Methodology for Assessing Risks to Ship Traffic from Offshore Wind Farms

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VINDPILOT-Report to Vattenfall AB and Swedish Energy Agency

SSPA Sweden AB

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REPORT

Subject	Report
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This report summarise the findings of a research project funded by Vattenfall and the Swedish Energy Agency and conducted by SSPA Sweden AB. The project addresses methodologies for risk assessment concerning navigational risks to ship traffic from offshore wind farms and aims to develop a consistent and conclusive approach for risk based decision making.

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SUMMARY

As the number of offshore wind farms continues to grow, it becomes apparent that there is a need for comprehensive assessment guidelines and recommendations to ensure safe maritime operations and to protect the marine environment. Risk analyses for estimation of the risks associated with wind farm establishment and for the identification of relevant risk reduction measures have been conducted for many projects but the results are sometimes difficult to assess and compare because different methodologies are used and because there is a lack of established evaluation criteria. In some countries, governmental agencies and other organisations have tried to establish harmonised risk assessment methods and formulate guidelines for the performance of risk analysis of offshore wind farms and their potential impact on maritime safety. Geographical, environmental and navigational conditions as well as the permit process differs in different countries and regions and the wind power industry as well as the competent authorities in Sweden have identified a need to investigate the current international state-of-the-art and to develop and establish relevant guidelines to be applied for offshore wind park projects in the waters around Sweden.

SSPA Sweden AB has extensive experience of maritime and navigational risk assessment including a large number of navigational risk assessments for offshore wind farms for various Swedish wind energy companies. In 2005, Vattenfall AB applied for and was granted financial support of 40% from the Swedish Energy Agency and commissioned SSPA to conduct the present study. The remaining 60% is funded by Vattenfall. In addition, some of the material presented in this report has been developed in cooperation with SSPA internal research projects.

The objectives of this study were to provide recommendations for a methodology for assessing risks resulting from ship navigation in the vicinity of offshore wind farms, where Kriegers flak would serve as a reference for comparing and evaluating selected techniques. Methodology used includes collection and review of literature and published material on wind farm risk assessment, comparative studies on collision risk models, and regulatory guidelines; information collection and discussion through email and telephone contact with international experts on offshore wind farms; consultation and discussion with the project reference group; case study analysis to assess and compare collision probability methods for assessing risks of wind farm / ship collisions.

Conclusions and recommendations in general regarding risk assessment methodology and in detail regarding calculation models are presented and discussed below.

It is important that the calculation models are transparent. The intention with the model developed by SSPA (see Appendix) is that all information about the model should be explicitly stated. This includes the model structure as well as the input data. The structure of the SSPA calculation model is similar to other models used for wind farms and offshore platforms. However, there are models using simulations (e.g. Monte Carlo simulations) but in the SSPA model no simulations are used since these make the model less transparent. It is questionable whether simulations give more accurate results of a risk analysis. The SSPA model is designed to be simple and transparent, which gives a good prerequisite for explaining the physics behind the model.

A German harmonisation process has laid a basis for a common harmonised set of parameters which should be used in risk calculations. However, one should be attentive to that the process has a set of models as a basis and there may be recommendations that are valid only for these models and can therefore not be used commonly. Harmonisation processes such as the German one also requires transparency in order to give recommendations about for example input data. Harmonisation can be a natural step to take when the models are presented in detail. However, as shown in chapter 2, the conditions in the different EU-member states vary a lot and each country may identify and prioritise various safety aspects differently, and total harmonisation may be difficult. The pilot site for this project, Kriegers Flak, may serve as an illustration of the need for harmonisation and bilateral/international assessment discussions.

If several wind farms are planned in the area, cumulative effects on the risk should be studied. This may require cooperation between different countries. One example is the proposed Swedish and German parks at Kriegers Flak that are close neighbours, but are processed separately without consideration of cumulative effects, while other more distant wind farms on the German side are considered from an interaction point of view with Kriegers Flak.

Collision frequency models are in general sensitive to changes of certain assumptions. They also contain an amount of uncertainties. Calculated results in absolute terms should therefore be carefully interpreted. One way of doing this is to make relative comparisons instead of using absolute values of acceptance criteria. If acceptance criteria should be used, it should be stated for which type of calculation model and with which input data these criteria are valid. One important relative comparison is a zero-alternative discussion where the navigational risk in a specific area is compared quantitatively with and without the presence of the wind park. Comparative studies of the calculated collision frequency of different traffic lanes can also be applied in order to identify which ones that stands for the largest contribution.

The aim for the SSPA model is to be as clear as possible concerning sensitivity/ uncertainty. This openness makes the SSPA model more useful and shows the way to improvements of the model. It has for example become obvious during the progress of this research project that the function describing the probability that the crew onboard is not able to react in time to correct the navigational error (onboard crew reaction) needs to be further investigated together with the causation factor. One way of doing this would be possible if the processing of recorded AIS-data could be further developed.

Another way of relating the results of a risk assessment/analysis is to put it in an economic context. Cost-benefit analysis is not included in this research project but could be an interesting task for future projects.

Example of risk reduction measures are presented in this report. Measures that are associated with low economic costs should always be considered even if the estimated risk is low. If the estimated risk is high, also more expensive measures must be considered.

Accident preparedness includes various safety measures but should also be linked to a control program. One of the objectives with establishing and follow a control program is that the risk and safety issues will be continuously checked and updated during the whole life time of the wind farm.

ACKNOWLEDGEMENTS

This project has been conducted within the "Vindpilot" framework for support of technical development and market introduction of wind power energy production in Sweden. The Vindpilot programme is based on a government decision and the financial support is administered by the Swedish Energy Agency. Large scale offshore wind farms and wind energy projects located in the northern fjeld regions are specifically addressed by the support programme. Since the start of the programme in 2003 the Energy Agency has supported six large projects and this project, focussing on risk assessment methodology for offshore wind parks with the Kriegers flak park as a demonstration site, is one of the six projects supported.

Sweden Offshore Wind AB, a daughter company to Vattenfall AB, is planning to build 128 wind turbines on Kriegers Flak, about 30 km south of Trelleborg. Vattenfall outlined the project on risk assessment methodology in cooperation with SSPA Sweden AB and applied for support from the Vindpilot programme. According to the programme's conditions for support, a 40% grant is supplied from the Energy Agency and the remaining 60% is to be funded by the applicant (Vattenfall). In addition, some of the material presented in this report has been developed in cooperation with SSPA internal research projects (see Johansson (2007) and Johansson et al (Ongoing project)).

The project work started in 2006, when Vattenfall contracted SSPA to prepare and conduct the project work. A project reference group was established and about five meetings were arranged. The reference group provided key input and advice throughout the project. This reference group consisted of the following:

Sven-Åke Blomén, Master Mariner/Senior Administrative Officer at the Swedish Maritime Safety Inspectorate
Fredrik Dahlström, Project Manager at the Swedish Energy Agency
Amelie Gustafsson Fürst, M.Sc. Eng., Consultant Windpower, Vattenfall Power Consultant AB
Mats Hörström, Nautical Administrator at the Swedish Maritime Safety Inspectorate
Anders Lancing, Pilot/Master Mariner/OSC at the Swedish Maritime Administration
Göran Loman, Ph.D., Director, Project Development at Vattenfall
Markus Lundkvist, Ph.D., Risk Analyst at the Swedish Maritime Administration
Thomas Stalin, B.Sc., Director, Project Development at Vattenfall

The participation of the group, through attendance at meetings, and provision of reference material, comments, and valuable insight, is greatly appreciated. The picture below shows some of the members in the project team and in the reference group.

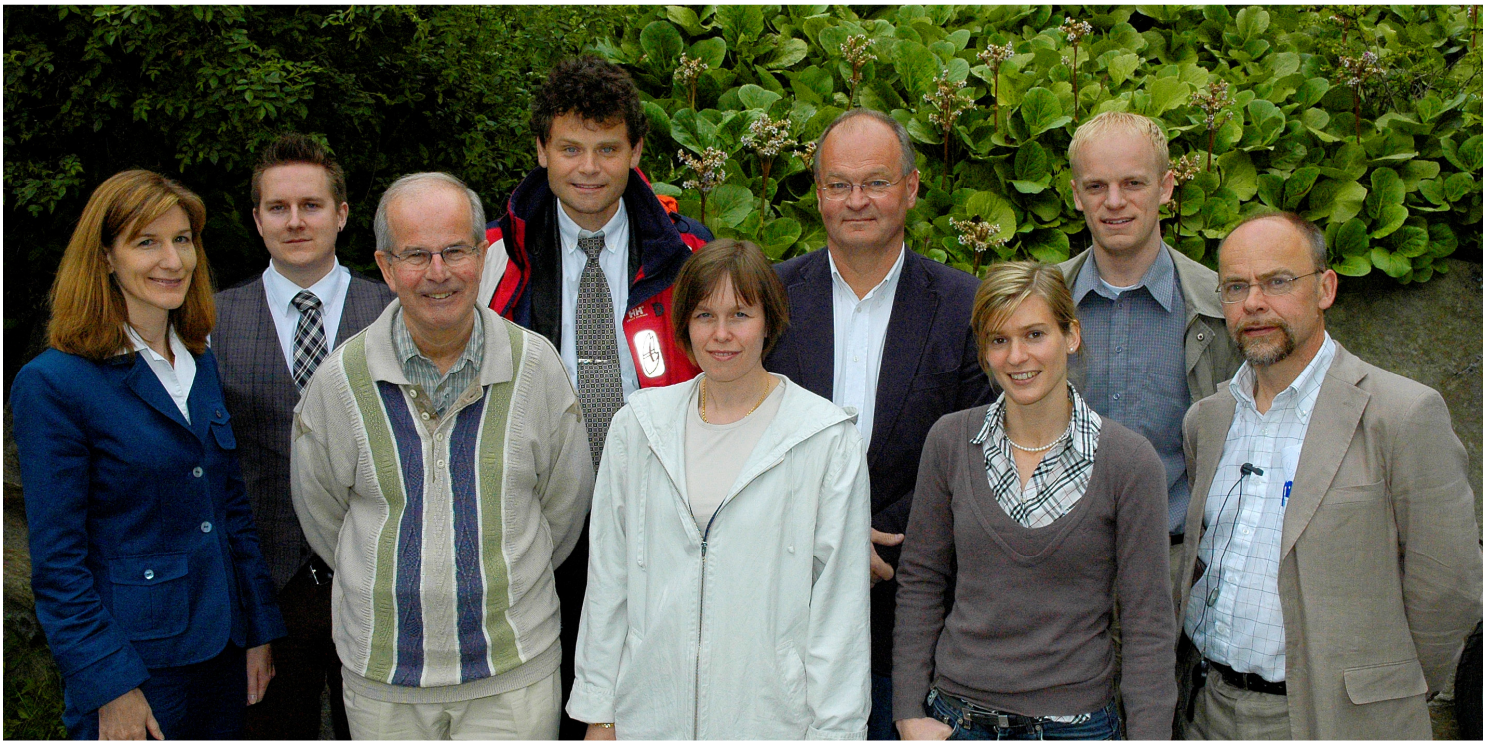


Figure A.1. Picture from reference group meeting June 2nd, 2006.
Back row from the left: Fredrik Dahlström (Swedish Energy Agency), Thomas Stalin (Vattenfall), Jim Sandkvist (SSPA), Markus Lundkvist (Swedish Maritime Administration).
Front row from the left: Joanne Ellis (SSPA), Sven-Åke Blomén (Swedish Maritime Safety Inspectorate), Jessica Johansson(SSPA), Amelie Gustafsson Fürst (Vattenfall), Björn Forsman (SSPA).

1 INTRODUCTION

1.1 Background

Wind energy is currently one of the fastest growing sources of energy worldwide, with annual production increases of about 29% per year in recent years (Earth Policy Institute, 2006). The Vindeby wind farm in Denmark, built in 1991, was the first offshore wind energy facility to be built in the world. As of 2007, seven countries (six in Europe) had operational offshore wind farms (see Appendix for a summary of offshore wind farms). There are also many offshore wind farms under construction and in the planning and permitting process. The size of turbines installed continues to increase – the Beatrice Wind Farm Demonstrator Project in Moray Firth will install two 5 MW turbines in Moray Firth, off the coast of Scotland. These turbines will be installed in 45 m deep water (Talisman Energy, 2004).

As the number of offshore wind farms continues to grow, it becomes apparent that there is a need for comprehensive assessment guidelines and recommendations to ensure safe maritime operations and to protect the marine environment. One of the phases in the permit process for new offshore wind farms is consultation and consideration of the project with the maritime safety authorities. The most important issue for these authorities is the location of the farm, its impact on ship traffic and the potential hazards of ship collisions with the wind turbine structures. Risk analyses for estimation of the risks associated with wind farm establishment and for the identification of relevant risk reduction measures have been conducted for many projects but the results are sometimes difficult to assess and compare because different methodologies are used and because there is a lack of established evaluation criteria.

In some countries, governmental agencies and other organisations have tried to establish harmonised risk assessment methods and formulate guidelines for the performance of risk analysis of offshore wind farms and their potential impact on maritime safety. Geographical, environmental and navigational conditions as well as the permit process differs in different countries and regions and the wind power industry as well as the competent authorities in Sweden have identified a need to investigate the current international state-of-the-art and to develop and establish relevant guidelines to be applied for offshore wind park projects in the waters around Sweden.

SSPA Sweden AB has extensive experience of maritime and navigational risk assessment including a large number of navigational risk assessments for offshore wind farms for various Swedish wind energy companies. In 2005, Vattenfall AB applied for and was granted financial support of 40% from the Swedish Energy Agency and commissioned SSPA to conduct the present study. The remaining 60% is funded by Vattenfall. In addition, some of the material presented in this report has been developed in cooperation with SSPA internal research projects (see Johansson (2007) and Johansson et al (Ongoing project)).

1.2 Scope

The objectives of this study were to provide recommendations for a methodology for assessing risks resulting from ship navigation in the vicinity of offshore wind farms, where Kriegers flak would serve as a reference for comparing and evaluating selected techniques.

The risk components covered in this methodology are related to ship operation in the vicinity of an offshore wind park, and include:

- Ship navigation and probability of an accident or incident:
  current situation, and change in probabilities resulting from the offshore wind farm

- Consequences resulting from ship-related accidents and incidents:
  environmental consequences, consequences to the ship and personnel, third-party consequences

All ship types, including commercial vessels, fishing boats, and pleasure craft will be covered to some extent in this report, although the focus will be on commercial vessels.

Other issues to be addressed in the study include:

- Effects on Search and Rescue operations and effects on oil spill monitoring, surveillance, and response.

- Risk reduction measures.

1.3 Methodology

The research study included the following main components:

- collection and review of literature and published material on wind farm risk assessment, comparative studies on collision risk models, and regulatory guidelines
- information collection and discussion through email and telephone contact with international experts on offshore wind farms
- consultation and discussion with the project reference group
- case study analysis to assess and compare collision probability methods for assessing risks of wind farm / ship collisions

Literature reviewed for the study included navigational risk assessments completed for existing wind parks, published papers, regulatory documents and guidelines, and reports from international research projects.

A case study approach was used as part of the investigation and development of recommendations for collision probability analysis. Data for the Kriegers Flak wind park site was used to undertake a comparison of calculation models used by MARIN and GL. The method used for the case study was to simulate or emulate the two models with SSPA's model as a starting point.

1.4 Risk Assessment

Risk assessment is a process for identifying and analysing undesirable events or results of a process, and determining whether the risks are acceptable. If risks are unacceptable, the process may include recommendations and assessment of risk control measures. The process can include the following steps:

- Description of activity or process
- Hazard identification
- Accident and Incident Scenario generation
- Frequency estimation
- Consequence Estimation
- Risk evaluation

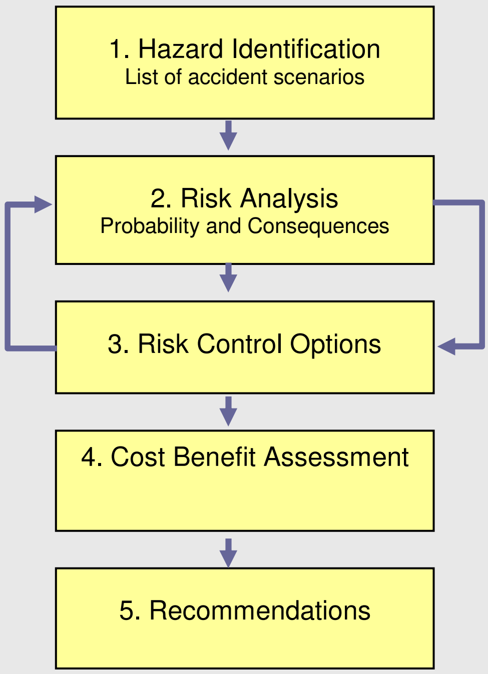
Further steps can include generation of risk control measures, and a repeat of the steps to evaluate the potential risk reduction resulting from implementation of the risk control measures.

In order to make the output of the risk assessment useful for decision making there is also a need for risk acceptance criteria to guide decision makers to be consistent in the permit processes.

Risk assessment is used in many industries, and although the steps are similar, there can be variations to reflect specific industry concerns and focus. The International Maritime Organization (IMO) has developed a specific risk assessment process, which is referred to as a Formal Safety Assessment, to be used in the IMO rule-making process. Guidelines for this process were approved by the Maritime Safety Committee and the Marine Environmental Protection Committee in 2001 and 2002 (IMO, 2002). The IMO describes the FSA as “a rational and systematic process for assessing the risks related to maritime safety and the protection of the marine environment and for evaluation the costs and benefits of IMO’s options for reducing these risks”. The steps of FSA are briefly summarised in the following figure.

What is FSA?

Formal Safety Assessment, FSA is a proactive process introduced by the IMO (International Maritime Organization) to be used as a tool in the rulemaking process – it is "*one way of ensuring that action is taken before a disaster occurs*". The FSA preferably addresses a specific category of ships or navigational area but may also be applied to a specific maritime safety issue to identify cost effective risk reduction options. The FSA process includes five basic steps:



More information on the FSA process:
Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process (MSC/Circ.1023 -MEPC/Circ.392)

Figure 1.1. Formal Safety Assessment Procedure

There are a number of tools for carrying out the “risk analysis” step of a risk assessment or safety assessment procedure. Tools that have been commonly used as part of marine risk assessments include:

- Fault tree analysis
- Event tree analysis
- Bayesian network analysis

Fault tree and event tree analysis are two of the main methods for researching factors and causes contributing to accidental events. The event tree method focuses on events that occur after some critical event, such as “loss of power (black out)” while the fault tree method examines all events leading up to the critical event. The event tree is an ‘inductive’ type of analysis, while the fault tree is a ‘deductive’ type of analysis. Event tree analyses are helpful for analysing mitigating measures that can help reduce the consequences of some critical occurrence. Fault tree analyses are concerned with investigating underlying causes that result in accidental events such as “loss of power”. Bayesian network analysis involves constructing a graphical model that shows the probabilistic interdependencies between a set of variables. In the marine industry, Bayesian networks can be used for decision support for maintenance planning and risk-related issues (Friis-Hansen, 2000). Within the Safeship project, a Bayesian net was developed for calculation of collision probabilities of ships with wind farms (Germanischer Lloyd et al., 2005). This was constructed to help serve as the basis for assessing the risk reduction possibilities of AIS and VTM.

2 REVIEW OF CURRENT METHODS/GUIDELINES AND STATE OF THE ART

2.1 National Guidelines

This chapter presents a review of guidelines in use in other jurisdictions and methodologies recently used to conduct navigational risk assessments for offshore wind farms. All information is based on publications or personal contact with individuals involved with guidelines or projects. The review includes a summary of the guidelines used or process followed in all countries where offshore wind farms have been constructed as of 2007 (except Japan, which has one small offshore installation consisting of 2 individual turbines installed inside a breakwater). A number of other countries where offshore wind farms are in the planning stages have also been included, particularly those countries where navigational risk assessments have been carried out as part of the planning process.

2.1.1 Belgium

Belgium currently has one offshore wind farm under construction - Thornton Bank. The first phase of this wind farm is expected to become operational in 2008. A risk assessment was performed by Germanischer Lloyd (GL) (Neuhaus and Thrun, 2003) as part of the approvals process. This assessment followed the GL guidelines published in 2002 (see section 2.1.5 for a description of the GL guidelines). There are currently two new projects planned within the near future for Belgium, and the risk assessments will be based on the state-of-the-art of other risk assessments in Europe (Di Marcantonio, 2007).

2.1.2 Canada

In Canada, there are currently no offshore wind farms that have been constructed or in operation. There are, however, a substantial number of wind farm installations on land and on shorelines at a variety of locations across Canada. There is currently an offshore wind development in the planning stages in British Columbia, on the west coast of Canada. The NaiKun wind development is currently in the process of conducting an environmental assessment review, which will include information on navigation and marine safety (Pottinger Gaherty, 2007). There are no specific Canadian guidelines for conducting a navigational risk assessment.

2.1.3 Denmark

Denmark currently (in 2007) has 8 offshore wind farms in operation (Dansk Vindmølleforening). The Danish Energy Authority is responsible for granting approval for offshore wind energy projects in Denmark and for deciding whether a specific project requires an environmental impact assessment (EIA) (BalticMaster 2007). The Danish procedures for granting approval for offshore wind farms have developed over time as experience has been gained with offshore wind farms. The Danish Energy Authority screens potential wind farm locations at sea to assess suitability of locations. The screening process includes consultation with the general public and concerned authorities with regards to environmental conditions and concerns, navigational safety, and aesthetic/landscape related concerns. The tender process incorporates results of the screening, through requirements for tenderers for the EIA process and for specific location and design requirements (Danish Energy Authority 2005).

The navigational risk assessment carried out for Rødsand II, a large offshore wind energy development planned for 2010, is an example of the type of navigational safety assessment currently being carried out for developments in Danish waters. The proposed Rødsand II project consists of 92 turbines plus 3 possible test turbines (Christensen 2007). The risk assessment followed the steps in the International Maritime Organization's (IMO's) Formal Safety Assessment process. A hazard identification procedure was carried out to identify the risks. Collision frequencies were evaluated for a number of different scenarios. Automatic Identification Systems (AIS) data for the area was used to identify shipping lanes, ship types, distributions, etc. (Christensen 2007). Ship traffic for the year 2020 was forecast, and scenarios were considered for both current traffic and the traffic levels for 2020. Both powered and drifting collision frequencies were estimated using DNV's MARCS (Marine Accident Risk Calculation System) model. DNV's model is discussed in more detail in Chapter 3.

2.1.4 France

Construction of the Côte d'Albâtre offshore wind farm, the first offshore wind farm in France, is expected to begin in 2008 (Enertrag 2007). The wind energy development will be located 6 to 11 km off the coast of Normandy, and will consist of 21 turbines of 5 MW capacity each. The Côte d'Albâtre development is the first offshore wind farm to be constructed in France, and was the only one approved during the first French offshore wind energy tender (closed in 2005). French government maritime agencies were involved the consultation and approvals process. Potential effects on other users of the sea were considered as part of the tender evaluation process.

2.1.5 Germany

Germany has considerable experience with planning offshore wind power generation, although to date (2007) only 2 offshore wind installations have been built, each with only 1 turbine. The procedures for application and approval are well established and include an assessment of the navigational risks. Detailed guidelines on how to carry out and present risk assessment studies have been published by Germanischer Lloyd (GL).

Currently thirteen projects in the North Sea and two projects in the Baltic have been approved for construction. Almost twenty additional wind farms are planned in the North Sea. A further four projects are planned in the Baltic and two wind farms did not get approval because of environmental concerns. New wind farms have to be approved by the German authorities (Bundesamt für Seeschifffahrt und Hydrography). For the risk analysis Germanischer Lloyd’s guidelines are to be followed (Richtlinie zur Erstellung von technischen Risikoanalysen für Offshore-Windparks, 2002).

