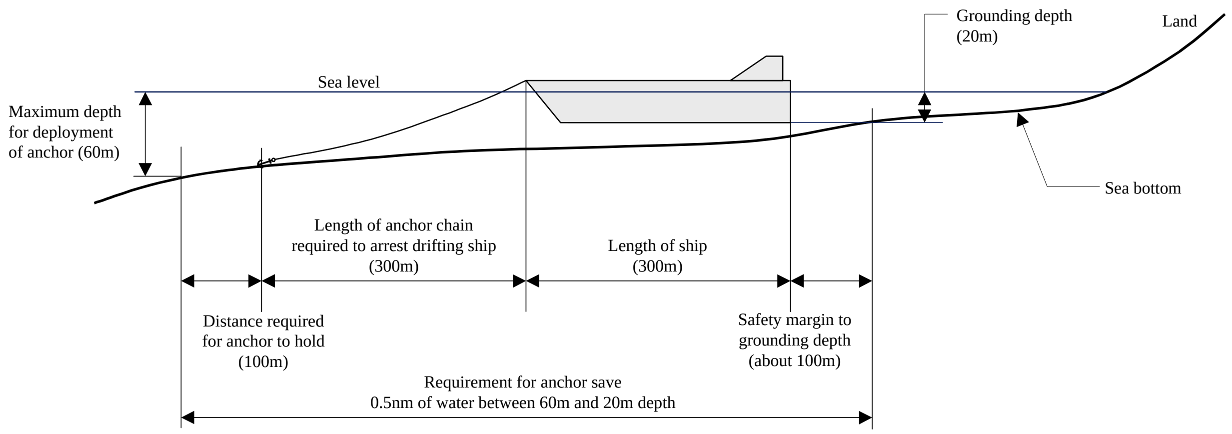

Figure 13-8: Graphical representation of the Anchor save mechanism

The anchor save model is conservative in that it under-predicts the effectiveness of this save mechanism for average and smaller ships.

13.8 Description of Accident Consequence Models

Marine transport risks are estimated by combining the frequencies of serious accidents with the accident consequences, given a serious accident. Marine accident consequences are typically expressed in terms of cargo spilled, lives lost or financial loss.

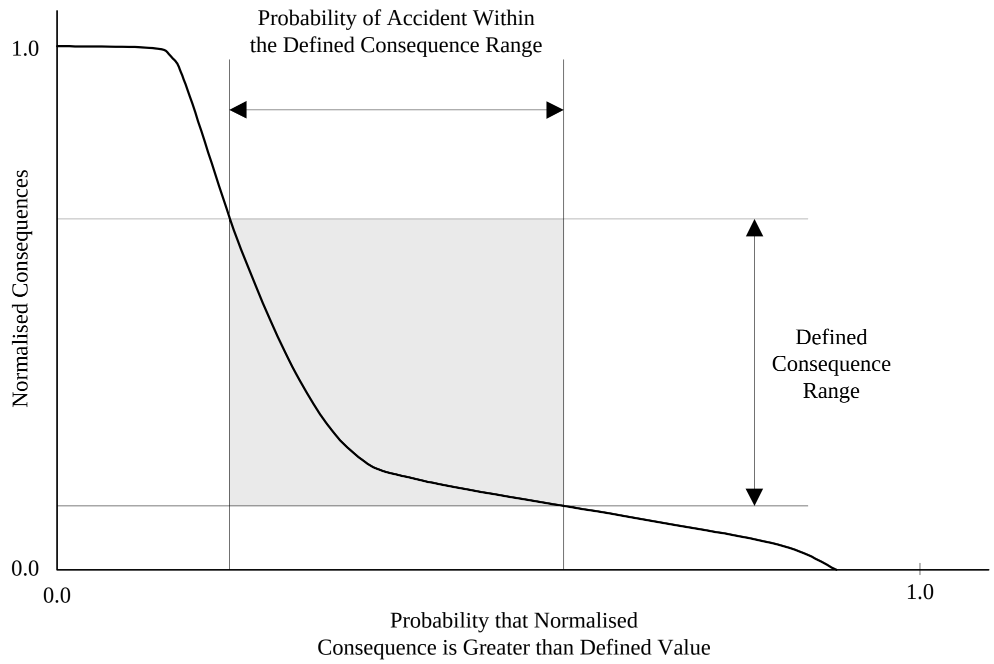

Figure 13-9: Generic Accident Consequence versus Probability Curve

Previous projects performed by DNV have developed crude oil outflow models for different accident types (collision, fire/explosion etc) and different hull configurations (single hull, double hull etc). These models (normalised cumulative probability distributions) take the generic form shown in Figure 13-9. The curve shows the normalised consequence (in terms of, for example, cargo mass outflow into the environment) versus the probability that the consequence is greater than this value. Thus the normalised consequence of 1.0 (equal to total loss of all cargo carried) occurs for relatively low probabilities, whereas the probability that the normalised consequence is greater than a small fraction of the cargo carried generally approaches 1.0 for single hulled ships.