2.1.5.1 Germanischer Lloyd Guidelines

The risk analysis is carried out using the following base data:

- description of the planned wind farm including position, dimensions, number and arrangement of the wind energy plants, substation, cable, operation and safety concept
- detailed description of the individual wind energy plants (construction, materials, etc.) and related auxiliary devices
- the sea area including the meteorological data
- the maritime traffic including fishery
- other offshore installations
- the air traffic
- the coastal protection equipment/procedures including salvage and rescue

It is recommended that a risk analysis be carried out for each phase of the project (installation, operation and removal), and a risk analysis is mandatory for the operational phase. The following assumptions are made for the analysis:

- future ship techniques and ship traffic are not included in the analysis
- negligent actions, failures, omissions and mistakes are disregarded

- warlike and criminal actions are ignored
- aircraft accidents are not quantified
- the wind energy plant is assumed to be inherently safe and analysis of function and stability of the plants are not included in the risk analysis
- small vessels (<500 t) are included qualitatively
- possible extensions of the plants or substations are not part of the analysis
- ship-ship collisions within the wind farm are not included
- no calculations nor simulations of spills after a collision are done and their consequences are not part of the analysis
- maintenance works during operation are disregarded

For each scenario considered as part of the analysis, probability and consequences should be determined. The overall risk should then be compared to published statistical values for the risk and the results evaluated. The risk assessments should be done both qualitatively, where the occurrence probability and the consequences of the identified risks are described in subjective terms, and quantitatively, where calculations/numerical estimates are obtained for both probability and consequences.

According to the GL guidelines, the following analytical methods can be used:

- qualitative, formal hazard analysis: this is a deterministic, formal and inductive method for the identification of hazards and can be used as the base for fault tree and the Monte-Carlo analysis. All systems have to be included in the simulation and the fault or undesirable event is identified. In addition, the consequences have to be considered. The severity of the incident and the probability are estimated and the risk priority number is calculated.
- risk matrix: a risk priority number is estimated for each scenario identified and placed in a risk matrix. Values between one and three indicate a low risk, while four is seen as critical, and all values from four to seven are considered unacceptable and must be analysed in depth using quantitative methods.
- “Pedersen” method: this method can be used for the scenario “collision maneuverable ship – wind energy plant”. A Gaussian distribution is assumed for the shipping traffic without restrictions and an unsymmetrical distribution for bouyed fairways.
- fault tree analysis: this method can be used for the scenarios “collision maneuverable ship – wind energy plant” and “collision disabled ship – wind energy plant”. As a minimum, this should be done graphically.
- Monte-Carlo simulation: this method can be used for the “collision disabled ship – wind energy plant”.
- Consequence analysis: Potential spills of hazardous materials from the damaged ship and the wind energy plant need to be considered for all collision cases. Oil spill (both fuel and cargo) is of particular concern.

For each ship type and size, probability of an oil spill and mean amount of oil spilled after a collision should be estimated.

GL will publish new guidelines in the near future based on new experience gained, new data, and new models.

2.1.6 Ireland

A navigational risk assessment is required for any proposed offshore wind park in Ireland according to the Irish authorities. Initially, a Foreshore Licence is required to allow investigations to access the suitability of the site. Where the site is deemed suitable, an application may be made for a Foreshore Lease to construct an Offshore Electricity Generating Station. It should be noted that maritime safety would be a primary concern when assessing a site's suitability. For this reason a number of statutory bodies are consulted, including Irish Lights (statutory body for Irish Lighthouses), Irish Aviation Authority and the Marine Safety Directorate. In addition, a member of the Marine Safety Directorate sits on the Marine Licensing Vetting Committee (MLVC) which advises the Minister of Communications, Marine and Natural Resources on whether a Foreshore Licence / Lease should be granted to an applicant.

Although the risk assessments are generic in nature the developer is required to address the specifics associated with the particular proposed development to determine the degree of impact on the safety of navigation. The following should be addressed:

- The proximity of the wind park to main shipping routes.
- The proximity of the park to shipping lanes, traffic separation schemes, port entry channels, navigation marks, etc. The above are generic and require a study of shipping activity - commercial transit traffic, regular ferry routes, fishing and leisure craft associated with the area. This information can be sourced from local harbour authorities, fishing co-ops and yacht / sailing clubs.
- The specifics of the footprint of the proposed wind park should be given careful consideration in that it may result in radar interference and visual interference where one vessel may be obscured from another vessel because, for example, the wind park was arranged as a block.

Guidelines similar to the ones published in the U.K. on navigational risk assessments should be used in Ireland, but common sense should prevail and as a minimum the developer should engage the services of a marine consultant who would have a full understanding of the requirements from a navigational safety perspective (Foley, 2007).

2.1.7 The Netherlands

In the Netherlands, the navigational risk assessment has a strong focus on consequences, and modelling to determine effects of a potential oil spill is required. The navigational risk assessment carried out for the Egmond aan Zee offshore wind farm can serve as an example of what is currently required by the authorities in the Netherlands. This wind farm, a development with 36 turbines located approximately 10 km off the Dutch coast, commenced operations in 2007. The navigational risks assessment carried out for Egmond aan Zee consisted of the following main elements:

- assessment of the collision probabilities due to the presence of the wind farm
- assessment of impacts resulting from oil and chemical spills due to shipping collisions with the wind farm
- assessment of the effects of the wind farm on shipping radar.

(Kleissen, 2006).

The SAMSON model was used to estimate collision probabilities (see Section 3.4.1 for a discussion of this model). The probability of a passing ship ramming or drifting against a wind turbine was estimated. Consequence modelling was also carried out to estimate the damage to ships and wind turbine structures. Human consequences from ramming and drifting incidents were estimated. Hypothetical spills were also modelled, to determine the potential effects of any spills on the coastline. Effects of the wind farm on shipping radar were studied using a full mission bridge simulator (see Section 3.5 for a brief summary). Furthermore, an estimation of the effects of the presence of the wind farm on shipping outside the location of the wind farm was made (Kleissen, 2006).

2.1.8 Norway

The Havsul project is the first offshore wind energy project in Norway to apply for a license from the NVE, the Norwegian regulatory body for energy. According to email contact with the author of the risk analysis for this project, the assessment has been based on purely nautical problems. A risk analysis for collisions has not been performed, because there was not a sufficient data basis for a scientifically credible risk estimation. Calculations would therefore have a lack of statistical significance. Moreover the wind farm is located in a shallow fairway area which is not trafficked by large ships.

Figure 2.1. Full mission simulations were used for navigational farm analyses in Norway (photos and illustrations provided by Norvald Kjerstad, Professor at Høgskolen i Ålesund).

The study for the Havsul project was mainly based on simulations with a focus on navigational systems, anchoring and rescue issues. Simulations were carried out for a ship sailing close to the farm and to determine if the wind power plants could be used as navigational lights. Experts such as pilots, captains and mates were invited to navigate virtually through the wind farm. The conclusion was that the positive effects of the wind farm make up for the negative impacts (Dirdal (2007) and Kjerstad (2005, 2006, and 2007)).

2.1.9 Spain

A new Spanish law allowing the construction of offshore wind parks came in to force on August 1, 2007 (Burgermeister, 2007). This new law simplifies the authorisation process by giving the power to just one office (European Wind Energy Association, 2007), and it is expected to pave the way for the construction of offshore wind farms in Spain. Although Spain is the world's second leading producer of wind power (Burgermeister, 2007) there are currently no offshore wind farms.

The Ministry of Industry in Spain is carrying out a study to identify the best sites along the Spanish coast for offshore wind farms, which is expected to be completed in July 2008. A programme is also being launched to establish a licensing procedure for Spain (European Wind Energy Association, 2007).

2.1.10 Sweden

So far there are no national guidelines, official policies or governing documents with respect to navigational risk assessment for offshore wind farms. This report is, however, intended to provide input for such a document. The National Board of Housing, Building and Planning (Boverket), however, has published a book on the planning and approval processes for wind power plants (Boverket 2003). A new edited version is under way. A brief description of the Swedish permission process is provided in the BalticMaster project's case study of Kriegers Flak (BalticMaster 2007).

In Sweden, SSPA has performed a number of risk analysis studies on the navigational risks associated with offshore wind farms. Figure 2.3 shows the steps carried out and the components included in the analyses performed by SSPA. The focus of the studies has been on ship traffic but fishing vessels and pleasure craft have also been included to a certain extent. A list of some of the risk analyses performed by SSPA is presented below and the location of the proposed offshore wind farms is illustrated in Figure 2.2.

- **Storgrundet**, off the Coast of Söderhamns region, in the southern Gulf of Bothnia (Johansson et al 2007b).
- **Finngrunden** in the southern Gulf of Bothnia, off the coast of Gävle, Sweden (Johansson et al 2007a).
- **Utgrunden II** in the southern Kalmar sound (Baltic Sea) (Sandkvist och Hammar 2002).
- **Hanöbukten** (Johansson och Forsman 2007).
- **Kriegers flak II** in the southern Baltic Sea (within the Swedish exclusive economic zone). (Hammar och van Berlekom 2004).
- **Skottarevet** in the Kattegatt, off shore from Falkenberg (Johansson et al 2005 and Forsman et al 2007).
- **Fladen** in the Kattegatt (Magnusson 2002).

Figure 2.2. Map showing locations of proposed offshore wind farms for which SSPA has carried out navigational risk assessments.

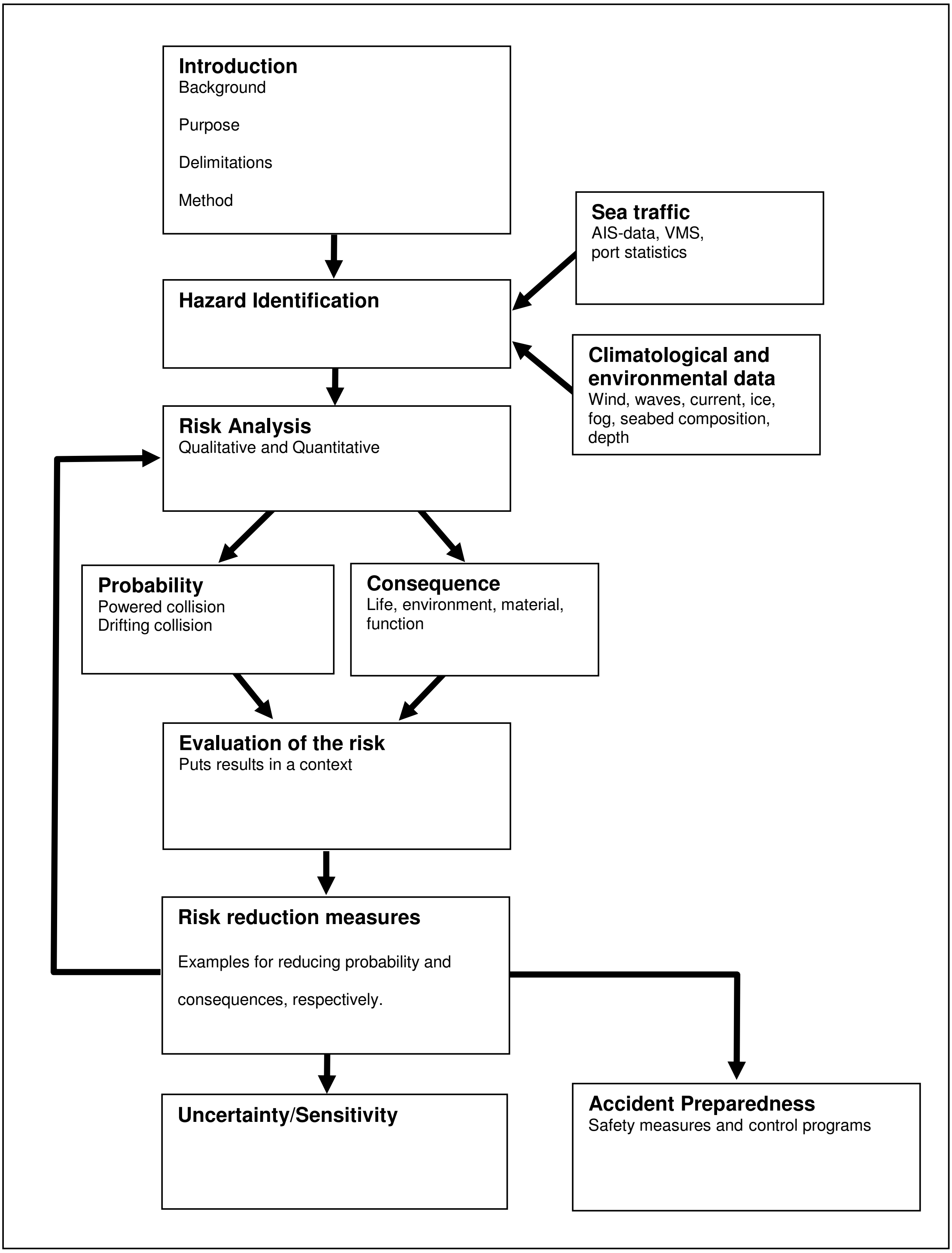


Figure 2.3. SSPA's procedure for assessing navigational risks associated with offshore wind farms.

2.1.11 United Kingdom

The UK's Department of Trade and Industry (DTI) (now known as Department for Business, Enterprise, and Regulatory Reform (BERR)) have published a methodology to guide offshore wind farm developers in assessing marine navigational safety risks of their proposed wind farms (DTI, 2005). The methodology states that developers should base their submissions on a Formal Safety Assessment, and should use "numerical modelling and / or other techniques and tools of assessment acceptable to government and capable of producing results that are also acceptable to government". This allows developers to select tools and methods that are appropriate to the site under consideration, rather than prescribing specific methods to be used by all. The methodology was produced in association with the Maritime Coastguard Agency (MCA) and BMT Renewables Limited. BMT Renewables also participated in the Safety at Sea project and the harmonised methods recommended in that project are in line with DTI's methodology. The Maritime and Coastguard Agency (MCA) provides guidance and recommendations on navigational safety issues in their document "Marine Guidance Note 275" (MCA 2004), which should be used in conjunction with the document "Methodology for Assessing the Marine Navigational Safety Risks of Offshore Wind Farms" (DTI 2005). The marine guidance note will be updated in 2008, and proposed updates include guidance for emergency response issues and an annex with an MCA shipping template for assessing wind farm boundary distances from shipping routes.

The key features of DTI's methodology are stated in DTI (2005) as follows:

- Define a Scope & Depth of the submission proportionate to the scale of the development and the magnitude of the risks
- Estimate "base case" level of risk
- Predict "future case" level of risk
- Create a hazard log
- Define risk controls and create a risk control log
- Predict "base case with wind farm" level of risk
- Predict "future case with wind farm" level of risk
- Submission

(DTI, 2005)

The Marine Guidance Note on navigational safety (MCA 2004) addresses issues such as site position (including guidance on traffic surveys), structures and safety zones (covered in Annex 1); "developments, navigation, collision avoidance and communications (Annex 2), safety and mitigation measures recommended for OREI during construction, operation and decommissioning (Annex 3), search and rescue matters (Annex 4)" (MCA 2004).

All offshore wind farm projects in the UK must first obtain a licence from the Crown Estates, which owns the seabed of the UK out to the 12 nautical mile territorial limit. The Crown Estates has awarded agreements for leases in two "rounds". The first round of agreements was granted in 2001, and the leases are for a period of 20 years. A total of 18 companies were awarded leases during this round. The second round, announced in 2003, resulted in 12 companies/consortia being awarded leases in 3 strategic areas. These leases are for a 40 year period. Companies must be pre-qualified before they can be considered for a lease. To pre-qualify, they must have financial standing, offshore development expertise, and wind turbine expertise.

Once a developer has obtained a lease for an offshore wind farm site, they must obtain a number of statutory consents, and must publicise an application, to ensure the public and interested organisations have an opportunity to comment and express concerns before a decision is made. Developers are required to provide a comprehensive assessment of likely impact on factors such as marine environment, visual impact, fishing, and shipping. The assessment must be carried out for all phases of the development: construction, operation, and decommissioning (UK Department for Business, Enterprise & Regulatory Reform, 2007). This assessment should be described in the developer's Environmental Impact Assessment, and included in a resulting Environmental Statement.

There are many wind farms in operation or under development in the UK. As of October 2007, there were six operational wind farms (British Wind Energy Association (2007)): Barrow, Blyth Offshore, Kentish Flats, North Hoyle, Scroby Sands, and Burbo Bank. A further six were reported to be under construction: Beatrice, Inner Dowsing, Lynn, Rhyl Flats, and Solway Firth/Robin Rigg A and B. At least six more projects had been approved, and a number have been submitted for approval. To date there have been no recorded incidents for a ship collision with a wind turbine structure (personal communication, Navigation Safety Branch, November 2007).

Some examples of the range of techniques used for navigational risk assessment are as follows:

- Gunfleet Sands Wind Farm: This project has been approved for development. For the collision risk assessment carried out for this project, the COLLIDE 2.60 model was used to estimate collision frequency (Safetec Ltd., 2002). In terms of consequence assessment, a log-log plot of annual collision frequency versus impact energy was generated for the two park locations which were identified to have the highest and lowest annual collision frequencies.
- Burbo Bank Offshore Wind Farm: This wind farm was officially inaugurated in October 2007. For the navigation risk assessment, quantitative risk modelling was carried out using Anatec's COLLRISK model (Anatec, 2002). Passing drifting ship and anchor drifting ship collision rates were estimated. In addition, a fishing vessel risk assessment was carried out.

2.1.11.1 Safety Zones

The UK recently introduced new regulations regarding safety zones around or adjacent to an offshore renewable energy installations. These regulations, "The Electricity (Offshore Generating Stations) (Safety Zones) (Application Procedures and Control of Access) Regulations 2007 (SI No 2007/1948)" came in to effect in August 2007. Standard dimension of the safety zone is 500 metres during construction (which is the maximum permissible under international law), and 50 metres during the operational phase of an installation's life (Department for Business Enterprise & Regulatory Reform, 2007). If it is considered that a larger safety zone is required for a specific case, an application for consent under Section 36 of the Electricity Act must be made. The requirement for a larger safety zone should be considered as part of the navigational safety assessment.

2.1.12 USA

In the USA, as of June 2007, there had not yet been any offshore wind farms constructed, although a number of projects have been proposed (Butterfield et al., 2007). The "Cape Wind" project in Massachusetts, the first project development in the USA (Ram, 2004), is a proposal for 130 wind turbines. The Long Island Power Authority had proposed a project off of Long Island, New York (Ram, 2004), and Winergy is considering a number of sites along the eastern seaboard of the USA (Winergy, 2007). Their initial project, Plum Island Wind Park, is a small scale research, development, and demonstration project to be located off the northeastern tip of Long Island, New York (Winergy, 2007). There is also a project in the development stages in Texas, being developed by Galveston Offshore Wind. The company plans to have 50 wind turbines installed by 2010 (Fowler, 2007).

There are no published US guidelines for navigational risk assessments for offshore wind farms. For the Cape Wind Farm, however, a navigational risk assessment was carried out and submitted to the US Army Corps of Engineers (USACE) as part of an environmental assessment conducted in 2004. At that time, the USACE was the lead agency for permitting offshore wind facilities, based on Section 10 of the Rivers and Harbors Act (Ram, 2004). This states that permits are required for any structures altering or obstructing navigable waters. The Energy Policy Act of 2005 granted the Interior Department's Minerals Management Service (MMS) new responsibilities related to renewable energy and now this national agency is the lead agency for permitting and regulatory oversight of offshore wind energy projects sited on federal offshore lands, on the outer continental shelf (OCS). The OCS extends from 3 nautical miles (nm) from the coastline out to 200 nm, except for Texas and Florida, where the state jurisdiction extends to 9 nm from the coastline (Ram, 2004). Although the MMS now has the role of lead agency and responsibility for coordinating the permitting process, the regulations pertaining to the USACE permits are still in place.

2.2 International Research Programmes and Harmonisation of National Assessment Schemes

2.2.1 Safeship

The project “Reduction of Ship Collision Risks for Offshore Wind Farms” (with acronym “SAFESHIP), was a 2-year project that was completed in January 2005. The project was co-financed by the European Commission as part of the 5th Framework RTD Programme (den Boon et al., 2005). The overall objective of the project was “to reduce the risks of ship collisions with offshore wind farms by development of appropriate cost-effective technologies and risk assessment methodologies, thereby reducing the production costs of offshore wind energy and removing development barriers” (den Boon et al., 2005).

In terms of the modelling of collision risks, the project compared the frequency models of Germanischer Lloyd AG (GL) and of the Maritime Research Institute Netherlands (MARIN), as both of these organisations were partners in the project. The model used by Det Norske Veritas (DNV) was also included in some of the comparison work. Models for both collisions of a powered ship with a wind farm and for collisions of a drifting ship with a wind farm were compared. After model comparisons, changes were made to the models to result in what was hoped to be more harmonised predictions. The collision models compared and developed in SAFESHIP are further discussed under Section 3.4.1, Ship – Wind Farm Collision Probability Estimation. Consequence modelling within the project was carried out using finite element modelling (using LS-Dyna).

With respect to the work carried out on risk reduction measures and technologies, the SAFESHIP project produced the following:

- a catalogue of cost-effective methods and technologies; the main result is the conclusion that AIS (Automatic Identification Systems) is the most effective risk reducing method;
- a detailed design of fendering for the HV station of a wind farm;
- an Emergency Response Management Plan for the 120 MW Q7-WP wind farm, to be used as a model for other wind farms.”

In addition, the project work resulted in the conclusion that placing fendering around offshore wind turbines was not cost-effective, although it was technically feasible.

2.2.2 Safety at Sea project

The partner countries and organisations of the Safety at Sea research program (an Interreg North Sea Region project) have developed a procedure of harmonised methods for carrying out a marine navigational safety assessment. The description is in line with the UK DTI Guidelines. The policy recommendation as part of the output of the Safety at Sea project is "that these methods are adopted by EMSA and developed into a standard to cover all EU waters and extended to cover all offshore renewable energy including tidal and wave energy." In addition, the EU Member State Maritime Administrations are invited to apply the draft procedure developed as part of the Safety at Sea program during the development of their own regulatory requirements (Starling, 2007).

The methods proposed and presented, however, do not provide details for procedures such as calculation of collision probability, and in reality there is no guarantee that the application of this general methodology would result in consistent results. The Safety at Sea report (BMT, 2005) states that there is a wide range of risk assessment techniques available, and those selected for a specific project should be in line with the scale of the project and acceptable to the involved Maritime Administration and regulatory bodies. This implies that a range of technical analyses techniques may be used for different parks and in different countries.

The Safety at Sea project also included a demonstration research project on offshore wind farm risk management (there were six demonstration projects in total). The project as a whole was co-funded by the Interreg IIIB North Sea Region Programme, and its primary aim is "to reduce the probability and impact of accidents in the North Sea". It was a three-year project that began in September 2004 (www.safetyatsea.se) and more than 20 organisations from countries surrounding the North Sea were involved. The project was managed by the Norwegian Coastal Administration.

The offshore wind farm risk management project resulted in a number of deliverables. A cumulative quantified risk assessment was carried out for an arbitrary sea area which had up to five wind farms and included a large range of other features including islands, oil installations, ports, etc. Simulated current and future marine traffic was created and used to carry out the risk assessment. Further, the project resulted in risk control provisions which were identified for an arbitrary wind farm within the arbitrary sea area (BMT Renewables, 2005).
One recommendation was that proportionality of the project be assessed to determine the amount of detail required in the submission and the Navigation Risk Assessment. A continuum of activities is described for support of the navigation risk assessment, starting with "area traffic modelling/assessment of the strategic area", and ending with specific traffic bridge control simulations and site specific trials that may be required for assessing risk control options and for more complicated projects.

2.2.3 Harmonisation discussions in Germany

In Germany the authorities appointed a group of experts to discuss harmonisation of the assumptions made in risk assessments (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005). The scope was also to find and agree on risk acceptance criteria. The goal of the group of experts was to find generally accepted values for the model assumptions, the collision frequency, the mean oil spill per year, risk reducing measures, the carving depth of cables and minimum distances. The results are seen as state-of-the-art which will be modified with increased knowledge in the field and adjusted to future developments.

3 NAVIGATIONAL RISK ASSESSMENT METHODOLOGY

The purpose of this chapter is to describe the different steps of a navigational risk assessment for offshore wind farms. It includes hazard identification, estimation of collision probability and consequences, discussion on uncertainty/sensitivity as well as risk acceptability. Effects on radar, radio, navigation equipment etc and on search and rescue operations are also included in this chapter but risk reduction measures are presented separately in the next chapter.

3.1 Initial qualitative assessment

As an initial step of the navigational risk assessment for proposed or existing offshore wind farms, qualitative hazard identification should be performed. All parties involved in the project and relevant maritime stakeholders should be addressed and asked for their concerns and opinions regarding possible hazards associated with the establishment of the wind farm. This may be conducted by public hearing, interviews or structured brainstorming sessions in selected groups of stakeholders. As an output, a catalogue of possible potentially hazardous scenarios can be identified.

Based on further qualitative considerations on the likelihood of the respective scenarios to occur and the potential consequences of the scenarios, an initial ranking and selection of prioritised scenarios that need to be further analysed quantitatively can be identified.

Taking into consideration the park location, its size and the output of the initial assessment, decisions are taken on the needs and levels of additional detailed studies and a detailed plan is outlined for further risk assessment studies.

The following sections describe a general methodology for detailed assessment of navigational risks associated with offshore wind farms.

3.2 Definition of Types of Risks to be Considered

The construction and operation of a wind farm will potentially have an effect on the risk of many types of incidents that involve ships operating in waters in the vicinity of the wind farm. Navigational risks which may be introduced or changed by the establishment of an off-shore wind farm include the following:

- Risk of a ship colliding with or contacting a wind turbine or wind farm structure
- Risk of ship to ship collision resulting from change in navigation to avoid the wind farm area
- Grounding Risks
- Possible secondary risks resulting from effects of the wind farm on for example radar operation

A methodology should include an assessment of each of these types of risks. These risks will be different during different phases of the project. Although the project construction time and decommissioning are relatively short compared to the wind farm operational phase, they should still be given some consideration during a risk assessment.

It is also important to select a time frame to be considered for future scenarios. The “base case” or “pre-wind farm” risk for ship-to-ship collisions and grounding needs to be compared to risk estimated for collisions when the wind farm is operational.

In addition, comparisons should be made for future scenarios of increased ship traffic and for changes to the ships such as increased average speed, and changes to draught and tonnage.

Finally, there should be some consideration given to the changes in risk that may result from future developments for wind farms (larger turbines, different foundation types, etc.) and for the cumulative risk that could result from the establishment of several wind farms along a navigation route and possible risk interactions.

Figure 3.1 illustrates the aspects of risk changes over time and from a regional scale perspective.

The quantitative risk estimation methods developed and analysed in this study are basically focused on estimating *absolute risk figures* associated with wind farms but, as also illustrated in the figure, for overall assessment, *relative risk figures* are generally more conclusive and provide important input in the decision making process. Risk assessments based on relative risk considerations are also less sensitive with regard to uncertainties and assumptions in critical numerical input parameters.

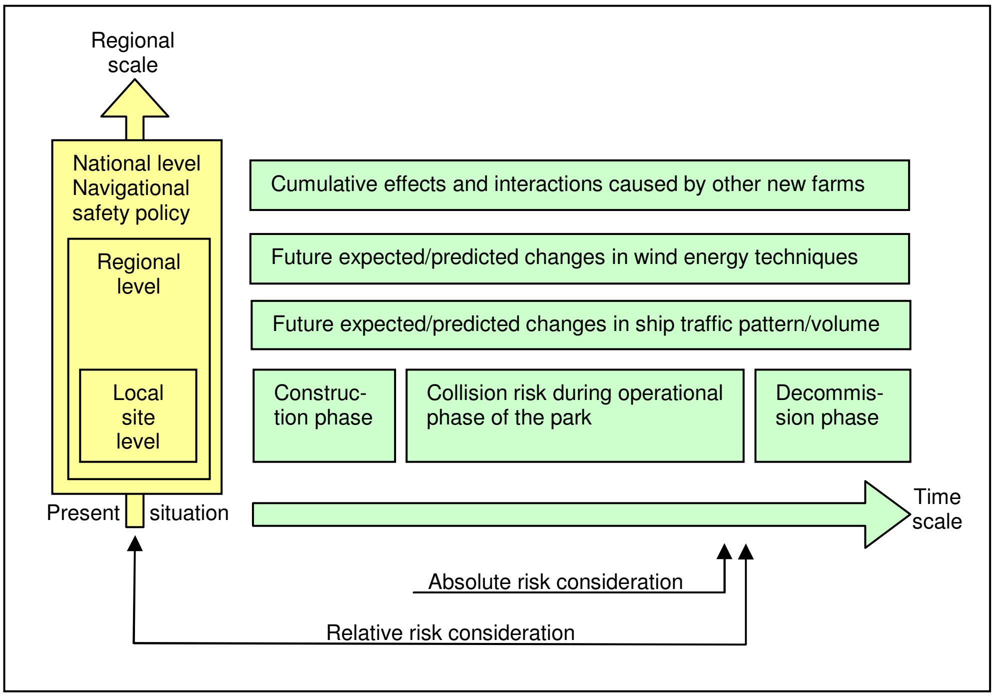


Figure 3.1. Various risk aspects considered from regional perspective and with respect to time.

3.3 Data Sources and Inputs to Analyses

The following sections provide a description of methods used for estimating probability and consequences of accident scenarios associated with interactions between ships and wind farms. Ship to ship collision and grounding are also discussed.

To estimate the probability of collisions between ship and wind farm, the following type of information is generally required:

- Wind farm data including:
  - Position of each wind turbine
  - Distance between turbines
  - Pile diameter
  - Hub height
  - Rotor diameter
  - Installations of navigational aids (lights etc) at the wind farm

- Vessel traffic information in the vicinity of the proposed wind farm, including:
    - Position of typical shipping lanes/operating routes (from AIS data and other sources)
    - Number of vessels (from AIS data and other sources)
    - Types of vessels such as cargo, tanker, passenger, etc. (from sources such as AIS data and general statistics for the Baltic Sea)
    - Characteristics of vessels such as size, length, breadth, draught, operating speed (from sources such as AIS data and general statistics)
    - Seasonal traffic variations (from AIS data, etc.)
    - Day/night traffic variations (data sources include local ports)
    - Future traffic scenarios (from Helcom, VTT, The Institute of Shipping Analysis in Göteborg, etc.)
    - Distance from the shipping lane to the wind farm (estimated from AIS data; estimations for lanes shifted to new location)
    - Standard deviation and mean for lateral distribution in cross-section (from AIS data (histogram) or general estimations)
    - Statistical distribution for course deviation, e.g. standard deviation and mean for Gaussian distribution in cross-section (may be possible to derive from AIS data or statistics)

- Climatological data including:
    - Wind speed distribution and wind direction distribution (10 meters over sea level)
    - Wave information
    - Current information
    - Ice conditions
    - Fog conditions (to assess hazards such as reduced visibility)

- Site data including:
    - Coast line geometry
    - Water depth, bathymetry and sea level variations
    - Type of sea bottom such as rock, clay, sand, etc.

- Frequency of machinery breakdown– blackout

- Ship self repair function (time for self repair)– duration of blackout

- Probability of unsuccessful emergency anchoring

- Tug boat assistance information including:
    - Distance from tug boat position to disabled ship
    - Operating speed of the tug boat (depends on the weather conditions)

    - Time to activate the tug boat, to connect and take control of the disabled vessel

- Probability of:
    - human failure during planning and execution of the passage of an object (navigation past an obstacle)
    - technical failure of navigational equipment or watchkeeping failure due to causes such as lack of attention during lookout on the bridge or bad visibility
    - failure of the wind farm safety equipment/crew or a potential stand-by boat to warn the passing ship in time to avoid a collision
    - the crew onboard being unable to react in time to correct the navigational error (dependent on the distance between ship and wind farm)

For future vessel traffic and ship sizes, information can be obtained from sources such as the Baltic Maritime Outlook (2006), which provides estimates on future maritime freight flow in the Baltic Sea Region, including projected flows on specific transport corridors. In addition, the characteristics of specific ship types on order as provided in sources such as Lloyd's Fairplay can give an indication of future ship sizes (DWT, draught) and speeds.

For consequence analysis, information such as the following is required:

- Information on the wind turbine structure, foundation type and distance between blade and water surface
- Information on soil types
- Environmental information such as specific species using the area, sensitive shoreline areas, etc.
- Information on vessel types and characteristics, including cargo and bunker fuel quantities for estimating collision results and potential spills

Data sources on vessel traffic information for Swedish waters include:

- Swedish Maritime Administration, which can provide AIS-data
- Ferry companies operating regular line services, such as Stena
- Port Authorities for information on line traffic. Number of ship arrivals in different ports is available from Sveriges Hamnar (2007).
- Information about fishing boats (VMS-data) can be obtained from the Swedish Board of Fisheries and information about recreational boats from Gästhamnguiden (2007).

3.4 Analysis Methods

A variety of methods have been used for estimating probability and consequences of navigational accident scenarios associated with construction and operation of offshore wind farms. When ship traffic in the vicinity of the wind park is very light and data on ship traffic is limited, methods have been more qualitative. More complete modelling and statistical analysis techniques have been used for offshore wind farms proposed in areas with significant ship traffic and where detailed information such as AIS data is available.

Similarly, consequence analysis methods for offshore wind farms range from qualitative to quantitative modelling, depending on availability of data and assessed probability of incidents. It is important to have appropriate data for model input to ensure confidence in the results.

The following sections provide a description of methods used for estimating probability and consequences of accident scenarios associated with interactions between ships and wind farms. Ship to ship collision and grounding are also discussed.

3.4.1 Ship – Wind Farm Collision Probability Estimation

There are a number of different models for estimating the probability of ships colliding with offshore platforms. The models have been developed and presented by various organisations, as shown in Table 3.1. The table also includes references to studies where the respective models have been described and/or applied.

Table 3.1. Collision models, companies/organisations responsible for development, and selected references.

Model	***Company/Organisation***	***Selected References***
COLLIDE	Safetec Nordic AS	Haugen (1998) Spouge (1999) Safetec (2002)
SOCRA[1]/SAMSON[2]	MARIN (Maritime Research Institute Netherlands)	van der Tak and Glansdorp (Year unknown) van der Tak und Rudolph (2003) van der Tak (2005a) van der Tak (2005b) SAFESHIP (2005) SAFESHIP (2006) Kleissen (2006)
CRASH/ MARCS[3]	DNV (Det Norske Veritas)	Spouge (1999) SAFESHIP (2005) Christensen (2007)
COLWT	GL (Germanischer Lloyd)	Germanischer Lloyd (2002) Neuhaus and Thrun (2003) Otto and Petersen (2003) Povel et al. (2004) Otto (2004) Povel and Petersen (2004) SAFESHIP (2005) SAFESHIP (2006) Povel (2006)
COLLRISK	Anatec UK Ltd	Anatec UK Limited (2002) SAFESHIP (2006)
DYMITRI	BMT (British Maritime Technology) Limited	Safety at Sea (2005)

[1] SOCRA (Ship Offshore platform Collision Risk Assessment) is a module in MANS (Management Analysis North Sea).
[2] SAMSON (Safety Assessment Models for Shipping and Offshore in the North Sea).
[3] CRASH (Computerised Risk Assessment of Shipping Hazards), MARCS (Marine Accident Risk Calculation System).

COLLIDE was originally developed for offshore oil platforms, but is now also used for offshore wind farms. A possible upgrading to a new version has been discussed (Eriksen and Haugen 2006).

MARIN's web page indicates that the SOCRA software is used for offshore oil platforms whilst SAMSON is generally used for offshore wind farms.

GL has issued guidelines for risk analysis for offshore wind farms (see Germanischer Lloyd (2002)). GL has estimated the collision frequencies for a planned offshore wind farm within the German exclusive economy zone (EEZ) of the Kriegers Flak area of the Baltic Sea (see Otto and Petersen 2003, Povel et al. 2004, and Otto 2004). MARIN has also estimated the collision frequencies for Kriegers Flak (see van der Tak und Rudolph (2003) and van der Tak (2005b)).

The various models have also been compared in previous studies. The most recent comparative study presents a comparison between COLLRISK, COLWT and SAMSON (see SAFESHIP (2006)). In SAFESHIP (2005) the models of MARIN, GL and DNV were compared, with the focus of the comparison on harmonising model assumptions. These three companies were part of a group of experts that were appointed by German authorities to discuss harmonisation of assumptions made in risk assessments (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005), as discussed in Section 2.2 of this report. Van der Tak (2005a) also compares the models in order to clarify differences, harmonise assumptions and enlarge transparency. Van der Tak focuses on the differences between SAMSON's calculation model for powered collision and other corresponding models based on Gaussian distributed offset of the ships sailing on the lanes which pass by the wind farm (see Figures 3.2 and 3.3).

SSPA's collision frequency model (see Appendix) is developed with the most recent available information on model assumptions etc as a basis. The structure of the model is similar to other models used for wind farms and offshore platforms. The derived harmonised values from the German harmonisation process mentioned above have become available during the work with this research project and have partly been used in the SSPA model.

Risk analyses and assessments have also been conducted by companies and organisation such as:

- COWI (Örestads Vindkraftpark AB (2000))
- Rambøll (Rambøll (2000a and 2000b), Christensen et al. (Year unknown) and Randrup-Thomsen et al. (Year unknown))

MARIN and Germanischer Lloyd are two of the major companies performing risk analysis for collisions of ships with offshore wind farms. This is based on the relatively high number of offshore wind farms which have been proposed and studied in the countries where the companies are based (the Netherlands and Germany respectively). Together with the Technical University of Denmark they conducted a study (SAFESHIP 2005) on the collision frequency of powered and disabled ships with offshore wind farms, in which they compared the models used by MARIN, Germanischer Lloyd (GL) and Det Norske Veritas (DNV). If no other references are stated, the material presented in the rest of section 3.4.1 is based upon that study in combination with the studies of van der Tak and Rudolph (2003), van der Tak (2005b), Kleissen (2006), Otto and Petersen (2003), Povel et al. (2004), Otto (2004), Neuhaus and Thrun (2003), Christensen (2007) and Bundesministerium für Verkehr-, Bau und Wohnungswesen (2005).

Further analyses and discussions on the differences between the models are found in Chapter 5, which describes the case study of Kriegers Flak carried out as part of this study.

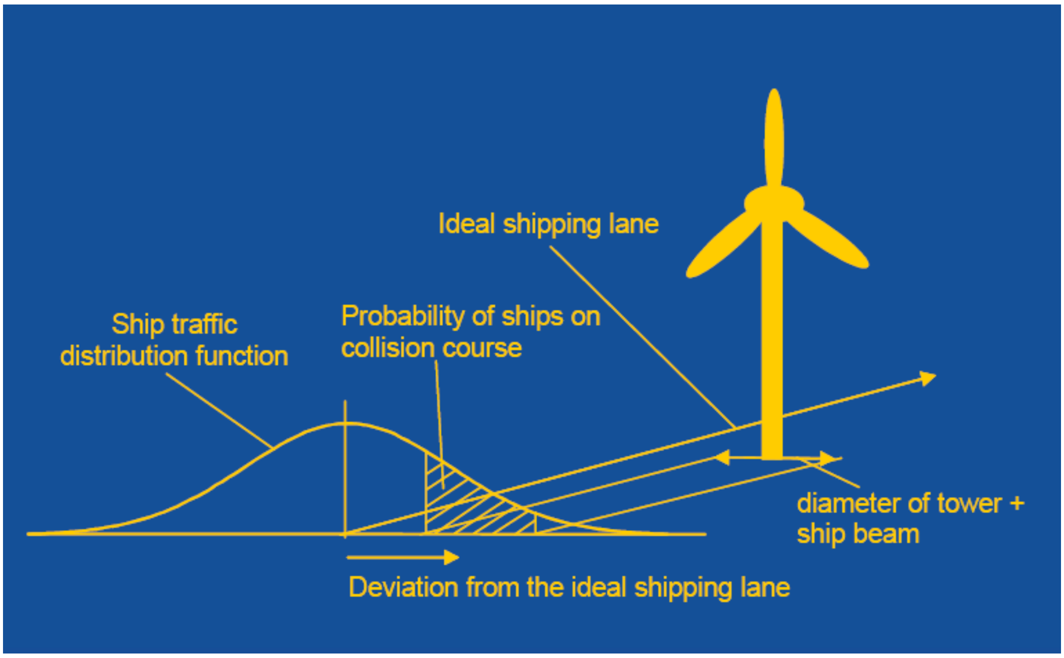


Figure 3.2. Illustration of general probability calculation model based on Gaussian distribution of ship traffic along a fairway. Collision course times causation factor. Source: van der Tak (2005a).

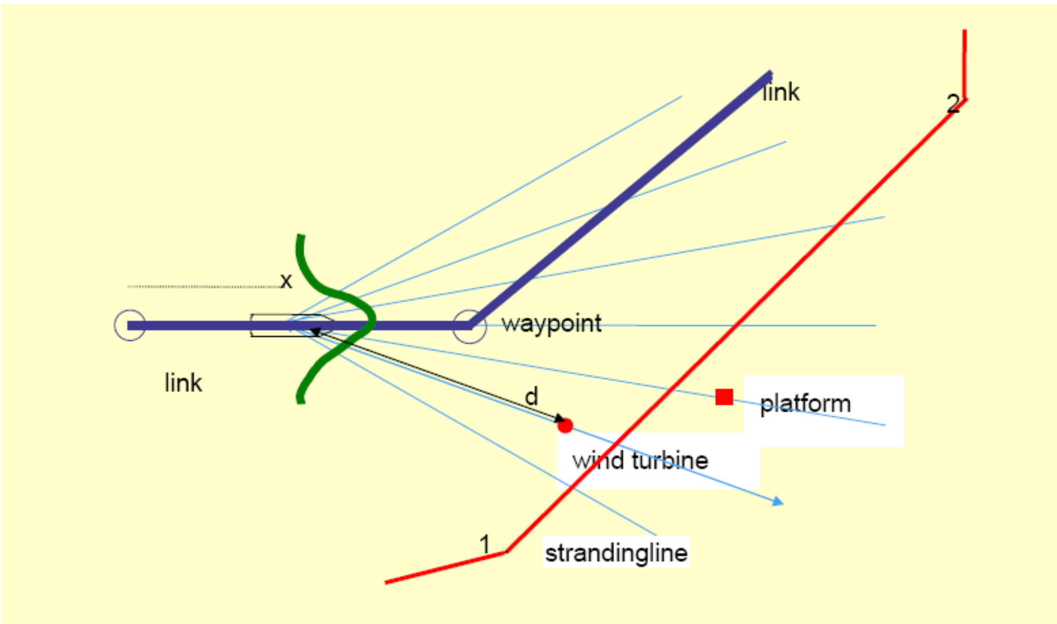


Figure 3.3. MARIN's model: Collision opportunity times Navigational Error Rate (NER). Source: van der Tak (2005a).

3.4.1.1 Powered collision

The models used by MARIN, GL and DNV are basically quite similar. GL's and DNV's models estimate the number of collision candidates and multiply this with a causation factor, while MARIN's model estimates the number of ramming (collision) opportunities and multiplies this by the Navigational Error Rate (NER). The models differ from each other in the assumptions made for the determination of the collision candidates and the ramming opportunities.

When estimating the probability of powered collisions, the assumptions made for the traffic around the wind farm are very important, specifically the parameters of the lateral distribution of the ship traffic and of the centre line of the ship traffic. These parameters are strongly dependent on the fairway (e.g. open sea, Traffic Separation Scheme (TSS), shallow water, buoyed fairway, etc.). All models are based on a Gaussian distribution to represent the lateral traffic distribution on the shipping lanes. GL and DNV add a uniform distribution of 2% to the Gaussian distribution (the width of uniform distribution is assumed to be 6 times the standard deviation), most likely in order to represent the traffic not following any route. MARIN calculates the non-route-bounded traffic separately.

GL uses the following parameters for the standard deviations if there are no local factors that otherwise influence the distribution.

Table 3.2. Standard deviations according to GL (SAFESHIP 2005).

Description	***Standard deviation for Gaussian distribution [nm]***
Port approach	0.2 to 0.3
Conspicuous navigational points, e.g. navigational marks, buoys	0.3 to 0.4
Navigational channel with traffic separation	0.5
Waypoints in wider shipping lanes	0.5 to 1.0
Waypoints in open sea areas	2.0

In order to derive the lateral distribution of the lanes on the North Sea, MARIN has made observations of actual traffic with a partition into lanes with Traffic Separation Scheme (TSS), connection between two schemes and with completely free shipping lanes. In the TSS lanes the observed type of distribution is used (which is dependent on the width of the shipping lane). For completely unrestrained lanes a Gaussian distribution with a standard deviation of 1 nm is used.

DNV and GL have agreed to use 1.2 times the ship breadth plus the dimension of the object perpendicular to the sailing direction as collision width (0.2 extra ship breadth includes an average drifting angle of 2 degrees. The kinetic energy for this

0.2 extra is assumed to cause less serious damage after a collision), while MARIN uses only the ship breadth.

DNV and GL both use a causation factor of 3.0E-4 for a ship not taking corrective action, which is meant to include all causes resulting from either human error or technical failure. MARIN used the same assumption in their original model but moved away from this because of the fact that the collision probability is very sensitive to the distance between the centre line of the traffic lane and the object. The collision probability is also dependent on the tail of the lateral distribution of the ships using the lane. MARIN uses a value called NER instead. The table below shows the relationship for the different Navigational Error Rates (NER) according to MARIN with an offshore platform as a basis. See also Figure 3.3.

Table 3.3. Relationship for the different Navigational Error Rates (NER) according to MARIN with an offshore platform used as a basis for comparison (data from SAFESHIP (2005)).

Type of obstacle	***Single offshore platform***	***Collision/ stranding with an island***	***Offshore wind turbine***
Relationship for the different Navigational Error Rates (NER)	1	6	2.5

MARIN uses the following formulas to calculate the number of powered collisions:

$$P_\psi = \int_{x_1}^{x_2} e^{-a\frac{d_{n\psi}(x)}{L_i}} dx$$

$$RO_k = \sum_n \sum_{n_\psi} \sum_i p_n p_{n_\psi} N_{ik} \cdot \int_{x_1}^{x_2} e^{-a\frac{d_{n\psi}(x)}{L_i}} dx$$

$$N_{ramming} = NER \sum_k RO_k$$

- RO: Ramming opportunities
- $N_{ramming}$: Number of collisions
- Pψ: Probability that a navigational error leads to a collision with an object in direction ψ
- L_i: Ship length (in nautical miles) of a ship from ship size class i
- x: Position of a ship on a shipping lane. The integration borders x_1 and x_2 follow from the reachability of the WPP (Wind Power Plant) from the shipping lane. These values are dependent on the size of the WPP and the ship size class and type.
- $d_{n\psi}$: Distance between a point x on a part of the route and the collision point (WPP) in direction nψ
- a: Dimensionless constant for the probability of having no collision avoidance measures taken in time after a change in course
- p_n: Probability of a certain load condition n
- $p_{n\psi}$: Probability of a certain course

- N_{ik}: Number of ships of ship class i on the shipping lane k
- i: Ship size class
- NER: Navigational Error Rate

NER is an empirical value based on accident statistics and geometrical collision candidates. No information has been found in the literature regarding the values of NER or the constant “a” in the equations described above.

DNV uses the following formula to calculate the ship-turbine collision frequency:

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

- *N* is the number of ships on the lane for the specific ship class per year.
- P_{Human} is the probability of 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 a uniform plus a Gaussian distribution 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.