13.9 Marine Accident Risk Acceptance Criteria, Targets and Benchmarks

In general, responsible operators define their objective as zero accidents. However a risk assessment that estimates zero risk from an operation is not credible. The objective of risk management is, therefore, to ensure that estimated risk levels for an operation are acceptable (by comparison to risk acceptance criteria or through cost-benefit analysis). Where risks are not acceptable, additional risk reduction measures are introduced to reduce the risks to acceptable levels.

Marine accidents result in losses/impacts in 3 main areas:

- Human fatalities;
- Environmental impacts due to cargo or fuel oil release;
- Financial impacts.

It would be convenient if established criteria existed to judge the acceptability of the risks posed by a specific operation or trade. However, at the present time there are no established, generally accepted criteria which can be used to judge if calculated marine risk levels are acceptable. This statement is especially true for accidents involving the release of cargo into the marine environment.

In order to address this lack of criteria, risk analysts within DNV have proposed risk acceptance criteria for application in the marine industry. It is important to emphasise that, at this stage, the criteria quoted below are neither official DNV criteria nor are they recognised by regulatory bodies. Individual human fatality criteria are given in Table 14.1.

Risk Acceptance Criteria	**Value**
Maximum tolerable risk for crew members	1 fatality per thousand at risk per year
Maximum tolerable risk for ship passengers	1 fatality per ten thousand at risk per year
Maximum tolerable risk for public ashore	1 fatality per ten thousand at risk per year

Table 13-1: Proposed Individual Human Fatality Risk Acceptance Criteria for the Shipping Industry (Spouge, 1997, ref. /9/; DNV 1999, ref /6/)

The criteria shown in Table 13-1 are closely related to the HSE individual risk criteria (HSE 99, ref. /8/), which in turn are based upon observed fatality rates in a number of industries in the UK.

Table 13-2 shows total loss and oil spill targets proposed by DNV for the shipping industry. It should be noted that DNV do not consider it is essential to meet these targets, but if they are not met it may indicate that cost-effective risk reduction measures may be available.

Risk Targets	**Value**
Target total ship loss frequency	2 losses per thousand ship-years
Target cargo spill risk	20 tonnes per million tonnes transported
Target bunker oil spill risk	20 tonnes per million tonnes consumed

Table 13-2: Proposed Total Loss, Cargo Spill and Bunker Spill Targets for the Shipping Industry (DNV, 1999, ref. /6/)

The targets shown in Table 13-2 are based on an analysis of the worldwide shipping fleet and accident data between 1981 and 1997. They may be seen as desirable “stretch targets” based on observed accident statistics, which show an average of 70 tonnes of cargo split per million tonnes transported. There are significant uncertainties in both the cargo/bunker pollution statistics and total cargo transportation tonnage. The pollution targets shown in Table 13-2 should, therefore, be regarded as preliminary at this stage.

The risk targets shown in Table 13-2 are derived from marine accident data, which is sometimes under-reported. Marine risk assessment uses conservative accident models, which tend to over-predict risk levels. Thus comparison of the risk targets shown in Table 13-2 with risk assessment results can give mis-leading results. For this reason, DNV often compare calculated risk levels with "risk benchmarks" (risks calculated in other areas). This comparison of "like with like" is thought to provide a better interpretation of risk results.

13.10 Risk Analysis, Assessment and Management

The process of estimating the frequency of accidents and the range of potential accident consequences (using MARCS, other quantitative methods or qualitatively) is called risk analysis. When combined with the evaluation of the significance of risk results the process is called risk assessment. In general, risk assessment entails finding robust answers to questions such as:

- Are the risks acceptable?
- What can be done to reduce the risks further?
- Are risk reduction measures cost effective?

Clearly the answers to these questions are related. For example, higher risks may be acceptable if there are no more cost-effective risk reduction measures to be applied.

The acceptability of risks can be determined by reference to risk acceptance criteria (such as those proposed in Section II.6 above), other risk targets or benchmarks, expert judgement or the ALARP (As Low As Reasonably Practicable) principle. Risk acceptance criteria are defined in some areas of risk assessment by regulators (mainly human fatality risk). Such criteria are often derived by expert judgement assessment of suitable benchmarks. For example, the UK Health and Safety Executive have set a maximum tolerable individual human fatality risk criteria for workers of less than 10^{-3} fatalities per year. This criterion is similar to fatality frequencies observed in the more dangerous UK industries, such as construction and mining.

When regulators have not set specific risk acceptance criteria, as is generally the case for risks to the environment, the acceptability of risks can be argued on the basis that other operations (benchmarks) with comparable or higher risks are accepted by regulators on behalf of society. Alternatively, or in addition, a thorough assessment of alternative risk reduction measures on risk levels could be used to argue a risk level is ALARP and hence acceptable. Such an analysis may be supported by a formal (quantitative) cost benefit analysis, which may show that implementing further risk reduction measures is disproportionately expensive compared with the risk reduction achieved.

Risk management is the process of using risk analysis, risk assessment and other inputs to maintain risk levels within bounds which are acceptable to the operator and their stakeholders.

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