GL and MARIN use different ship types and ship classes, therefore results are difficult to compare. In the EU funded project SAFESHIP 2005 the two companies compared their models in a sensitivity study, which showed that the GL calculations are very sensitive to the location of the centreline and the standard deviation of the lateral distribution of the traffic lanes. In their example the calculations were made for a wind farm project in the North Sea outside the Netherlands. One nm is used as the distance from the wind farm to the centre line of the closest lanes. For details see the tables below.

Table 3.4. Probability of a ship ramming a wind farm (wind farm P12, the Netherlands) (SAFESHIP 2005).

Model used	***The centre line of all traffic lanes is moved with … nm away from the wind farm***			***All standard deviations are multiplied by***			
	0 nm[1)]	***0.5 nm***	***1.0 nm***	***1.00***[1)]	***0.75***	***0.5***	***0.25***
GL	0.1418	0.0481	0.0137	0.1418	0.0542	0.0049	4.3E-08
MARIN	0.0060	0.0024	0.0009	0.0060	0.0040	0.0027	0.0019

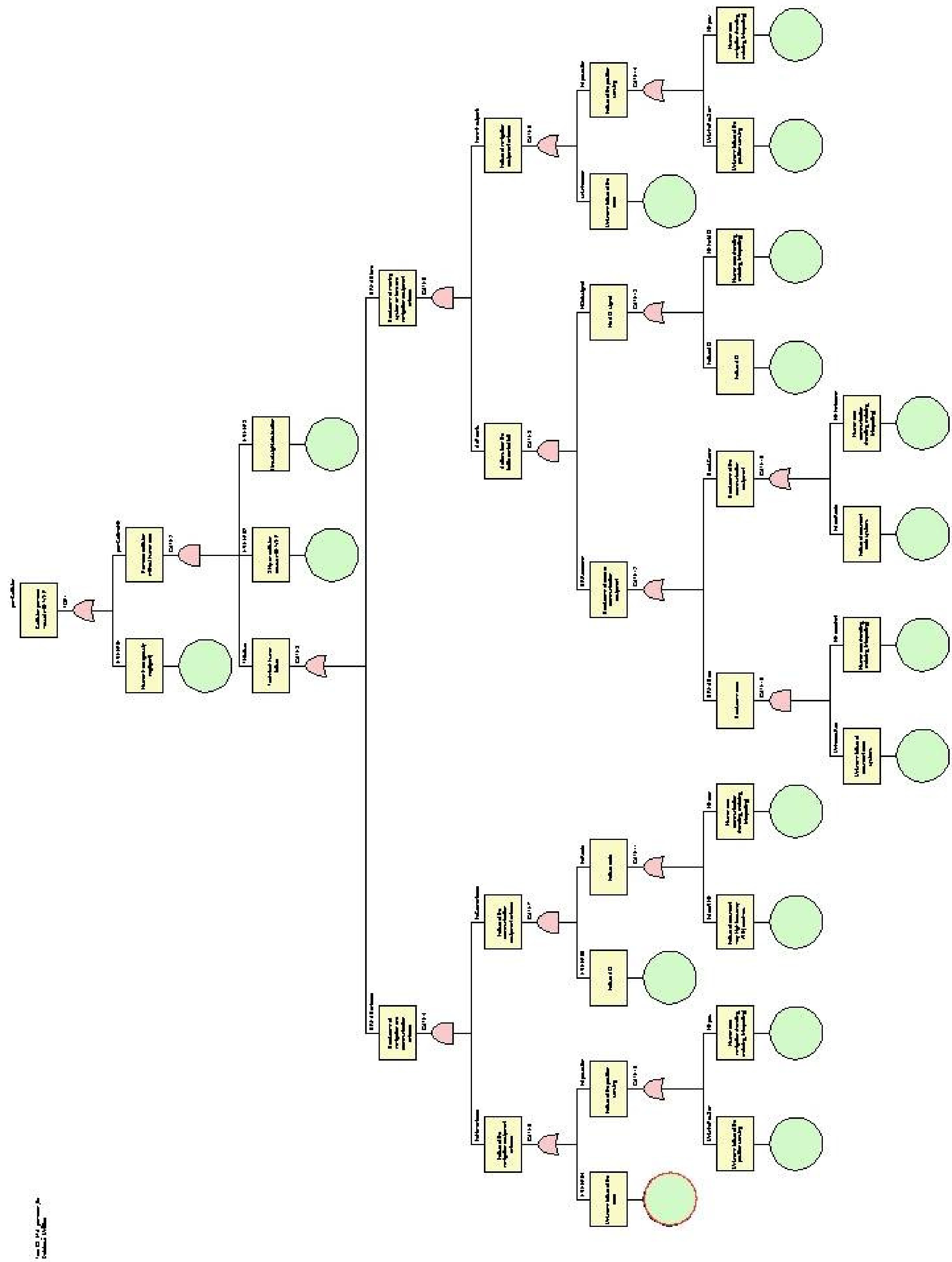
[1)] These are the base cases when the centre lines positions and the standard deviations are not changed.

Table 3.5. Sensitivity factors (SAFESHIP 2005).

Model used	***The centre line of all traffic lanes is moved with … nm away from the wind farm***			***All standard deviations are multiplied by***			
	0 nm[1)]	***0.5 nm***	***1.0 nm***	***1.00***[1)]	***0.75***	***0.5***	***0.25***
GL	1.0	0.339	0.096	1.0	0.382	0.035	3.0E-07
MARIN	1.0	0.404	0.154	1.0	0.670	0.451	0.313

[1)] These are the base cases when the centre lines positions and the standard deviations are not changed.

Methods such as Bayesian net, event trees, statistics and published values are used to estimate and verify causation factor. The figure below (Figure 3.4) presents a general event tree diagram which can be used for sensitivity analysis of the causation factor. The figure also includes a part of the tree in bigger size. The effect of risk reducing measures on the causation factor can also be evaluated with event trees or Bayesian net. Such studies have been conducted to evaluate the effect of the introduction of AIS (Lützen and Friis Hansen, Year unknown) and of different bridge designs.



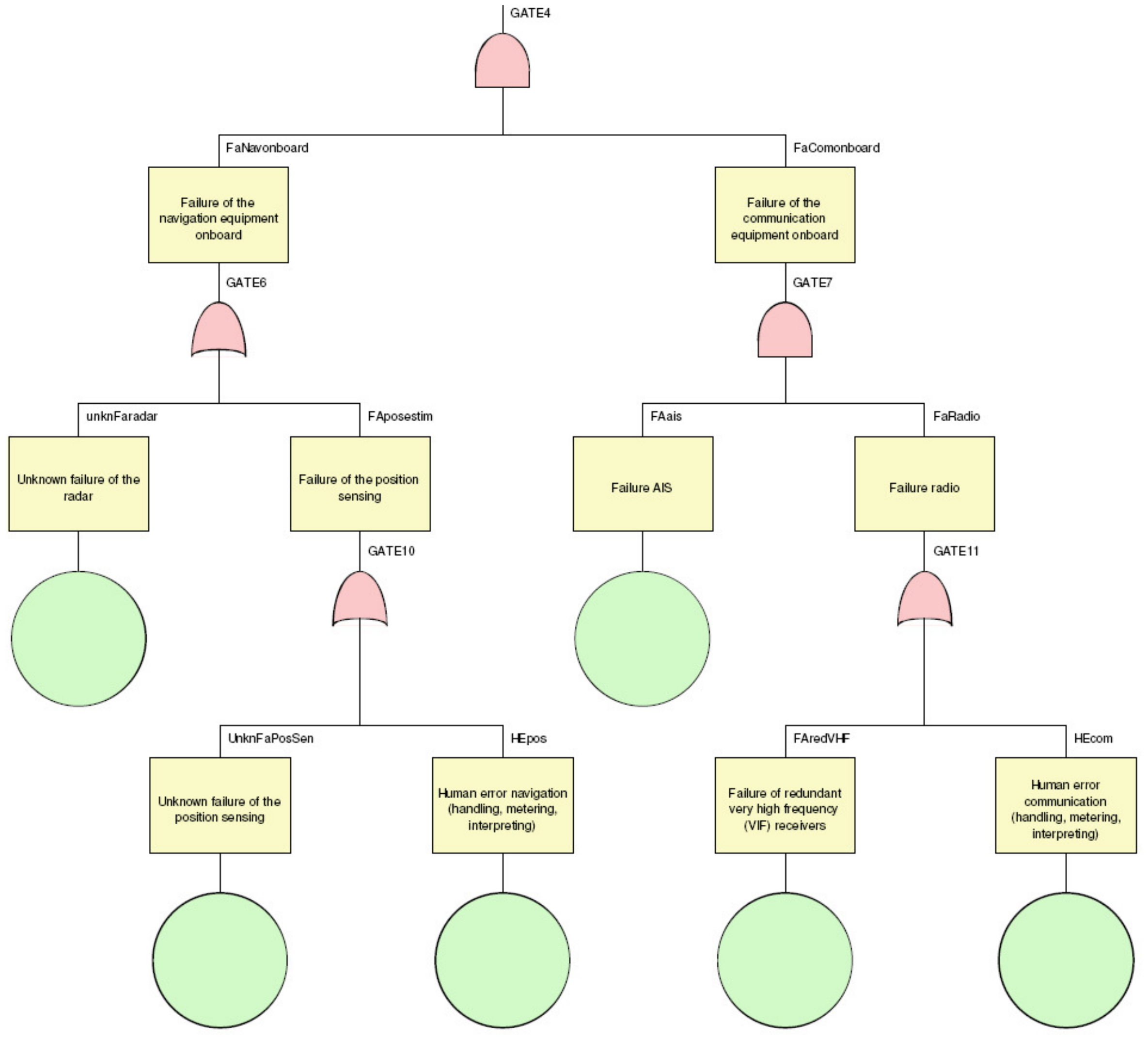


Figure 3.4. Upper part: General event tree diagram Lower part: Part of event tree diagram.

GL has developed a Bayesian net to reduce the uncertainties connected with the causation factor and to respond to the new and unknown influence of Automatic Identification System (AIS) and Vessel Traffic Monitoring (VTM) on the causation factor. The net is based on a Bayesian net developed by the Technical University of Denmark for ship-ship collisions. A part of the input parameters and their influence on the results are presented below.

The following assumptions have been made: visibility is 30 km during the day and 20 km at night; ships have a speed of 15 knots in high visibility and a speed of 7.5 knots in poor visibility (<1 nm); and the presence of the wind farms is known to 95% of the crews on board the ships and the officers on the watch are aware of the presence. The alertness of the officers, however, depends on their stress level. The alertness depends on factors that draw the attention of the officer to the wind farm as well as the situation on the bridge.

Table 3.6. Contribution of performed "Officer on watch" tasks (SAFESHIP 2005).

Alertness	*Wind farm unknown*			*Wind farm known*		
Stress level	***Low***	***Medium***	***High***	***Low***	***Medium***	***High***
Observing surroundings	0.55	0.5	0.458	0.7	0.65	0.6
Observing Radar/ AIS	0.2	0.182	0.167	0.25	0.25	0.2
Performing other duties	0.25	0.318	0.375	0.05	0.05	0.2

The results of the calculations are shown in the table below. The causation factor assumed by GL is 3.25E-04 (95% aware of the existence and position of the wind farm).

Table 3.7. Influence of the assumed level of alertness on the causation factor (SAFESHIP 2005).

Alertness	*Causation factor*
50%	5.97E-04
60%	5.36E-04
70%	4.76E-04
80%	4.15E-04
90%	3.55E-04
95%	3.25E-04
100%	2.95E-04

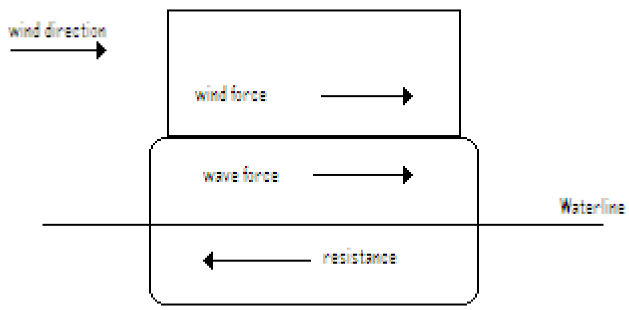
3.4.1.2 Drifting collision

The models for drifting collisions used by MARIN, GL and DNV are very much alike, while the assumption made for some important factors like drift speed, emergency anchoring, etc. differ. Quite a lot of assumptions have been made, which implies a lot of uncertainties. The first assumption made is for the probability that an engine failure occurs. The vessel starts drifting – if no redundant propulsion is installed – with a velocity that is based on the wind and waves, the current and ship characteristics such as ship size or loading conditions. To stop the drift, there are possibilities such as repairing the engine failure in a certain time or carrying out successful emergency anchoring procedures. To repair the vessel a specific amount of time is needed, depending on the type of failure. Emergency anchoring is only successful if the vessel is not drifting too fast, and there are other parameters which are important such as the seabed composition, the size of the vessel, etc. The drift can also be stopped by a salvage tug, if the tug can reach the vessel before a collision occurs.

Similar to the powered collision models, it is possible to identify an important parameter which results in a difference in the estimated collision frequency. A higher drift velocity means decreased time required for the drifting ship to reach the wind farm, leading to higher probability of failure to repair the engine in time. It also means increased probability of failure to anchor and decreased probability to assist the ship by a salvage tug because the time for a salvage tug to reach the disabled vessel has decreased. The models of GL, MARIN and DNV are difficult to compare with respect to drift velocity, because they are based on a different breakdown in classes of vessels and different assumptions for the wave component in the drift velocity. However, in the SAFESHIP 2005-project it was stated that the drift velocities calculated by GL are lower than the drift velocities used by MARIN, which explains why there are considerable differences in the collision frequencies. The main reason for the differences in the drift velocity is stated to be that the wave component of GL is nearly negligible, while in MARIN's model the wave component for the smaller Beaufort classes is even higher than the wind component.

The assumption made for the disabled ships are however the same:

- the wind and waves act in the same direction
- the wind direction and velocity are kept constant during the drifting
- mass effects are not included in the model
- the ship moves purely in the lateral direction which is equal to one degree of freedom
- the forces consists of the wind force, the averaged second order wave force and the resistance of the ship through the water
- The effective collision width is the ship length plus the dimension of the object perpendicular to the drifting path



MARIN uses the following formulas:

$$F_{Wind} = \frac{1}{2}\rho_{air} A_{Lin} C_{dWind} v_b^2$$

$$F_{Resistance} = \frac{1}{2}\rho_{water} L_i T_{in} C_d v_{drw\_bin}^2$$

$$F_{Wave} = \frac{1}{16}\rho_{water} g \zeta_b^2 L_i R^2$$

v_{drw_bin}	=	drift condition of ship i in loading condition n by wind and waves belonging to Beaufort class b as a result of the wind
v_b	=	wind velocity for Beaufort class b
v_{wi}	=	wind velocity
v_s	=	ship speed
$v_{T,Wd}$	=	velocity of tidal current and the current induced by drift
ρ_{air}	=	density of air (GL=1.3 [kg/m^3])
ρ_{water}	=	density of water (GL=1024 [kg/m^3])
A_{Lin}	=	lateral wind surface of ship i in loading condition n (GL 90° relative wind direction)
T_{in}	=	draught of the ship i in loading condition n
L_i	=	length of the ship i
ζ_b	=	significant wave height assumed to be generated by Beaufort class b
ζ_b	=	significant wave amplitude (Hs/s)
C_{dWind}	=	lateral wind resistance coefficient
C_d	=	lateral resistance coefficient of the underwater body of the ship (MARIN~0.9; GL~0.855)
C_{dWe}	=	wave induced drift coefficient (0.5)
C_{dcurr}	=	force coefficient (0.6)
R	=	wave drift coefficient
g	=	gravity
h	=	water depth
T_p	=	mean wave period for a given Beaufort class
∇	=	displacement of the ship

The wave drift coefficient is estimated from values from experiments and the relation for R is dependant on the wave number k and the draft T given by:

$$a*(Tk)^3 + b*(Tk)^2 + c*(Tk) = -1.4736*(Tk)^3 + 2.4765*(Tk)^2 - 0{,}0315*(Tk)$$

The wave number is derived from wave theory for shallow and deep water (h → ∞ : tanh(kh) → 1) waves:

$$\left(\frac{2\pi}{T_p}\right)^2 = kg\tanh(kh)$$

The equilibrium between all forces is assumed and this results in a drift speed of:

$$v_{drift,Wind}(i,b,n) = \sqrt{\frac{\rho_{air}}{\rho_{water}}\frac{A_{Lin}}{L_i T_{in}}\frac{C_{dWind}}{C_d}v_b^2 + \frac{1}{8}\frac{\zeta_b^2 g}{T_{in}}\frac{R^2}{C_d}}$$

GL uses the following formulas:

$$F_{Wind} = \frac{1}{2}\rho_{air}A_{Lin}C_{dWind}(v_{Wi} + v_s)^2$$

$$F_{Current} = \frac{1}{2}\rho_{water}L_i T_{in}C_{dcurr}(v_{T,Wd} + v_s)^2$$

$$F_{Wave} = \frac{1}{2}\rho_{water}g\nabla^{1/3}\zeta_a^2 C_{dWe}$$

DNV uses the following formula for the contribution of a piece of length d_i of the navigation lane:

$$F_{drift} = N \cdot f_{fop} \cdot \frac{d_i}{v_{ship}}\frac{\Theta_i}{360}W_{drift}\sum_{windclass}P_{windclass,i}(1 - P_{repair,i})(1 - P_{anchor})$$

- 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 successfully stop. 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 knots depending on the wind conditions, which may be conservative.

Again, a force equilibrium is assumed to derive the drifting speed.

The tidal current is included in GL's Monte Carlo calculations with a random value from the current distribution for each start position. MARIN includes a projected speed in the direction of the drift velocity, which is added to the drift velocity. This seems to be unnecessary, because the tidal currents should result statistically in the same collision frequency as without tides included.

Table 3.8 shows the engine failure rates used in the different models. The data from Lloyd's Register Fairplay (LRF) contains only engine failures which have lead to serious delay or cases where the vessel had to be towed. The different consulting companies agreed on the harmonised values but will continue to use their own models with different ship types and ship sizes.

To verify the assumptions made by MARIN, GL and DNV, the Technical University of Denmark performed a study on the probability of the propulsion machinery to fail (SAFESHIP 2005). Two Bayesian networks were used to model the failures of the main engine and the steering gear. The result was found to be 0.023 (1/year) for the main engine failure rate and 0.0147 (1/year) for the steering gear failure rate.

Table 3.8. Engine failure rates used in the different models (data from SAFESHIP (2005)).

Model	***DNV***		***GL***	***MARIN***		***Harmonised***
Based on	***one propulsion machine***	***more than one propulsion machine***		***LRF[1)]***	***Dutch coast guard***	
Breakdown frequencies (1/hour)	$4.6 \cdot 10^{-4}$ (large) $2.8 \cdot 10^{-4}$ (small ships)	$1.34 \cdot 10^{-5}$	$2.0 \cdot 10^{-4}$	$2.9 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$ (1/ hour at sea)	$2.5\ 10^{-4}$
Average cruising speeds	12 knots	16 knots				

GL's "self repair function" is based on a study made for Prince William Sound (DNV et al 1996). The function is described in the table below and illustrated in the Kriegers Flak case study in Chapter 5.

Table 3.9. GL's self repair function (data from Otto und Petersen 2003).

Time after engine failure	***Failure of self repair***
0-10 minutes	100%
10 minutes – 1 hour	decreases from 100% to 45%
1-11 hours	decreases from 45% to 10%
11-24 hours	decreases from 10% to 1%
24 hours – [1)]	1%

[1)] Otto und Petersen (2003) also says that after 24 hours, successful self repair is assumed.

MARIN bases their "self repair function" on statistics from the Dutch coastguard. They established a function which has to be multiplied by the average number of drifters per year (56.5 was obtained from statistics):

$f(t)=1$ for $t<0.25$
$f(t)=1/(1.5(t-0.25)+1)$ for $t>0.25$

where t = time after the engine failure occurred (hours)

The calculations are stopped after 24 hours. In the figure below the function is illustrated for 56.5 drifters per year.

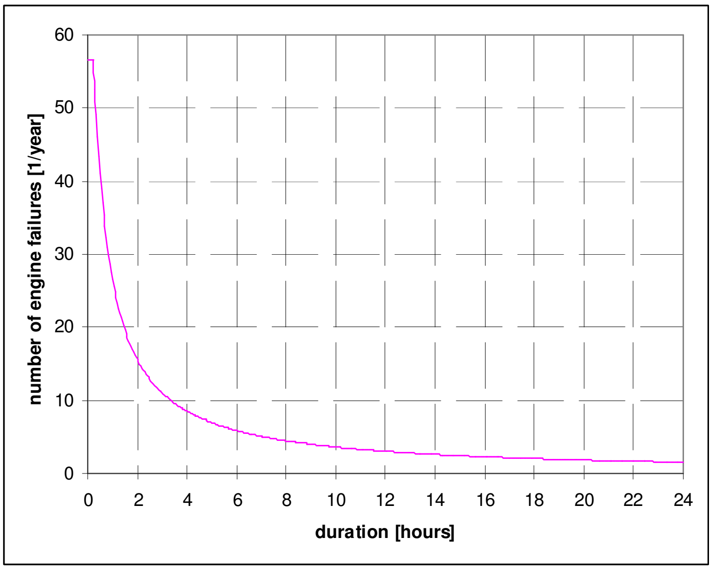


Figure 3.5. "Self repair function" used by MARIN with 56.5 drifters per year.

The probability that an emergency anchoring procedure is successful depends on factors including the drift speed, the vessel size, the weather conditions and even character of the sea bottom. Nevertheless, in order to harmonise their assumptions GL and MARIN have changed the determining factor for emergency anchoring in their models from the drift velocity to the wind speed. For mud/sand sea bottom

DNV, GL and MARIN will use proposal 2 from Figure 3.6. If the sea bottom is of a different type the function has to be adapted and will be somewhere between proposal 1 and 2.

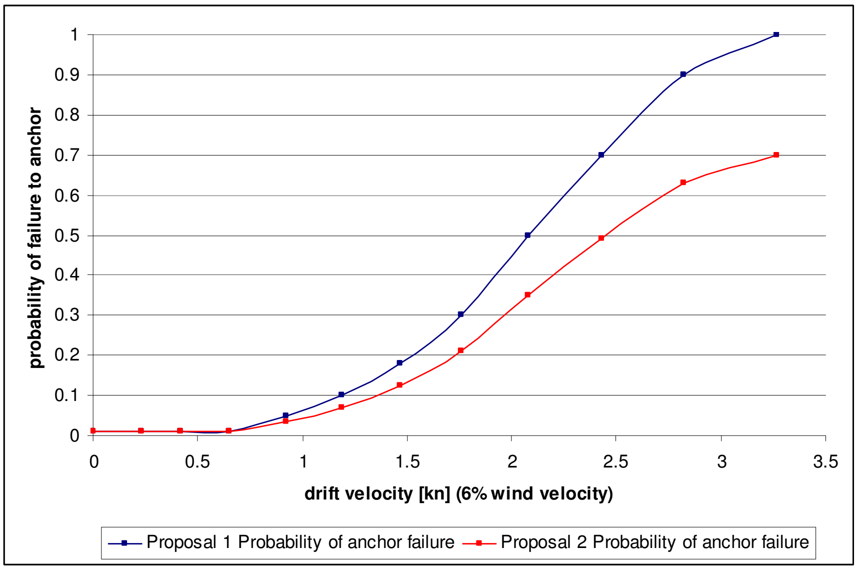


Figure 3.6. Probability of failure to anchor (data from SAFESHIP 2005).

3.4.1.3 Further work

- *Automatic Identification system (AIS)*

GL has tried to include the reduction of the collision risk resulting from the use of AIS in their Bayesian network model. This reduction results from the use of AIS transponders installed on the wind farm to warn the crews of the passing ships of the wind farm's existence, and the AIS receivers to warn the personnel of the wind farm of a ship on collision course with the wind farm so that the crew of that particular ship could be warned. Under the assumption that 70% of ships are equipped with AIS and use it, 68% of the potential powered collisions are likely to be prevented. Under the assumption that 50% of the ships are equipped with AIS, GL calculated a 50% reduction in collisions.

- *Vessel Traffic Monitoring (VTM)*

GL have also used included VTM in their Bayesian net model. From their study it can be concluded that VTM can have a positive impact on the causation factor.

- *Salvage tugs*

Tugs can have a positive impact on the risk of collision for disabled vessels, but there must be enough time available. It takes some time to issue an alarm and activate the salvage tug. The tug then needs time to reach the vessel, and this is dependent on the distance between the salvage tug and the disabled vessel, the drift velocity of the disabled vessel and the cruising speed of the tug (both dependent on the weather conditions). More time is then needed to establish a towing connection between the vessels, a factor which depends on the equipment available on the tug and the disabled vessel, the experience of the crews and the weather conditions. When the towing line is established, the tug can reduce the drift velocity of the drifting vessel. GL uses a conservative value of 1 hour for stabilising the vessel.

The required towing capacity of the tug boat is calculated by similar formulas for the forces as for the drifting speed. The coefficients are taken for a relative wind direction of 155°, which is an angle based on experience and simulations. The resulting coefficients are:

C_{dWind} =0.75, C_{dWe} =0.5 and C_{dcurr} =0.6

The required bollard pull is then calculated by the sum of the wind, wave and current forces divided by 0.6 which is the average efficiency of the towing capacity (the efficiency of the propeller can be reduced by factors such as heavy seas). According to GL, the risk reduction factor attributable to tugs is in the range of 3-14, which is probably a value only applicable to the coasts of Germany where there is a high density of salvage tugs.

3.4.2 Ship – Wind Turbine Structure Consequence Estimation Techniques

A vessel colliding with a wind turbine structure can result in damage to both the vessel and the wind turbine structure, and consequences can include the following:

1. Environmental damage:
    - Spill of fuel oil from the vessel
    - Spill of environmentally hazardous cargo from the vessel
    - Spill of oil and hazardous liquids from the wind turbine structure (gear-box oil, etc.)

2. Human injuries or fatalities:
    - Human consequences are possible if the vessel founders or sinks or if portions of the wind turbine structure fall and strike the vessel.

3. Economic loss:
    - Loss of revenue resulting from temporary loss of power generation capacity
    - Potential loss of good will or reputation for companies involved (especially if the accident is deemed the result of negligence).
    - Damage to the ship which results in delay of the ship, costs due to repair and stays at a repair yard, etc.
    - Costs for salvage

Navigational risk assessments that have been carried out to date have focussed primarily on consequences relating to spills, and the analyses have been rather limited. More recent analyses (e.g. the navigational risk assessment carried out by DNV for the Rødsand 2 Wind Farm (DNV 2007)) have included an assessment of human consequences but these have been quite broad estimates.

The two types of scenarios to be considered when assessing the consequences of a vessel impacting with a wind turbine structure include:

- Vessel drifting into the wind turbine structure, either head-on or at an angle
- Vessel collision while vessel is powered, possibly at full speed, either head-on or at an angle.

Factors that affect the severity of ship collision with a wind turbine structure include:

- Vessel weight
- Vessel speed
- Vessel stiffness
- Wind turbine structure dimensions and materials
- Wind turbine structure foundation type.

For conducting an analysis of collision severity, representative vessel types should be selected for the analysis, based on vessel traffic statistics for the area. Consideration should be given to those vessel types that may result in significant environmental damage as a result of potential fuel oil spills or cargo spills. In addition, "worst case" should be considered from the perspective of the wind turbine structure. In Germany, the Federal Environmental Agency (UBA) proposed a single hull 160,000 DWT oil tanker as the design ship in the accidental limit state (ALS) to determine necessary preventative action in the event of an offshore wind turbine failure (Biehl and Lehmann, 2006). For the Cape Wind Farm assessment, vessel traffic information for the area and information on navigation routes was consulted in conjunction with information on water depths to select the vessels that could reasonably be expected to be involved in a collision with the proposed wind turbine structures (Ali and Zheng, 2003).

For collision modelling, the angle of collision may have a significant impact on the type of damage that the vessel may sustain. An angled impact may be more severe than a head-on or a right angle impact and a sensitivity assessment of the impact angle should be considered.

The main types of consequence modelling that have been carried out for offshore wind farms include the following:

- Semi-quantitative assessment: Scenarios are developed based on probability modelling. Ship types that contribute the most to the collision frequencies are considered in more detail in an oil spill analysis. Possible spill volume is estimated based on bunker oil volume, number of bunker oil tanks, and location of tanks.
- Estimation of impact energy distributions for the structures: This is a simplified method that calculates total kinetic energy for collisions using displacement and velocity of vessels from local survey data.
- Finite Element Modelling: The collision is simulated using finite element analysis software to predict the collision sequence and specific damage to both the ship and the wind turbine structure.

Each of these methods is discussed in more detail in the following sub-sections.

3.4.2.1 Semi-quantitative assessment

Semi-quantitative assessments usually involve a review of the probability assessment and ship traffic data to identify those ship types that contribute most to collision frequencies or that could be considered a worst-case in terms of amount of oil spilled. The analysis described by Randrup-Thomsen et al. for Horns Rev is an example of this technique. Oil spill scenarios for specific ship types were developed based on the results of the ship collision frequency for the area. Possible spill volume was estimated based on information taken from Lloyds Register of Ships to develop a connection between the ship size and type and the bunker volume in the tanks. A ship drifting sideways into one of the wind turbines was considered to be the most likely collision scenario, and based on this it was assumed that 30% to 50% of the total bunker oil volume would leak from the tanks of each ship size. This was considered to be a conservative approach.

3.4.2.2 Estimation of Impact Energy Distribution

Collision software such as COLLRISK and COLLIDE generate impact energies for vessel types. COLLRISK, for example, bases its analysis on the following general equation:

$$E = \frac{1}{2} m (1 + a) v^2$$

where, E = total kinetic energy (kJ)
m = displacement of the vessel (tonnes)
a = hydrodynamic mass factor
v = velocity of the vessel (m/s)

(from Anatec, 2002).

This method was used in the Burbo Bank wind farm navigational risk assessment (Anatec, 2002).

For the Gunfleet Sands Wind Farm, the Collide 2.60 model was used to create a log-log plot of the annual collision frequency versus impact energy for locations judged to have the highest and the lowest annual collision frequencies (Safetec, 2002).

These reports did not provide any further analysis with regards to possible ship damage or spill volumes.

3.4.2.3 Finite Element Modelling

Finite element modelling develops a model of the collision and provides expected damage to the ship structure and the wind turbine structure. Detailed input data is required, including the following:

- Ship particulars, including materials information, sufficient to develop a finite element model
- Wind turbine structure and material information to develop a finite element model
- Soil condition information

Assumptions and simplifications are often made to be able to develop a model at a reasonable cost and to suit the requirements of the analysis. Although FEM-modelling provides the most information on the collision sequence, it is expensive due to the amount of time required, and the results are specific to the types of ships modelled. However, this may be something that could be warranted in cases where probabilities are relatively high or if there is a concern about a specific ship type or cargo.

Examples of finite element modelling used to assess consequences of ship collisions with offshore wind turbine structures are as follows:

Cape Wind Farm Analysis
An impact analysis model that used a "three degree of freedom dynamic impact analysis computer program that solves Newton's Second Law (i.e. Force equals Mass times Acceleration) over time" was used for the Cape Wind navigational risk assessment (ESS Group 2003). The largest ship size investigated in this analysis was a 1500 DWT ferry, which was considered to be the largest vessel that could possibly collide with the wind turbine structures (they were located on a shoal). A computer program was developed using Matlab to carry out the analysis. The program was referred to as "a multi-degree of freedom dynamical impact analysis". There was not very detailed information provided about the foundation type – the tower was considered to have a spring at the soil interface for the purposes of carrying out the impact analysis.

Biehl and Lehmann LS-DYNA Modelling of North Sea and Baltic Sea Wind Farms

Biehl and Lehmann (2006) carried out a quantitative analysis of several collision scenarios for different ship types and for 3 types of foundation structures (a monopile, a jacket, and two tripod foundations (North Sea and Baltic Sea locations). Soil properties varied significantly between the two locations. The collisions were modelled numerically using finite-element modelling and calculations were performed using LS-DYNA software. It was felt that due to shortcomings in the modelling procedure the results could not be considered as an exact representation of an actual accident. However, it was felt that they may show possible consequences of such an occurrence and were useful for developing preventative and response measures.

The numerical model developed by Biehl and Lehmann (2006) had two main parts:

- Offshore wind turbine: this includes the structure, the foundation, and the surrounding soil
- Ship and the surrounding water.

The two elements that are in direct contact during the collision, the wind turbine and the ship, were represented as finite element models. The actual contact area on both structures was modelled in more detail than other parts of the structure. The foundation soil was considered to be an elasto-plastic deformable body.

Three foundation types were modelled, as follows:

- Monopile: considered the most cost-effective foundation type, and is the preferred solution in areas with sandy soil and water depths up to 25 m. It does not offer much resistance in a ship collision scenario.
- Tripods: These are used primarily in areas with water depths greater than 25 m. There are three piles, and Biehl and Lehmann claim that the local stiffness of the diagonal is much higher compared to those of the jacket, and this results in higher resistance to structural failure.
- Jacket: May be used in water depths of 25 to 50 meters, and has higher global stiffness as compared to the monopile. Apparently it exhibits a large variation of failure modes during collision. The jacket structure is placed on four piles.

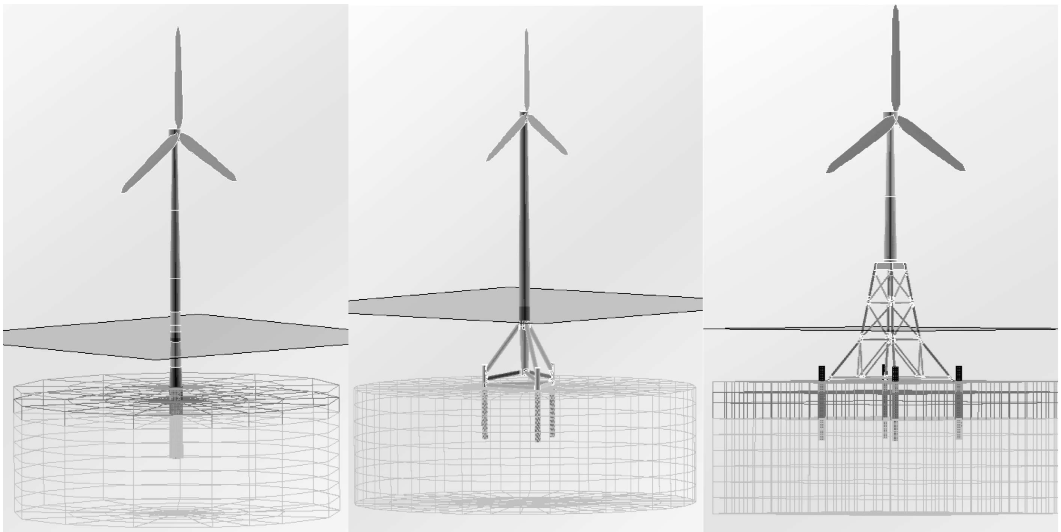


Figure 3.7. Offshore wind turbine support structures considered by Biehl and Lehmann (2006B). Figure taken from Biehl and Lehmann (2006B).

Four ship types were modelled, as follows:

- Medium size double hull tanker of 31,600 DWT
- Large single-hull tanker of 150,000 DWT
- 2300 TEU Container Ship
- Bulk carrier: 170,000 DWT

Results were as follows:

- Monopile: No serious ship damage or threat to the environment for the double hull tanker and the 2500 TEU container ship. For the single-hull tanker, however, a collision at an angle of 60 degrees caused the ship to fail at the contact area and develop a large hole in the side structure. It was estimated that this damage may allow the cargo from 2 holds to be released.
- Jacket: For the double hull ship, the estimated damage is more severe than for the monopile, but it is not considered to be enough to present a danger of spill.
- Tripod: For the double hull tanker, it was estimated that the ship may have severe damage resulting in penetration of both the outer hull and the inner hull. This was expected to happen only if the ship comes into contact with one diagonal during the collision sequence. If the ship does not hit a diagonal strut, the consequences of the collision are expected to be similar to those with the monopile. It was concluded that if the central joint is placed low enough (deep enough in the water) to prevent contact with the ship, collision consequences would be similar or better than what is observed with the monopile.

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Biehl and Lehmann concluded that the monopile and jacket foundation types should be considered before the tripod, unless the central joint of the tripod could be located lower than the maximum draught of ships expected to be trafficking the area. The modelling was only carried out for a drifting collision. A powered collision case was not modelled.

3.4.2.4 Environmental damage

The models developed by MARIN, DNV and GL include consequence models for the outflow of oil and chemicals. For MARIN's analysis of the Egmond aan Zee wind farm (Kleissen, 2006), assumptions for ship damage and oil spills were based on estimates of kinetic energy at the time of the collision. It was assumed that all energy would be absorbed, and damage to the ship was calculated "based partially on experience and partially based on complex calculations" (Kleissen, 2006). It was assumed that no spills would occur in the case of a drifting collision (Kleissen, 2006).

DNV has developed crude oil outflow models for different accident types and different hull configurations with normalised cumulative probability distributions.

GL also uses probabilistic and empiric formulas to calculate the oil spills.

The next step of a consequence analysis of a potential oil spill scenario may include drift, spreading and dispersion modelling of the oil spill. Drift modelling tools are regularly used in real response operations and may be combined with GIS-based coastline environmental sensitivity data to estimate the potential ecological damage and the beach clean up resources required and associated costs. The spill conditions, beach contamination and environmental impact vary from case to case and it is difficult to predict and to generalise in monetary terms the magnitude of potential environmental consequences.

The SeaTrack Web, developed by SMHI (Swedish Meteorological and Hydrological Institute), is a well established GIS-based modelling tool for drift predictions of oil and chemical spills at sea.

3.4.2.5 Human consequences

MARIN's risk analysis for Egmond aan Zee wind park only estimated potential injuries or fatalities resulting from the wind turbine structure falling on the ship's deck, and did not estimate injuries from other collision aspects (Kleissen, 2006). Estimates of the probability of a wind turbine collapse were based on kinetic energy estimates for specific ship types and operating speeds, as was done for the environmental damage estimates. Worst-case scenarios were assumed so that estimates would be conservative. For example it was assumed that in the case of a collapse, the wind turbine structure would always fall on the ship rather than away from it, and that the pile and the rotor would land completely on the deck, rather than grazing it. No dynamic modelling or experiments were carried out to validate assumptions.

DNV calculates the loss of lives based on statistics but states that the statistical uncertainty becomes large, because no accidents of this type have occurred. The basis for the detailed calculations was not provided, but the ship-ship collisions gave the biggest contributions. Considering the "worst-case" approach for the calculation of fatalities it was concluded for all calculations that the risk of dying due to collision with the wind farm is not significant.

3.4.2.6 Economic loss

DNV states that the loss of property is related to salvage, transfer or loss of cargo, repair cost and loss of profit due to downtime. In DNV's report for Rødsand (Christensen 2007), the expected costs are taken from information given by insurance companies and classified for different ship types. These values are then related to the most common ship sizes and connected to the probabilities for the different losses.

The German authorities (BSH) will include an assessment for the consequences of a collision in their newest guidelines. This assessment has to describe the safety of the foundation and the head bearing of the wind power plant (Biehl, 2007). Biehl also commented on the ongoing research project "Collisions of Ships and Offshore Wind Turbines: Risk of nacelle impact". Too many assumptions have to be made to include nacelle impact in the guidelines, because probabilities and consequences are unknown for many factors (e.g. forces acting on the head bearing, probability of a fall off, falling speed and direction of the hub or turbine, braking effect of the decks and cargo of the ramming vessel, etc.).

3.4.3 Ship to Ship Collision Probability Estimate

The wind park may affect the shipping traffic and can have positive or negative impact on the risk of ship-to-ship collision. The ship traffic routes might be modified due to the location of a wind park. Traffic separation schemes, improved buoyage and similar changes could lead to a reduced probability of ship-ship collisions, while changing the positions of existing shipping lanes, compression of the traffic, additional crossing of ships over main shipping lanes or other modifications could lead to increased probabilities of such a collision.
The probability is in general calculated for all shipping lanes by:

F(ship-ship collision)=P(collision| encounter)*F(encounter)

Many models exist to calculate the risk of ship-ship collisions. An investigation into the details of these models goes beyond the scope of this project. For further information on ship-ship collision models other references should be consulted (for example see Kristiansen (2005)).

3.4.4 Ship to Ship Collision Consequence Estimate

Consequences of ship to ship collisions which could be caused by navigation changes resulting from offshore wind parks include injuries, loss of life, environmental damage, cargo loss, and ship damage.

In terms of consequences the ship-to-ship collision might be worse than a ship-turbine collision, because usually higher kinetic energies are involved which lead to more extensive damage and the crew, cargo and bunker of two ships instead of one ship might be affected and might cause more fatalities, economic and environmental damage than the ship-turbine collision.

The consequences of ship-to-ship collisions resulting from the presence of a wind farm would be the same as for collisions caused by other factors such as equipment malfunction, navigational error, human error, etc. Historical accident databases such as LMIU can be consulted to provide empirical data on consequences from actual collisions. This type of detailed investigation of consequences has not been included in most navigational risk assessments for offshore wind farms, and changes in probability of ship to ship collisions are generally the extent of the work that is usually performed for this area.

If a ship-to-ship collision results in a spill that drifts towards an offshore wind farm, consideration should be given to the additional challenges of spill clean-up and recovery in a wind farm area. The Bonn Agreement Counter-Pollution Manual (Bonn Agreement, 2007) states that wind turbines should be turned off when recovery vessels are operating within a wind park, and that dispersant spraying, if appropriate, would need to be done from a vessel and not an aircraft.

3.4.5 Grounding Probability Estimate

Offshore wind farms may actually have a positive effect on the risk of grounding, as they may result in a reduced probability of grounding in the area of the farm. At the same time, the probability of groundings might be increased due to modifications of the shipping lanes. The potential of the grounding risk to increase or decrease significantly should be looked at on a case by case basis. Several models are used for risk analysis concerning grounding of ships and the discussion of these risks goes beyond the scope of this work. The technical literature is again referred to if more detailed information is desired.

3.4.6 Grounding Consequence Estimate

If it is the case that groundings are increased, consequences may need to be considered. Historical accident databases such as LMIU can be used to obtain empirical data on consequences from actual groundings. It is unlikely that detailed investigation of consequences from groundings would be necessary for navigational risk assessments for offshore wind farms. For a zero-alternative risk analysis, the grounding consequences are of importance.

3.5 Effects on Radar, Radio, Navigation Equipment, etc.

A number of studies have investigated the effects of wind turbines on navigation equipment, as follows:

- North Hoyle Wind Farm: Experimental field tests were carried out to assess the effects of the wind farm structures on marine systems in operational scenarios. The work was commissioned by the UK Maritime and Coast Guard Agency, Navigation Safety Branch, and was carried out by QinetiQ (Howard and Brown, 2004). A summary of the goal of the work and results was provided by Howard and Brown (2004) as follows:

  > "The trials assessed all practical communications systems used at sea and with links to shore stations, shipborne and shore-based radar, position fixing systems, and the Automatic Identification System (AIS). The tests also included basic navigational equipment such as magnetic compasses. The effects on the majority of systems tested by the MCA were found not to be significant enough to affect navigational efficiency or safety, and an on-going collection of data on such systems is expected prove these conclusions."

  Additional work was carried out at North Hoyle in March 2005 to investigate the effects on aircraft systems (Brown, 2005). Tests were carried out with a Sea King Mark II aircraft, and results indicated that "radio communications from and to the aircraft operated satisfactorily, as also did its VHF homing system" (Brown 2005).

- Horns Rev (as reported in ESS Group, 2003): It has been reported that there have been no disruptions or difficulties observed with VHS communications between vessels in and around the wind park, or between vessels in and around the wind park and the traffic coordination centre at Esbjerg and the Coast Guard/Rescue Centre. In addition there have been no radar shadows observed from the towers' rotating turbines in the Horns Rev park.

- Egmond aan Zee Wind Farm (OWEZ): As part of the risk assessment for the OWEZ monitoring and evaluation program (Kleissen, 2006), MARIN carried out simulations to assess the effects of the planned wind farm on shipping radar. The simulations were performed on MARIN's full mission bridge simulator, and three runs were performed. Radar observations on a containership were simulated, and a coaster and a tug were used as radar targets. The study concluded that the wind farm has a negative influence on radar performance, but not to the level that detection of other vessels becomes impossible. It was also concluded that radar performance improves when the number of wind turbines between two ships decreases, as would occur when ships are sailing to the same corner. The study did not consider the impact of ghost targets resulting from reflections of side bundles, because the simulator was not equipped to include the reflections. It was recommended that a field trial be conducted after completion of construction of the wind farm to assess this issue.

3.6 Effects on Search and Rescue Operations

Possible speculated effects of an offshore wind park on search and rescues (SAR) operations include both positive and negative influences. Positive influences include the establishment of a place of refuge at each wind turbine structure. A negative influence is that any collision with wind turbine structures will add additional cases to the coast guard's SAR work load. Another potential negative influence is interference of wind farm structures with search and rescue helicopters.

An assessment was carried out for Cape Wind Farm (ESS Group, 2003) in Massachusetts, USA, by reviewing information from the coastguard's database of missions, by reviewing USCG SAR operational guidelines, and through consultation with coast guard staff involved in SAR. Data from a ten-year period for the area around the proposed wind farm was evaluated. The majority of the responses were by sea, although 4% were by air. The study concluded that the presence of the wind farm would be a benefit for search and rescue for the following reasons:

- each wind turbine structure would have an alphanumeric identifier painted on it, and the coast guard and other rescue agencies would have a plan showing the location of each tower, thus helping them with planning rescue operations.

- the wind turbine structures would have rescue lines attached and could serve as a place of refuge for persons in the water after abandoning ship or falling overboard.

- work vessels would be in the area periodically for wind farm maintenance and these vessels would be able to assist vessels in distress in the area.

The UK's Maritime and Coast Guard Agency undertook helicopter trials in March 2005 at the North Hoyle offshore wind farm to investigate whether marine and shore-based radar systems would be adversely affected by the presence of an offshore wind farm (Brown, 2005). The study also included a discussion of how search and rescue helicopters may be affected by the presence of offshore wind farms. Results showed that radio communications to and from the aircraft were satisfactory; vessels, turbines, and personnel in the wind farm could be clearly identified in dry weather on the aircraft's thermal imaging system; and there were no compass deviations (Brown, 2007). Some of the issues identified were as follows:

- there are "significant radar side lobe returns from structures" (Brown, 2005), and these can limit detection of vessels that are within 100 metres of the turbines;
- turbine blades must be confirmed to be locked before helicopter rescue can be considered safe. The North Hoyle wind turbine blades could not be remotely locked and thus helicopter rescue from these turbine structures was considered extremely (and perhaps prohibitively) dangerous;
- thermal imaging is limited when there is mist or precipitation;
- vessel or shore-based marine radar tracking of helicopter movements within the wind farm was poor;
- aircraft power requirements are increased downwind of the wind farm.

There were also limitations identified for the specific SAR helicopter, equipment, and crew in the study area. The Sea King Mark III helicopter used has a radar console that was not visible from the cockpit, and the radar operator doubled as a rescue hoist operator. This meant that surface rescue from the helicopter would not be feasible in restricted visibility conditions, as the crew would be "radar blind" when operating the winch.

3.7 Validation of Risk Assessment/Quality Control/Uncertainty/Sensitivity

Available data for validation could include empirical accident and incident data from contacts with offshore structures, and comparison with risk assessments carried out for other wind farms. A discussion of model uncertainty and validation is provided below.

3.7.1 Model accuracy and uncertainty

A number of uncertainties are introduced when risk calculation models are elaborated. Various degrees of uncertainty are associated with the following areas and factors.

- Ship traffic statistics – recorded AIS ship traffic data have high accuracy but need to be simplified for modelling purposes to a limited number of main shipping lanes and all ships do not follow the lanes
- The outlined risk model
  - there may be potential accident scenarios that are not included or unknown secondary hazards
  - limitations in the possibility of describing the reality in a model
- Engineering judgements and assumptions on key model probability parameters
- Assumptions regarding the consequences of collision accidents in terms of fatalities per final outcome, potential environmental impact and economic damage value.
- Statistical and empirical probability data - historical data on collision probabilities are incomplete and reflect historical safety regimes and technical standard of ships

If the range of uncertainty for each parameter is estimated, the possible impact of the uncertainties and needs for further information and analysis may be identified. Sensitivity analysis can be conducted by systematically varying some key parameters in the calculation of the final outcome. In the case study for Kriegers Flak (Chapter 5) this is exemplified.

3.8 Risk Acceptability and Risk Acceptance Criteria

There are no internationally adopted general standards for risk acceptability applicable to the issue of navigational safety and offshore wind farms. There are also no quantitative acceptance criteria established in Sweden that may be applied in this area.

The formulation of quantitative accident risk acceptance criteria is a sensitive political issue and very much associated with the subjective perception of risk and risk aversion.

The qualitative risk estimations addressed in this study basically focus on the probability of ship wind turbine collision and are expressed in probability per year or expected return period (in years) for the event. The consequences of the collision events are not quantitatively modelled in detail and no evaluation in relation to possible or proposed acceptance criteria are presented.

3.8.1 Individual and societal risk

When both the probability and potential consequences of accidental events are analysed, the combined risk figures are usually quantified in terms of expected fatalities. Acceptance criteria can then be formulated either based on individual risk or societal risk.

For specific occupations, locations or activities, individual acceptance criteria may be expressed by an annual fatality risk. For large systems, which expose a large number of people to risks, and where a large number of people are affected by possible accidents, societal risk considerations provide a more appropriate basis for risk acceptance criteria. The societal risk is expressed in terms of frequency versus number of fatalities, and two of the most commonly used methods of describing such risks are risk matrices or FN-curves. Risk matrices and FN diagrams will also indicate which levels of risks are acceptable and which are not. Potential Loss of Lives (PLL) is another measure of societal risk for a defined system or activity.

Table 3.10. Example of Risk Matrix.

Example of Risk Matrix with Risk index figures and indicative acceptance criteria. Red area is unacceptable risks, Green is acceptable					
Frequency index		***Severity index***			
		Minor	Significant	Severe	Catastrophic
		1	2	3	4
Frequent	7	**8**	**9**	**10**	**11**
Probable	6	**7**	**8**	**9**	**10**
Reasonable probable	5	**6**	**7**	**8**	**9**
Remote	3	**4**	**5**	**6**	**7**
Extremely remote	1	**2**	**3**	**4**	**5**

The area between the red intolerable area and the green tolerable area is called the ALARP area (As Low as Reasonably Practical) and indicates that risk reduction measures should be applied. The scale of consequences illustrated by the risk matrix above may also be transformed into terms that represent environmental consequences (e.g. volume of spilt oil) or economic loss figures.

3.8.2 Individual risk acceptance in shipping industry

With regard to maritime safety and acceptable risk exposure of crew members, risk acceptance criteria have been proposed. The criteria proposed in MSC 72/16, based on figures published by the UK Health & Safety Executive, have been used by various FSA studies. The table below presents the suggested acceptance levels for the individual risk to crew members.

Table 3.11. Individual risk levels for exposed crew members.

Individual risk levels for exposed crew members	
Risk level	***Annual fatal risk***
Maximum tolerable risk for crew members	10^{-3}
Negligible risk	10^{-6}

3.8.3 Different types of criteria for offshore wind farms

As illustrated in Chapter 3.2, a number of different views on risk acceptance for offshore wind farms can be identified, and relevant acceptance criteria may consequently be formulated in different terms.

In this study, the *navigational safety perspective* is the main focus and criteria may be based on *relative risk evaluation*. For example a criterion could be that the park establishment shall not generate increased probability for ship-structure collision, ship grounding, ship stranding or ship-ship collision in a specific navigational area where the farm is located.

If the criterion is formulated in *absolute risk figures*, e.g. by ALARP limits, then it is still important to compare the risk figures with the baseline case before the wind farm is established.

In many cases it is also relevant to study the risks from the proposed *wind farm's point of view*. This is of course relevant for the farm owner and operator and may for example influence insurance discussions. Calculation of expected collision probability or return periods is also relevant for comparing different wind farm layout or localisation alternatives from a navigational safety point of view.

3.8.4 Acceptance criteria in Germany

The German authorities have agreed with a group of experts on risk acceptance criteria. Offshore wind farms that result in a collision probability with a return period of more than 100-150 years are generally accepted by the German authorities. This range of return periods covers the results from different models (i.e. no specific model type is specified). A precaution and safety concept might still have to be developed for the facility. If the collision frequency of crude oil tankers and chemical or product tankers plays a major role in this collision frequency, further studies might be necessary. If the return period is between 100 and 50 years the project might be rejected. Further studies are required and a more detailed look into possible consequences is mandatory. Return periods below 50 years are generally unacceptable and the wind farm may only be considered for possible approval from the authorities if risk reducing measures which increase the return period above 50 years or more are applied (Bundesministerium für Verkehr-, Bau und Wohnungswesen, 2005).

Table 3.12. Risk acceptance criteria in Germany (based on data from Bundesministerium für Verkehr-, Bau und Wohnungswesen (2005)).

Acceptance	***Time between collisions [years]***
Acceptable	>100 (100-150)
Further analysis necessary: acceptability considered on a case by case basis,	50…100
Not acceptable	<50

With regards to oil spills or other pollution resulting from a collision of a ship with a wind power plant the park can receive approval, if the return period is between 300 to 450 years for a spill volume of 50 m^3 or more.

The group of experts in Germany (Bundesministerium für Verkehr-, Bau und Wohnungswesen, 2005) gave also orientation values for different assumptions made for the calculations. The German risk acceptance criteria presented above are valid only in combination with these orientation values. This includes a minimum distance from shipping lanes to a wind park of 2 nautical miles plus the 500 meter safety zone (safety zone according to UN law of the sea convention article 60). Other values specified by the experts are as follows (for more values, see Bundesministerium für Verkehr-, Bau und Wohnungswesen, (2005)):

- The minimum ship size to be looked at: 500 GRT
- the maximum drift speed of disabled ships: 4 kn
- average ship speed: 11 to 18 kn for RoRo; about 20 kn for RoPax; 25 kn for large container vessels; and 35 kn for High Speed Craft (HSC)

- lateral distribution should consist of a Gaussian distribution and a uniform distribution with a size of 2% of the Gaussian distribution (the width of the uniform distribution is assumed to be 6 times the standard deviation)
- Orientation values for different fairways are:

Table 3.13. Standard deviation for the Gaussian distribution describing the lateral distribution of ships on the lanes (Bundesministerium für Verkehr-, Bau und Wohnungswesen, 2005).

Description	***Standard deviation for Gaussian distribution [nm]***
Port approach	0.2 to 0.3
Conspicuous navigational points, e.g. navigational marks, buoys	0.3 to 0.4
Navigational channel with traffic separation	0.5
Waypoints in wider shipping lanes	0.5 to 1.0
Waypoints in open sea areas	2.0

- The relevant area to be looked at for powered collisions is 15 nm (20nm) from the outermost wind power plants.
- The causation factor (probability for a ship on a collision course to not take any corrective action, due to technical or human failure) is 3.0E-04.
- The effective collision breadth is 1.2B plus the diameter of the obstacle for powered collisions and the ship length (90 degree drift direction) plus the obstacle width for drifting collisions.
- the maximum drift time is 24h.
- The rudder/ engine failure rate is 2.5E-04 per hour. For ships with double engine-rudder installations this factor can be reduced.
- The probability of anchor failure is dependent on the wind speed, waves and sea bottom characteristics. The following probabilities are assumed for Baltic Sea conditions:

Table 3.14. Probability of anchor failure (Bundesministerium für Verkehr-, Bau und Wohnungswesen, 2005).

Beaufort scale	*Probability of anchor failure*
0	0.01
1	0.01
2	0.01
3	0.01
4	0.035
5	0.07
6	0.126
7	0.21
8	0.35
9	0.49
10	0.63
11	0.7
12	0.7

- The following formula can be used for the failure rate depending on the time required to repair the failure:

  $f(t)=1$ for $t<0.25$ h

  $f(t)=1/(1.5(t-0.25)+1)$ for $t>0.25$ h

- When including effects of AIS an efficiency is assumed with a factor of 1.25
- When including effects of VTM an efficiency is assumed with a factor of 2-4

3.8.5 Other acceptance criteria

In GL’s risk analysis report for the Belgian wind farm “Thornton Bank” the risk matrix and values shown in the table below are used for defining the qualitative frequency, which is the background for acceptance/ non acceptance.

Table 3.15. Classification of consequence severity and occurrence frequency (Neuhaus and Thrun 2003).

Frequency H [1/year] safety (quantitative)	$H>10^{-1}$	$10^{-1}\geq H>10^{-2}$	$10^{-2}\geq H>10^{-3}$	$H\leq 10^{-3}$
Frequency H [1/year] environment (quantitative)	$H>2x10^{-1}$	$2x10^{-1}\geq H>2x10^{-2}$	$2x10^{-2}\geq H>2x10^{-3}$	$H\leq 2x10^{-3}$
Frequency (qualitative)	probable	improbable		extremely improbable
	frequent	remote	extremely remote	
Consequence / failure severity classification	minor	major	severe	catastrophic

In MARIN's study by Kleissen (2006) a so-called "orientation" value is used for societal risk; the frequency of 10 people dying per seaway (per kilometre) is allowed to be a maximum of 10^{-4}. The "orientation" value is taken from the risk-standards for the transport of dangerous goods and it is stated by Kleissen (2006) that it is questionable whether or not this standard can/may be used for their study.

DNV has proposed risk acceptance criteria for application in the marine industry. The criteria are neither official DNV criteria nor are they recognized by regulatory bodies. The criteria are as follows:

Table 3.16. Proposed individual human fatality risk acceptance criteria for the shipping industry (Spouge 1997 and DNV 1999).

Risk acceptance criteria	***Value***
Maximum tolerable risk for crew members	1 fatality per thousand at risk per year
Maximum tolerable risk for 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 3.17. Proposed total loss, cargo spill and bunker spill targets for the shipping industry (DNV 1999).

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

Swedish Rescue Services Agency presents principles or general starting points for design of risk criteria. These four principles are (Davidsson et al 2003):

- Rimlighetsprincipen (principle of reasonableness)
- Proportionalitetsprincipen (principle of proportionality)
- Fördelningsprincipen (principle of apportionment)
- Principen om undvikande av katastrofer (principle of avoiding catastrophes)

3.9 Statements and recommendations from other stakeholders

In this context it may be interesting to note that the German Nautical Association proposes a safety zone of 1 000 meters around offshore wind farms instead of the 500 meters established by international law of the sea and agreed zones of national jurisdiction at sea. The proposal is based on navigational safety considerations (Deutscher Nautischer Verein 2004).

4 RISK REDUCTION MEASURES

This chapter includes a discussion of risk reduction measures that are appropriate for addressing specific hazards and risks. In addition methods for evaluation of risk reduction measures will be recommended.

Risk reduction measures can be grouped into the following main categories:

- Measures to reduce the probability of accidents and incidents
- Mitigation measures to reduce consequences (ship-related consequences, environmental consequences, etc.)

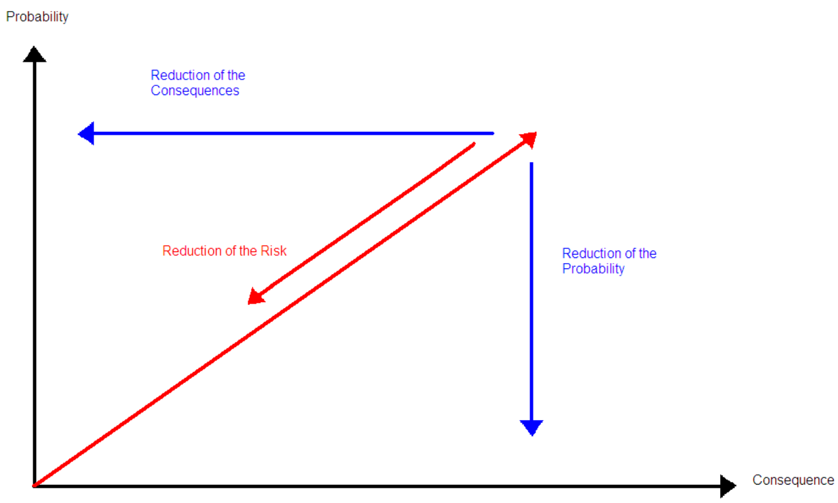

Figure 4.1. Risk reduction measures.

Examples of risk reduction measures include improved tug boat response time, installation of lights and navigation aids on wind turbine masts, and establishing safety management plans. It may be possible to assess some measures such as improved tug boat response time in a quantitative manner, while others, such as those targeted at reducing human error, may be assessed qualitatively. Measures can be grouped into categories based on the primary area of application, as follows:

- measures that can be applied at the wind farm;
- measures for ships, including specific measures for those transporting dangerous goods;
- measures to be applied to the whole marine area surrounding the park.

Examples of risk reduction measures in each category are provided in the following list.

Risk reduction measures that can be applied at the wind farm level to reduce the probability of a collision are as follows:

- Optimising the assembly of the wind power plants. This can be done using a risk analysis, even though the arrangement has a low impact on the collision frequency.
- Marking the wind farm as a prohibited area in the sea charts, the aeronautical charts and the nautical handbooks.
- Equipping the wind farm radar equipment and radar antennas with at best with redundant transmission. Further possibilities are VHF, radio frequency units, etc.
- Installing equipment with navigation lights on each WPP.
- Declaring safety zones around every WPP.
- Installing AIS transponders (at least two) at the wind farm. Studies carried out as part of the SAFESHIP project (SAFESHIP 2006) have shown that the use of AIS equipment on wind farms and ships will result in a reduced collision frequency.
- Producing a safety manual and preparing emergency plans.
- Installing camera and video equipment for observation of the wind farm area.

Measures for the wind farm to reduce the consequences:

- Constructing the WPPs in such a way that as little damage as possible is inflicted on the ship during a collision. This includes ensuring that the structural damage are kept low, and that the tower, the housing and the rotor blades of the WPPs fall away from the ship in the event of a collision.
- Structural construction of the surrounding of the power plants in a “collision-friendly” way, i.e. using fenders, etc.
- Using environmentally friendly coolants for the transformers.
- Equipping the WPPs with a fast shutdown and an emergency brake.

- Installing the turbines at such a height that crews of colliding ships cannot be hit by rotor blades.

- Equipping the substation with a helicopter platform and installing docking possibilities for salvage tugs and SAR boats.

- Marking every power plant with a unique ID to simplify search and rescue operations.

- Producing a safety manual and preparing emergency plans.

- The cables should run covered in the ground to minimise dangerous situations in case of emergency anchoring

Measures for ships to reduce the probability of collision with wind farms include:

- Equipping the vessels with AIS, redundant navigational equipment, redundant propulsion systems, good conditions to make the connection by ropes to a tug easy, and reinforced towing bollard.

- Equipping ships with ECDIS (Electronic Chart Display and Information System), to potentially reduce navigational errors

- Education and training for the crew and preparedness for critical situations.

- Vessels which sail in the surrounding of the wind farm should be prepared to execute an emergency anchoring.

Measures for the sea area to reduce the probability of a collision:

- Establishing a traffic separation scheme.

- Constant monitoring and observation of the area, of the passing ship traffic and of the wind farm by Vessel Traffic Management. A study based on empirical data [Safeship, 2006] showed that VTM might lead to a reduction by a factor 2-10 of powered collisions. The German harmonisation group states that a factor of 2-4 is realistic.

- Observation and control of the vessels and their operation by the authorities.

- Emergency management

- Monitoring and reporting mechanism for passing and drifting vessels. In the Netherlands for example every disabled ship in the EEZ is obliged to report to the Dutch coast guard immediately.

- Allocation of salvage tugs including a certain sea position in heavy weather for the tugs close to areas with a high frequency of collision and grounding.

- Clear marking of the modified shipping lanes to avoid ship-ship collisions and groundings.

- A boarding team should be accessible at all time to assist the ship crew in establishing a connection to the salvage tug.

- Updated sea charts showing the wind farm should be available as early as possible to the public.

- A safety zone should be announced around the wind farm.

- It should be forbidden to sail through the wind farm.

Measures for the sea area to reduce the consequences:

- The private or state-owned tug assistance needs to have the ability to reach the disabled vessel in time and should have sufficient bollard pull to stop the drifting of the disabled vessels.

- Oil spill response plans should be made and sufficient capacities for response should be available.

- Regular training of SAR and oil spill response units should be conducted in or close to the wind farm.

A navigation channel from the base harbour of the working vessel to the working area together with a traffic controller coordinating the working vessels shall be introduced.

For the most exposed turbines the gravity foundations should be designed so the foundation plate is in level with the seabed. Alternatively scour protection or similar should be made with a minor gradient towards the centre column in order to avoid bottom rupture. None of the hazards related to the smaller boats were found to be in the unacceptable region.

Because the probability for a collision between a wind power plant and the service vessel is high, SAFESHIP suggests SWATH (Small Waterplane-Area Twin Hulls) for the work.

From the risk analysis point of view, damage of the wind power plant is the most probable consequence. The gearbox oil and the light diesel oil used in the power plants should therefore be environmental friendly.

During the construction of the park special measures should be conducted:

- Special sailing routes for the transport vessels.
- Clear marking of the area where the power plants are to be constructed, i.e. with lights, radar equipment, etc.
- Providing notification designating the wind farm as an air obstacle before the start of the construction.
- Special safety and rescue plans during construction of the wind farm.
- Safety notices to be sent out to ships which regularly sail within a designated proximity to the wind farm construction site.
- Informing the public and all the involved stakeholders in the area

4.1 Bonn Agreement Counter-Pollution Recommendations

The Bonn Agreement refers to a mechanism by which North Sea states, together with the European Community, work together to combat oil pollution in the North Sea and to perform surveillance to detect pollution. North Sea states include Belgium, Denmark, France, Germany, the Netherlands, Norway, Sweden, and UK and Northern Ireland. The Bonn Agreement Counter-Pollution Manual (www.bonnagreement.org) includes a chapter on offshore wind farms, which recommends that response authorities be prepared to handle incidents where oil slicks drift in to offshore wind farms. Chapter 8 of the manual discusses various measures that can be taken to reduce risk of oil spills in the vicinity of wind farms. Possible response mechanisms to a spill drifting towards a wind farm are described as follows:

- where mechanical recovery is feasible, recovery vessels will need to be allowed in to the park. It is proposed that turbines should then be switched off, even if there is adequate clearance between the ship and the rotor-blade.

- where the use of dispersants is recommended, the dispersant spraying should be done from a vessel, and spraying aircraft would not be permitted to operate within a wind farm.

Several preventive measures are also recommended in the Bonn Agreement Counter-Pollution Manual, as follows:

"the definition of a safety zone around the area, use of mist horns, signalisation of all structures at all times for nautical and aerial purposes, installation of oil retention tanks, list-keeping of all ships operating on behalf of the owner of the windfarm, numbering of structures, early warning of the authorities for all park-related activities in the shipping routes, the organisation by the owner of (multi-) annual simulation exercises on various subjects such as nautical emergencies, towing or pollution response, and the obligation on the owner (to be determined case-by-case) to follow the requirements of the competent authorities with regard to navigational requirements and safety."

4.2 Evaluation of Risk Reduction Measures

If a quantitative risk analysis has been carried out for a wind farm, it should be possible to quantitatively assess at least some of the risk reduction measures, depending on the type of model that has been used for the risk analysis. For example some estimates of the probability of drifting collisions include inputs on tug response times – if these times can be shortened due to additional tugs or faster tugs, then the effect on the probability of collision can be estimated.

Construction of an event tree using an initiating event such as "engine failure" or "black out", and developing branches to describe different chains of events would be useful in identifying and evaluating risk reduction measures for a drifting failure.

5 CASE STUDY: APPLICATION OF SELECTED METHODS TO KRIEGERS FLAK PROPOSED PROJECT

The Kriegers Flak project was chosen as the site for a case study for this report. This was because there have been two independently performed and documented risk analyses carried out for the site using models which have been used for many other risk assessments in Europe. The previous analyses were carried out by Maritime Research Institute Netherlands (MARIN) and Germanischer Lloyd, Germany (GL).

The reports available from GL (Otto and Petersen 2003, Povel et al. 2004 and Otto 2004) and MARIN (van der Tak and Rudolph 2003 and van der Tak 2005b) consist of one original report from GL and one from MARIN and reports with updates, extensions, harmonisations and corrections of the original reports. All the studies are for the offshore wind farm proposed in the German exclusive economy zone (EEZ) of the Kriegers Flak in the Baltic (also called Kriegers Flak I).

The table below shows selected results from MARIN and GL concerning route bounded ship traffic. The effect of emergency salvage is not included.

Table 5.1. Results from MARIN's first report (van der Tak und Rudolph 2003), their latest report (van der Tak 2005b) and from GL's latest report (Otto 2004) concerning route bounded ship traffic. The effect of emergency salvage is not included.

Company	***MARIN***			***GL***
	First report Year 2000	***First report Year 2010***	***Latest report Year 2010***	***Latest report Year 2000***
Return period, drifting [years]	36	29	67	578
Return period, powered [years]	1344	1043	330	218
Return period, total [years]	35	28	56	158

MARIN's latest report only includes calculations for the year 2010, which is not comparable with GL's latest report which is for the year 2000. In MARIN's first report, the results for 2010 are about 80% of the results of 2000. Assuming that the same relation could be applied to their latest report, the return periods for the year 2000 should be 84 years (drifting), 413 years (powered) and 70 years (total). Comparing these figures to GL's, the following could be stated:

- MARIN’s calculation is more conservative regarding drifting ships (GL’s return period is about 7 times larger than MARIN’s).
- GL’s calculation is more conservative regarding powered ships (MARIN’s return period is about 2 times larger than GL’s).
- MARIN’s calculation is more conservative regarding the total return period (GL’s return period is about 2 times larger than MARIN’s).

The approach and structure of the risk analyses presented by GL and MARIN are generally traceable. There are problems, however, with comparing the results because of the different assumptions made for the location of the wind park, the different traffic volume, the different shipping lane coordinates and the different models which are used and which are not fully transparent in the reports. The documentation of the calculations presented in the reports is often incomplete and not fully transparent with regard to assumed numerical parameters, etc. On the webpage of other companies involved in the project, the maps even show different locations for the wind farm.

The objective of carrying out this case study was to try to find out why the results calculated by GL and MARIN differ. The method used was to simulate or emulate the two models with SSPA’s model as a starting point. When available, model parameters and input data were compared. When data were available, the three models mentioned above were also compared to Det Norske Veritas’ (DNV) model “MARCS”.

It should be mentioned here that most models have undergone strong development in the meantime, not least because of the new possibilities offered by statistical processing of recorded AIS data, which is a corner stone for every state-of-the-art navigational risk analysis.

Within the Baltic Master project, another case study for Kriegers Flak is performed (see Baltic Master 2007).

5.1 Models

As previously described in the study, two different situations may result in collision of ships with offshore wind farms. The first one is the powered collision, in which a navigational error due to human or technical error in the navigational instruments or a combination of the two leads to the ship sailing into the offshore wind park if the error is not detected in time. The second one is the drifting collision in which parts of the propulsion system (which includes the engines) are affected by failure, the crew loses control over the vessel and the vessel starts to drift. If the vessel drifts towards the park, it may drift into it depending on other factors such as the wind speed and wind direction.

An overview of different models is given in the table below. The models of DNV and SSPA Sweden AB are included in the comparison. Model parameters were investigated systematically.

Table 5.2. Overview of models used for calculating collision frequencies.

Model	*GL KF* 1)	*GL new* 2)	*MARIN KF* 3)	*MARIN new* 4)	*DNV* 5)	*SSPA*
Hazard Identification	yes	yes	unknown	unknown	yes	yes
Collection of input data	yes	yes	yes	yes	yes	yes
Cruising speed 6)	unknown	ship type dependent	unknown	ship type dependent	ship type and size dependent	sea area and vessel size/type dependent
Powered model						
Standard deviation for course offset	yes	yes	yes	yes	yes	yes
Uniform distribution in addition to Gaussian distribution for course offset	no	yes	no, but fishing vessels included separately	no, but fishing vessels included separately	yes	yes
Course deviation	no	no	yes	yes	no	yes
Causation factor/ Navigational Error Rate	time dependent, about 1E-10	0.0003	unknown	unknown	0.0003	0.0003
Dependence on distance to wind farm to detect navigational error	no	no	exp-function	exp-function	within 20 minutes sailing time no detection	exp-function
Explicitly calculating for waypoints	no	no	no	no	yes	no
Includes effects of AIS	yes	yes	no	yes	unknown	no
Includes effects of VTM	no	yes	no	yes	unknown	no
Models TSS	yes	yes	yes	yes	unknown	yes
Calculations for	every power plant	every power plant	every power plant	every power plant	unknown	park area
Drifting model						
Wind induced forces	dependent on ship type, ship size, load condition and speed over ground	dependent on ship type, ship size, load condition and speed over ground	dependent on ship type, ship size and load condition	dependent on ship type, ship size and load condition	unknown	dependent on ship type and load condition
Wave induced forces	dependent on ship type, ship size and load condition	dependent on ship type, ship size and load condition	dependent on ship type, ship size and load condition	dependent on ship type, ship size and load condition	unknown	dependent on ship type and load condition
Current induced forces	yes	yes	no	unknown	unknown	possible

Tidal induced forces	no	yes	yes	yes	unknown	possible
Engine failure rate (1/hour)	0.0002	unknown	unknown	0.00025	ship type and size dependent	0.00025
Self repair	function	unknown	constants, dependent on time	function	function	function
Emergency anchoring dependent on	drift velocity	wind velocity	drift velocity and ship size	wind velocity	wind velocity, distance to wind farm	wind velocity
Salvage tug	time dependent	time and weather dependent	no	time and weather dependent	time and weather dependent	time and weather dependent
Calculations for	every power plant	every power plant	every power plant	every power plant	unknown	park area
Consequences						
Estimate of amount of oil spilled	empirical	empirical	empirical	empirical	based on statistics	empirical, based on statistics
Oil drift model	no	no	possible	yes	no	possible
Estimate of number of fatalities	no	no	empirical	empirical	based on statistics	no
Estimate of size of economic damage	no	no	no	no	based on statistics	no
Estimate of influence on radar	no	no	no	by simulation	no	no
Cost-Benefit Analysis	no	no	no	no	yes	no

1) GL KF: The models used in GL's original report for Kriegers Flak (Otto and Petersen 2003).

2) GL new: Most recent information on GL's models based on GL's later reports for Kriegers Flak (Povel et al. 2004 and Otto 2004), the SAFESHIP project (SAFESHIP 2005 and 2006), the harmonisation process (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005), other wind farm risk analyses (Neuhaus and Thrun 2003) and personal communication (Povel 2007).

3) MARIN KF: The models used in MARIN's original report for Kriegers Flak (van der Tak and Rudolph 2003).

4) MARIN new: Most recent information on MARIN's models based on MARIN's latest report for Kriegers Flak (van der Tak 2005b), the SAFESHIP project (SAFESHIP 2005 and 2006), the harmonisation process (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005), other wind farm risk analyses (Kleissen 2006) and personal communication (Koldenhof 2007).

5) DNV: Information on DNV's models based on the SAFESHIP project (SAFESHIP 2005), the harmonisation process (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005) and wind farm risk analyses (Christensen 2007).

6) It is assumed from the harmonisation process (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005) that the cruising speed is ship type dependent in GL's and MARIN's new models. In SSPA's model it is possible to implement sea area and vessel size/type dependent cruising speed in future model versions.

GL's and MARIN's models calculate the probability of collisions for every wind power plant separately. In the SSPA calculation approach the entire wind farm area is considered as a navigational hindrance and all uncontrolled or unplanned ship entrances into the farm area generates obvious collision/contact hazards. It is difficult to predict how a crew will react when the ship drifts or sail into the park area. Will they take the necessary steps to avoid a collision or not? What will these steps look like? Is there a chance that there will not be a collision and how probable is it that a collision can be avoided? Therefore it seems to be more reasonable to calculate the frequency of drifting and powered ships reaching the park area. However, to be able to compare the results the model of SSPA was adjusted so that the calculations lead to a collision frequency with the single power plants and not the whole park area (see model description in Appendix).

Initially there was an attempt to keep SSPA's model for drifting collisions as simple as possible. In SSPA's initial risk modelling, various variables were averaged and unified. However, the averaged drift speed that was used in this simplified model leads to an infinite return period for Kriegers Flak. The fast drifters (vessels with high superstructure in relation to their underwater lateral area), which are the only vessels that reach the wind farm before the salvage tug arrives, will, however, not be included if averaging of the drift speed is applied. Other parameters in this simplified model were also found to restrict the applicability of the model and during the progress of the project different parameters have been modified and improved in order to make the calculation model more accurate and generally applicable. Introduced modifications and elaboration of more detailed calculation routines include, for example, the influence of the wind on emergency anchoring, salvage tugs, etc.

5.2 Input data

5.2.1 Description of the wind farm and the ship traffic

Offshore Ostsee Wind AG is the company developing the Kriegers Flak I project. The offshore wind farm will be located in the German exclusive economy zone (EEZ) in the Baltic sea, about 32 km northwest of the island Rügen, about 35 km east from the Danish island Moen and about 35 km south of the Swedish coast around Trelleborg. The overall dimension of the planned area is approximately 27 km^2. The wind park will have an extension of about 7.5 km x 6 km and include a maximum of 80 power plants. The power plants will have a capacity between 3 MW and 5 MW. The water depths in the area are around 20 to 45 meters. A permit was granted in April 2005 for the construction of the wind farm (Windpark Kriegers Flak 2008).

In MARIN's investigation, only a preliminary study of the navigational risk is conducted and therefore the wind park coordinates are roughly assumed. The coordinates of the 52 power plants used in MARIN's calculations are presented by van der Tak and Rudolph (2003) and are also shown in Appendix. For the simulations of MARIN's results with SSPA's model, these 52 coordinates are used. The original calculations of GL (Otto and Petersen 2003) included nine different wind park configurations. One of them was modified in their later reports, ending up with a farm consisting of 80 power plants (see Otto 2004). The coordinates of the power plants are not explicitly stated in GL's reports. However, WindPRO calculations for Kriegers Flak from October 22nd, 2004, shows the coordinates of 80 power plants. Since the shape of this farm looks the same as the one presented in GL's latest report, the coordinates from the WindPRO calculation (see Appendix) are used for the simulations of GL's results with SSPA's model.

The data for the calculations which concern the shipping lanes used by MARIN differs from that used by GL. MARIN (in van der Tak and Rudolph 2003) presents 20 lanes that stand for the main contribution to their calculated results for drifting and powered collision for the year 2000 and 2010, respectively. In total they give a contribution of more than 99% of the total collision frequency. For the simulations of MARIN's results with SSPA's model, these four sets of lanes are used (see Appendix). GL (in Otto 2003) presents the 10 lanes that stand for the main contribution to their calculated results for drifting collision and the 6 lanes that stand for the main contribution to their calculated results for powered collision. For the simulations of GL's results with SSPA's model, these two sets of lanes are used (see Appendix). The traffic flow of the lanes is not explicitly stated by GL. The figures presented in Appendix are estimated from Otto (2004) and Povel and Petersen (2004). The length of the lanes used in SSPA's simulations are the same as presented by MARIN and GL. It has not been checked whether these lengths are following the criterias presented in SSPA's model description (see Appendix).

Further data concerning the shipping traffic are not given in the reports by GL and MARIN and are therefore assumed in SSPA's calculations based on statistics. For example, the ship type distribution used in SSPA's calculations for drifting collision are based on general statistics for the Baltic Sea with the assumption that 50% of the tankers are in loaded condition and that 50% are in ballast condition (see table below).

Tabel 5.3. Ship type distribution (%) used in SSPA's calculations for drifting collision.

	Bulk/ comb	Tankers loaded	Tankers ballast	Gas	Gen. cargo	Container	Reefers	RoRo	Passenger	Others
%	5.52	7.92	7.92	1.27	56.26	3.73	2.01	11.61	3.52	0.24

From statistical data for the area, average length and breadth of the ships are assumed by SSPA to be 150 m and 25 m, respectively. The average vessel speed is assumed to be 15 knots based on values presented in Chapter 3.

In SSPA's simulations of MARIN's and GL's results, the power plant diameter is assumed to be 5 m and the distance between the power plants is estimated to be 600 m (based on 80 power plants on an area of 27 km^2).

The figures below shows the wind farm's location and an example of lanes used by MARIN and GL, respectively. For more illustrations, see MARIN's and GL's reports.

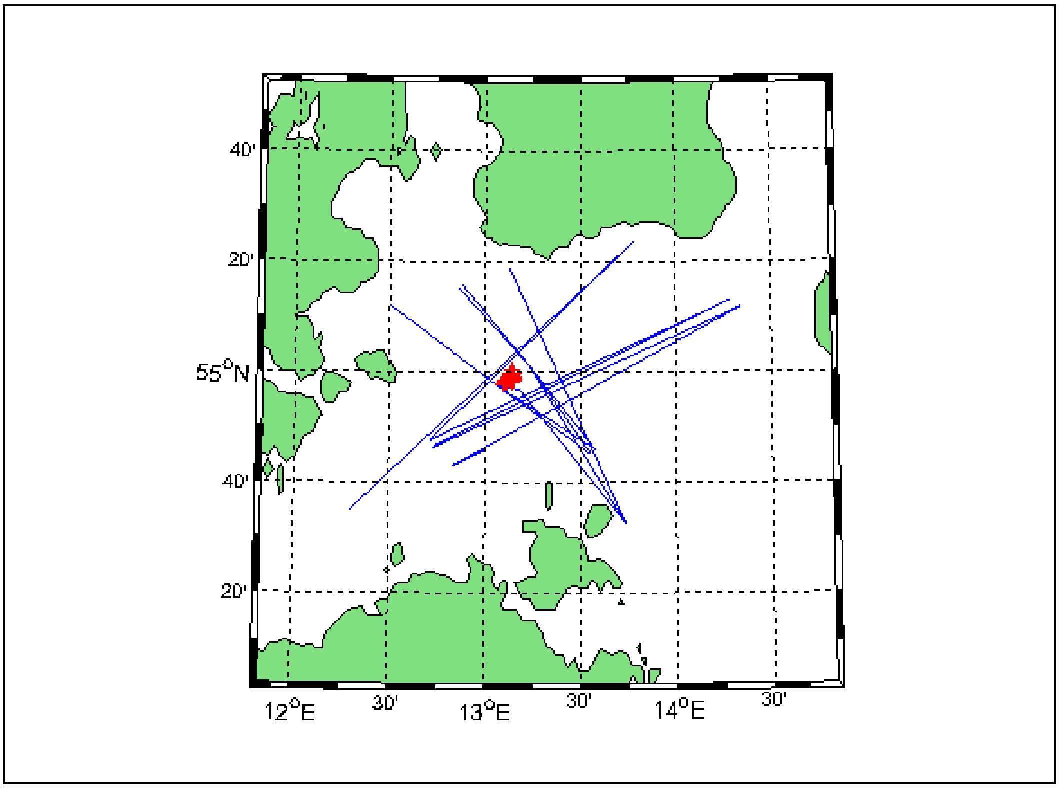

Figure 5.1. MARIN's wind farm and shipping lanes for powered collision (illustrated by SSPA's calculation program).

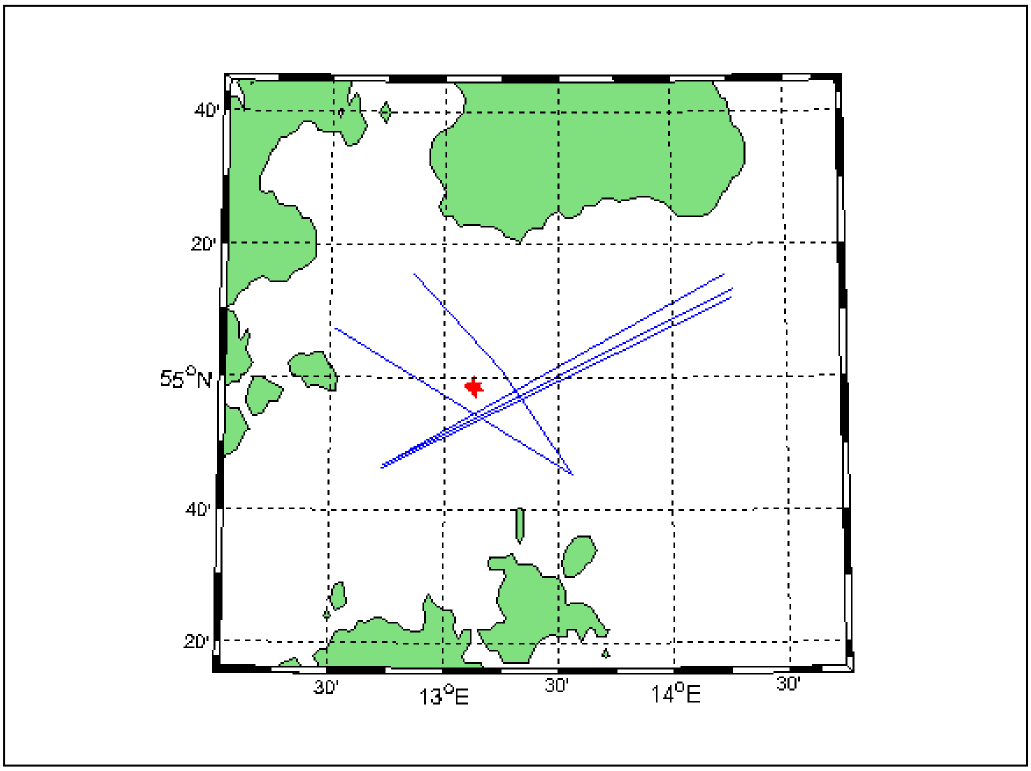

Figure 5.2. GL's wind farm and shipping lanes for powered collision (illustrated by SSPA's calculation program).

To further illustrate the ship traffic situation, the figure below shows an AIS-plot for the area, provided by the Swedish Maritime Administration for this project.

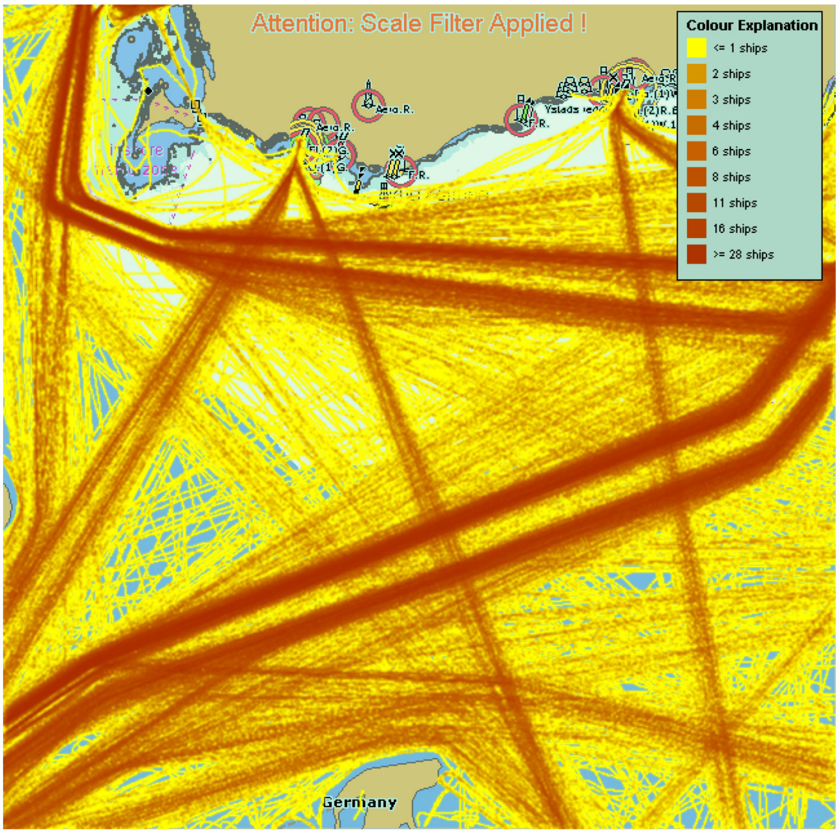

Figure 5.3. Example of density plot of recorded AIS track plots around the Kriegers Flak 1 Site – 15 July 2006. (processed by Swedish Maritime Administration (2006) using Gatehouse RAIS software).

5.2.2 Climate

Weather data, ice data, etc. are mainly provided in a text description in GL's and MARIN's reports. Of special interest for the study in question is the wind statistics. The figures below show the wind statistics presented in MARIN's and GL's original reports. These data have been used in SSPA's simulations.

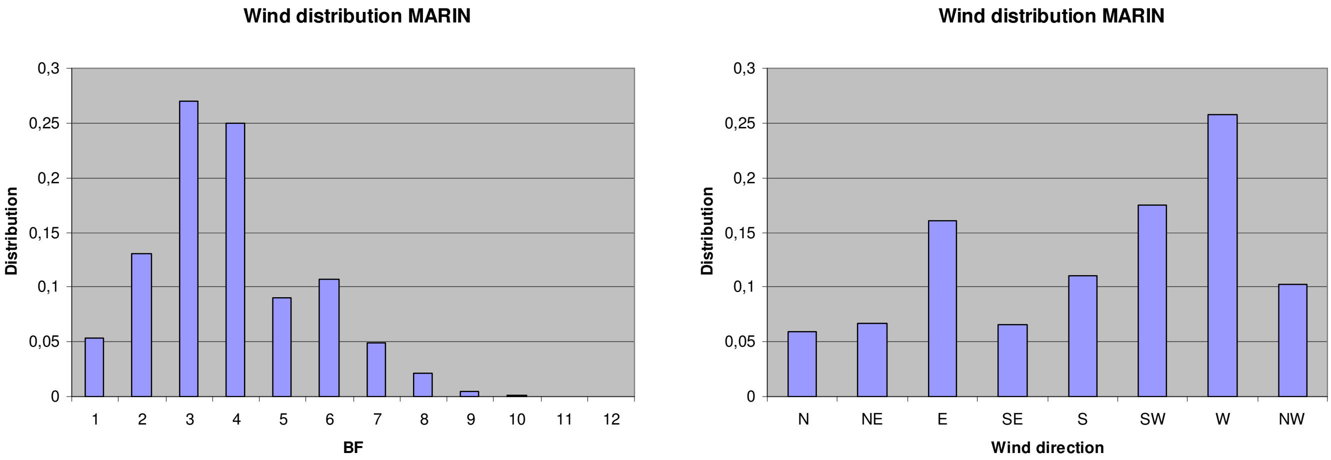

Figure 5.4. Statistical wind distribution at Kriegers Flak according to MARIN (van der Tak and Rudolph 2003).

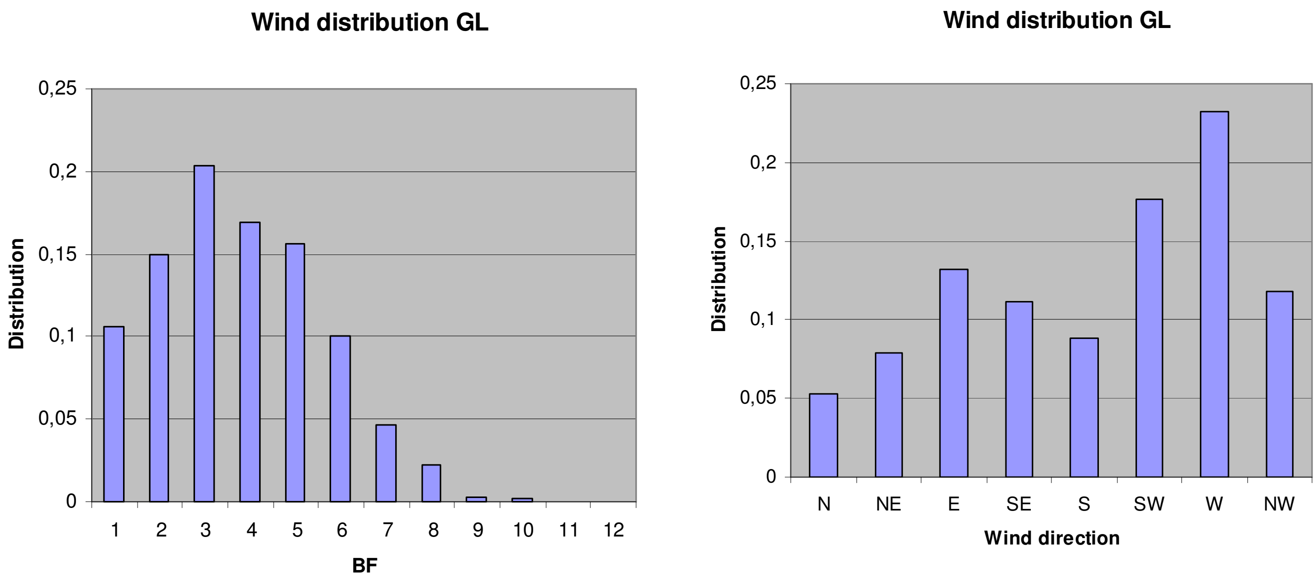

Figure 5.5. Statistical wind distribution at Kriegers Flak according to GL (Otto and Petersen 2003).

5.2.3 Self repair and Emergency anchoring and salvage

In MARIN's latest report for Kriegers Flak it is stated that harmonised assumptions have been used, which is why these assumptions are also used in SSPA's simulation of MARIN's calculation. The assumptions are as follows:

- Engine failure rate: 2.5E-4 per hour (see Chapter 3)
- Self repair function: see Chapter 3 and Figure 5.8
- Probability of anchor failure: see SSPA's model description in Appendix (based on Proposal 2 in harmonised diagram in Chapter 3 or below)

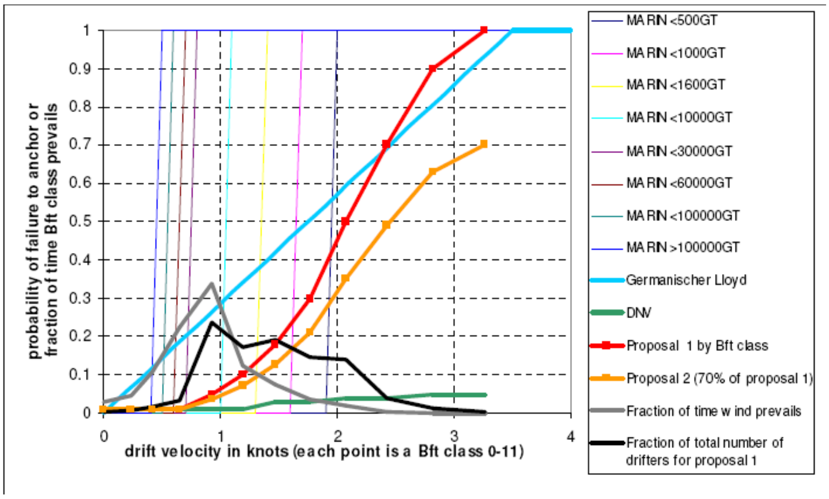

Figure 5.6. Probability of anchor failure (SAFESHIP 2005).

In GL's latest report for Kriegers Flak the harmonised assumptions are not mentioned, which is why the anchor failure curve presented in their original Kriegers Flak report is used in SSPA's simulations (see Germanischer Lloyd in figure above). In SSPA's simulations the drift velocity has been translated to wind velocity (see figure below).

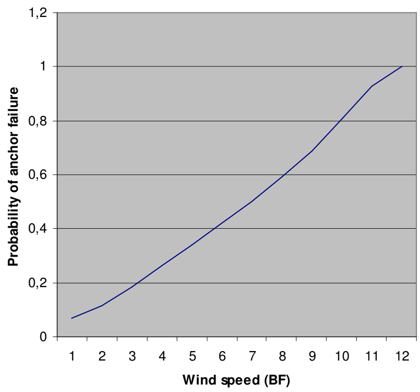

Figure 5.7. Probability of anchor failure used in SSPA's simulations of GL's calculations for Kriegers Flak.

Instead of the harmonised engine failure rate and self repair curve, the data presented in GL's original report are used.

- Engine failure rate: 2E-4 per hour (Otto and Petersen 2003)
- Self repair function: see GL in figure below

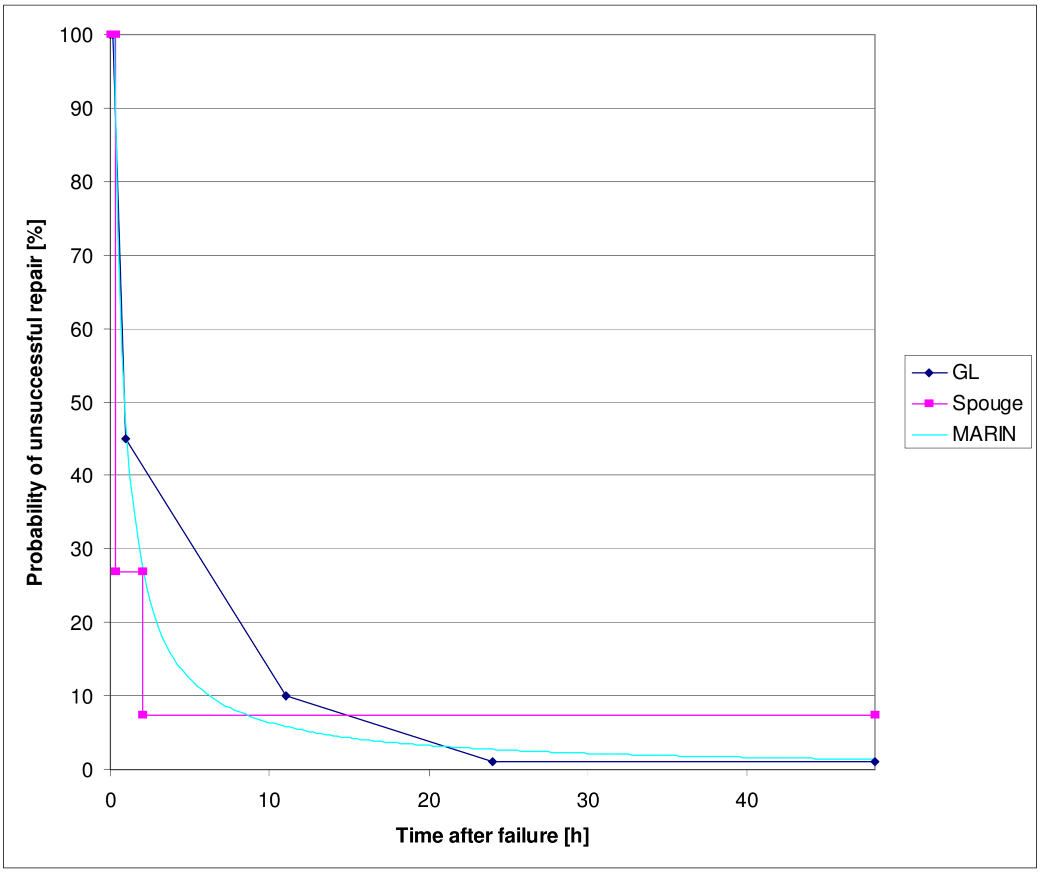

Figure 5.8. Probability of unsuccessful repair. GL: Otto and Petersen (2003). MARIN: SAFESHIP (2005) and Bundesministerium für Verkehr-, Bau und Wohnungswesen (2005). Spouge: Spouge (1999).

Spouge (1999) has also presented frequencies of breakdowns for single engine ships (see table below). He assumes engine failure rates which are independent of the ship types and propulsion systems. He states that the rate can be divided into three categories, which are shown in the table below. The first column represents the average time which is needed until the failure is repaired and the crew has taken control of the vessel again. The last category requires tug boat assistance and repair in port. Spouge's values are illustrated in the figure above.

Table 5.3. Frequencies of breakdowns for single engine ships (Spouge 1999).

Category	Frequency (per hour)
20 minutes	1.5×10^{-4}
2 hours	4×10^{-5}
2 days	1.5×10^{-5}

In SSPA's simulations for both MARIN and GL it is assumed that the water depth and the sea bed condition do not restrict the possibilities for emergency anchoring.

The calculations presented from MARIN and GL do not include effects of emergency salvage, which is why this possibility is also excluded from SSPA's simulations.

The drift velocity due to wind and waves is suggested to have a maximum value of 4 knots, which has been agreed on by a group of experts (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005).

5.2.4 Position on shipping lane

In SSPA's simulations for both MARIN and GL, the probability of being on position x on the shipping lane (P_x) is assumed to be:

$P_x = 1/300$

For more information, see SSPA's model description in Appendix.

5.2.5 Course offset

The standard deviation for the course offset was not explicitly stated in the reports of MARIN and GL, except for the lane south-east of the wind farm containing tanker traffic. Otto (2004) states that the standard deviation for this lane is 1.23 nautical miles. In the simulations of SSPA, the standard deviation for similar lanes has also been chosen to be 1.23 nautical miles. The standard deviation for the remaining lanes has been chosen according to the harmonised assumptions presented in SSPA's model description (see Appendix) and the values chosen are presented in Appendix.

5.2.6 Course deviation

In GL's model, the calculations are very sensitive to the assumptions made for the standard deviation describing the lateral distribution and the distance of the shipping lane to the offshore wind farm (see Chapter 3). MARIN overcomes the problem by introducing an improved model with a function representing the course deviation. Based on some assumptions a distribution for the course deviation is chosen, where the courses -30, -20, -10, 0, 10, 20, 30 have the probability of 0.05, 0.1, 0.2, 0.3, 0.2, 0.1 and 0.05 respectively (van der Tak and Rudolph 2003). SSPA's model uses instead a Gaussian distribution which seems more realistic. The standard deviation has to be chosen for the course deviation. Fitting a Gaussian distribution on these values, with the mean value (μ) assumed to be zero, gives a standard deviation of 15 degrees.

In the simulation of MARIN's calculations, SSPA has described the course deviation with a Gaussian distribution (standard deviation 15 degrees) as described above. For the GL-simulations no course deviation is assumed since GL's model does not include that (standard deviation 0.0001 degrees is used).

5.2.7 Causation factor and onboard crew reaction

MARIN's model includes the probability of detecting the navigational error and to take measures to avoid a collision. In SSPA's model, the probability that the crew onboard is not able to react in time to correct the navigational error is called $P_{react}(x)$. It is dependent on the distance between the wind farm and the position of the ship (D), and is therefore modelled as dependent on the x-position on the shipping lane. The figure below shows weightings for offshore platforms presented by MARIN (all curves except for exp(-D/(6L))) (van der Tak and Glansdorp (Year unknown)). As already mentioned, MARIN uses the Navigational Error Rate (NER) instead of the causation factor.
$P_{react}(x) = \exp(-D/(6L))$, where L = ship length, is suggested in the literature to be used together with the causation factor (Fujii and Mizuki 1998). The function is, however, derived for navigation on lanes with a bend passing bridge piers. The parameter D in the formula stands for distance from bend to bridge. In the SSPA model, it is assumed that this function could be used for offshore wind farms with D equal to the distance between the wind farm and the position of the ship. In the figure below the ship length (L) is assumed to be 150 m.

In SSPA's simulations of MARIN's calculations $P_{react}(x) = \exp(-0.2D^{1.5})$ is used together with the causation factor since this is a more conservative approach than using $P_{react}(x) = \exp(-D/(6L))$. The harmonised value of the causation factor is used, i.e. 3E-04. The numerical value of NER is unknown.

In the simulations of GL's calculations, it is assumed that $P_{react}(x) = 1$ since GL's model does not include that probability factor. In GL's latest report for Kriegers

Flak (Otto 2004) the value of the causation factor is not explicitly stated. However, Povel et al (2004) state the causation factor to vary between 1.11E-04 and 1.165E-04. The causation factor used in SSPA's simulations of GL's calculations is 1.165E-04.

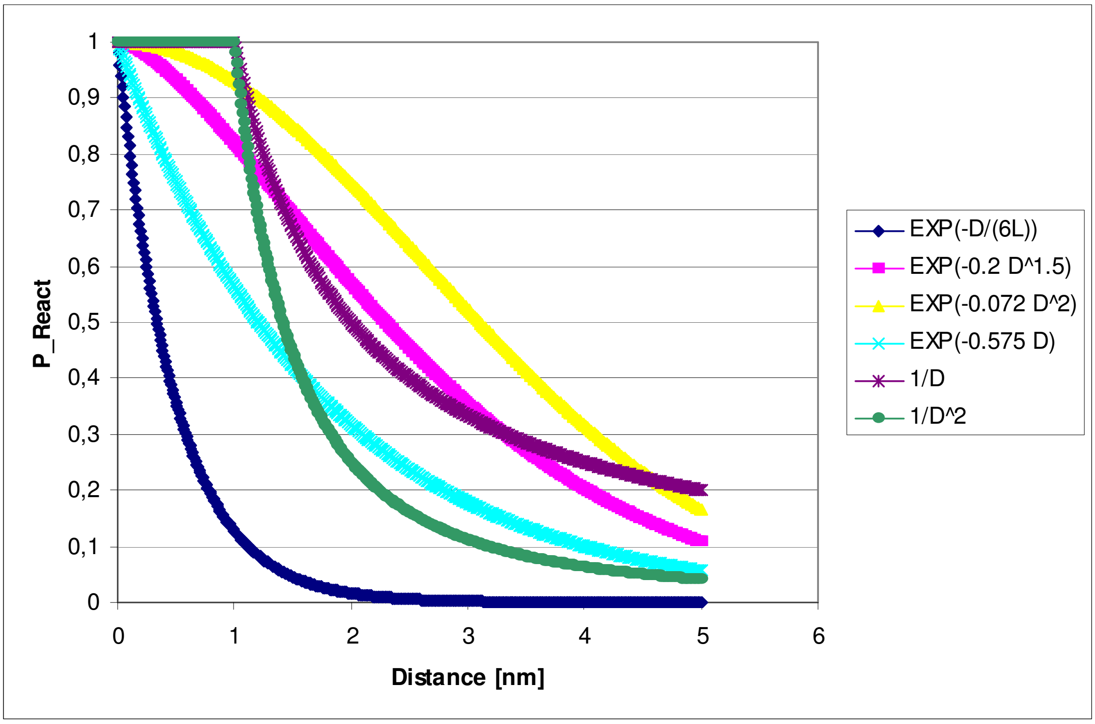

Figure 5.9. Weightings for offshore platforms presented by MARIN (all curves except for exp(-D/(6L))) (van der Tak and Glansdorp (Year unknown)). $P_{react}(x) = \exp(-D/(6L))$, where L = ship length, is suggested in the literature to be used together with the causation factor (Fujii and Mizuki 1998). The ship length (L) is assumed to be 150 m.

5.3 Results

The table below shows SSPA's simulations of GL's and MARIN's calculations for Kriegers Flak compared to corresponding results presented by MARIN and GL. Data and assumptions for the simulations are presented in previous chapters. Note that the effect of emergency salvage is not included in the calculations and simulations presented in the table.

Table 5.4. SSPA's simulations of GL's and MARIN's calculations for Kriegers Flak compared to corresponding results presented by MARIN and GL. The effect of emergency salvage is not included.

Company	***MARIN***	***GL***	***SSPA***	
	Latest report Year 2010	***Latest report Year 2000***	***MARIN[1)] 2010***	***GL[2)] 2000***
Return period, drifting [years]	67	578	71	10
Return period, powered [years]	330	218	305	77
Return period, total [years]	56	158	58	9

1) SSPA's simulations of MARIN's calculations.
2) SSPA's simulations of GL's calculations.

5.4 Conclusions and Discussion

5.4.1 Drifting collision

The return period from SSPA's simulation is about the same as the one calculated by MARIN. When it comes to the simulation of GL's calculation, the difference is large. If the harmonised functions for self repair and emergency anchoring are used instead of GL's original functions, the return period increases from 10 years to 51 years. In such a simulation it is only the wind farm configuration, the shipping lanes and the wind distributions that differ from the simulation of MARIN's calculation. It is difficult to find an explanation for the difference between GL's return period and the simulations made by SSPA of their calculations. One possible reason could be the drift velocity. In the SAFESHIP 2005 project it was stated that the drift velocities calculated by GL are lower than the drift velocities used by MARIN, which is the explanation for considerable differences in the collision frequencies. However, if the drift velocity in the simulation by SSPA of GL's calculation is divided by a factor of 25, the return period increases from 10 years to 516 years. This result indicates that the drift velocity is most likely not the only reason.

5.4.2 Powered collision

The return period from SSPA's simulation is about the same as the one calculated by MARIN. The return period calculated by GL is about 3 times higher than the one simulated by SSPA. As described earlier, the models for powered collision are sensitive to changes of certain parameters.

A sensitivity analysis regarding different standard deviations for the course offset (i.e. standard deviations describing the lateral distribution of the ships) has been performed for the two versions of SSPA's model. One version is used for simulating MARIN's calculations and includes course deviation and onboard crew reaction. The other one is used for simulating GL's calculations and does not include course deviation and onboard crew reaction. To be able to compare the results, the same data regarding wind farm coordinates and shipping lanes are used (MARIN's data has been chosen). The standard deviations chosen in the base case has been multiplied with a factor that varies from 0.25 to 1.5. The results are presented in the table below. In SAFESHIP (2005), MARIN's and GL's models were compared in a similar way (see Chapter 3).

Table 5.5. Sensitivity analysis regarding different standard deviations describing the lateral distribution of the ships for two versions of SSPA's model.

	Sensitivity expressed as collision frequency divided by collision frequency for the base case	
All standard deviations are multiplied with	*SSPA's model: version MARIN*	*SSPA's model: version GL*
1.5	3.5	4.2
1.0 (base case)	1.0 (base case)	1.0 (base case)
0.75	0.42	0.18
0.5	0.28	0.01
0.25	0.25	0.01

As indicated above, the SSPA model version used for simulating MARIN's calculations is less sensitive to the assumptions made for the standard deviation describing the lateral distribution of the ships. However, there are reasons to believe that it is sensitive to assumptions regarding $P_{react}(x)$ instead. The table below shows the results of SSPA's simulations of MARIN's calculation for Kriegers Flak for year 2010 regarding powered collision with different $P_{react}(x)$.

Table 5.6. SSPA's simulations of MARIN's calculation for Kriegers Flak for year 2010 regarding powered collision with different $P_{react}(x)$.

$P_{react}(x)$	***Return period [years]***
1/D	49
$\exp(-0.072D^2)$	248
$\exp(-0.2D^{1.5})$	305
exp(-D/(6L))	720

As described in SAFESHIP (2005) (see Chapter 3), following the model of GL, calculations of powered collision are very sensitive to the location of the shipping lanes and the assumptions made for the standard deviation for the course offset. The sensitivity analysis above also indicates this regarding the standard deviation. From the results of the latest report of GL it is notable that the main risk contribution is generated from shipping lanes at large passage distances. Shipping lanes which are far away from the wind park are shown to give a bigger contribution to the powered collisions than the shipping lanes which are less than 5 nm away from the planned offshore wind park.

5.4.3 Historical empirical accident statistics

Historical accident statistics can be used to compare and validate the predicted results with real values. The zero-alternative calculations may also be based on statistics on total accident frequencies in the region under consideration for wind farm establishment. Accident statistics for grounding/stranding in the Swedish EEZ are presented in the table below and show the recorded grounding statistics between 1985 and 2006.

Table 5.7. Recorded grounding of ships in the area Sandhammaren-Falsterborev on the coast of Skåne. Original material on reported accidents provided by the Swedish Maritime Safety Inspectorate (Sjöfartsinspektionen 2006) has been processed and compiled (see Appendix).
Time period: 1985-01-01—2006-07-13 (approximately 21,5 years).

	Powered Grounding		***Drifting Grounding***	
	No.	***Return period (year/grounding)***	***No.***	***Return period (year/grounding)***
Passing ships	3	7	1	Not possible to calculate [2)]
Ships calling at port [1)]	4	5	1	Not possible to calculate [2)]

[1)] Ships calling at port in Ystad and Trelleborg in Sweden
[2)] Only 1 grounding.

In the discussion about acceptance criteria, the zero-alternative calculations have been found to be relevant. The question here might be, if it is more important to look at the return period for a wind park independently or if it is more relevant to discuss the total increase of grounding frequency and collision frequency compared to the present-day situation.

5.4.4 Consequences

MARIN classifies the consequences into damage for the wind power plants, damage for the ship, human incidents, and environmental damage. The probabilities for an oil spill and the spill volume are based on the kinetic energy, on statistics and very simplified assumptions for how the damaged power plants fall (direction away from the ship - on the ship, number of people hit by the falling turbine, etc.).

GL calculates the probabilities for an oil spill and the spill volume based on empirical formulas. Mainly the oil spill from tankers is looked at.

In SSPA's case study the consequences are not included.

5.4.5 Influence of Kriegers Flak II on the calculations

The wind park Kriegers Flak II in the Swedish EEZ and the wind park Kriegers Flak III in the Danish EEZ will influence the collision frequency of Kriegers Flak I. So far the only studies which have been performed were made independently. Following the analysis by SSPA interference of the different parks will be present and cumulative risk aspects must be considered. The navigational risk should be looked at for all parks independently as well as with a combination of all parks. According to the information available at SSPA the parks I and II will be situated so close to each other that it will not be possible to sail between the parks. If this is the case the two parks can be considered as one big park.

6 RECOMMENDATIONS AND DISCUSSION

The objectives of this study were to provide recommendations for a methodology for assessing risks resulting from ship navigation in the vicinity of offshore wind farms. In the chapters below, conclusions and recommendations in general regarding risk assessment methodology and in detail regarding calculation models are presented.

6.1 Risk assessment methodology

The list below contains important areas identified during the progress of this research project. Recommendations for each area are also discussed.

- Transparent calculation models
- Cumulative effects
- Relative comparison
- Cost-Benefit
- Risk reduction measures
- Accident preparedness

It is important that the calculation models are transparent. The intention with the model developed by SSPA (see Appendix) is that all information about the model should be explicitly stated. This includes the model structure as well as the input data. The importance of transparent calculation models are exemplified in the Kriegers Flak case study (see Chapter 5) where different versions of the SSPA model and also different input data are used to illustrate how the calculated collision frequency (or return period) is affected. Harmonisation processes such as the German one also requires transparency in order to give recommendations about for example input data. Harmonisation can be a natural step to take when the models are presented in detail. However, as shown in chapter 2, the conditions in the different EU-member states vary a lot and each country may identify and prioritise various safety aspects differently, and total harmonisation may be difficult. The pilot site for this project, Kriegers Flak, may serve as an illustration of the need for harmonisation and bilateral/international assessment discussions.

If several wind farms are planned in the area, cumulative effects on the risk should be studied. This may require cooperation between different countries. One example is the proposed Swedish and German parks at Kriegers Flak that are close neighbours, but are processed separately without consideration of cumulative effects, while other more distant wind farms on the German side are considered from an interaction point of view with Kriegers Flak.

As illustrated in chapter 5, collision frequency models are sensitive to changes of certain assumptions. Calculated results in absolute terms should therefore be carefully interpreted. One way of doing this is to make relative comparisons instead of using absolute values of acceptance criteria. If acceptance criteria should be used, it should be stated for which type of calculation model and with which input data these criteria are valid. One important relative comparison is a zero-alternative discussion where the navigational risk in a specific area is compared quantitatively with and without the presence of the wind park. Comparative studies of the calculated collision frequency of different traffic lanes can also be applied in order to identify which ones that stands for the largest contribution.

Another way of relating the results of a risk assessment/analysis is to put it in an economic context. Cost-benefit analysis is not included in this research project but could be an interesting task for future projects (see next chapter). One way could be to study the estimated risk in relation to the electricity production of the wind farm.

Example of risk reduction measures are presented in chapter 4. Measures that are associated with low economic costs should always be considered even if the estimated risk is low. If the estimated risk is high, also more expensive measures must be considered.

Accident preparedness includes various safety measures but should also be linked to a control program. One of the objectives with establishing and follow a control program is that the risk and safety issues will be continuously checked and updated during the whole life time of the wind farm.

6.2 Calculation Models

The structure of the SSPA calculation model (see Appendix) is similar to other models used for wind farms and offshore platforms. However, there are models using simulations (e.g. Monte Carlo simulations) but in the SSPA model no simulations are used since these make the model less transparent. It is questionable whether simulations give more accurate results of a risk analysis.

The SSPA model is designed to be simple and transparent, which gives a good prerequisite for explaining the physics behind the model. Especially the model for drifting collisions is straightforward, based on geometry. The one for powered collisions is associated with questions concerning how to model navigational behavior and human error. This is common questions for developers of this type of models.

Collision frequency models are in general sensitive to changes of certain assumptions. They also contain an amount of uncertainties. Calculated results in absolute terms should therefore be carefully interpreted. This is also valid for the SSPA model and the aim is to be as clear as possible concerning sensitivity/uncertainty. This openness makes the SSPA model more useful and shows the way to improvements of the model. It has for example become obvious during the progress of this research project that the function describing the probability that the crew onboard is not able to react in time to correct the navigational error (onboard crew reaction) needs to be further investigated together with the causation factor. One way of doing this would be possible if the processing of recorded AIS-data could be further developed (see next chapter).

The German harmonisation process has laid a basis for a common harmonised set of parameters which should be used in risk calculations. However, one should be attentive to that the process has a set of models as a basis and there may be recommendations that are valid only for these models and can therefore not be used commonly.

6.3 Follow up activities

Follow up activities to be included in future research projects includes:

- further develop processing of recorded AIS-data in order to improve model input data.
- develop calculation models in order to study possible increase of ship-ship collisions due to more congested traffic lanes after a wind farm establishment.
- study accident statistics more thoroughly in order to improve model input data as well as providing a basis for a zero-alternative discussion.
- develop criteria for cost-benefit analysis for offshore wind farms.
- further develop calculation models describing the consequences of a collision.

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APPENDIX A – SUMMARY INFORMATION ON EXISTING OFFSHORE WIND FARMS

Offshore wind farms in operation or under construction as of November 2007

Site	Country	Operation Start	Total Capacity, lay-out	Distance to shore	Water Depth (m)	Hub height (m)	Foundation Type	Annual Output [1] (kWh / y)
Vindeby	Denmark	1991	5 MW / two rows, 11 turbines	1.5 – 3 km	2.5 – 5	37.5	Concrete caisson	10,309,000
Lely	Netherlands	1994	2 MW / single line, 4 turbines	800 m	4 – 5	39	Driven monopile	4,000,000
Tunø Knob	Denmark	1995	5 MW / two rows, 10 turbines	6 km	3 - 5	40.5	Concrete caisson	13,459,000
Dronten	Netherlands	1996	16.8 MW / single line, 19 turbines	30 m		50	Driven monopile	36,700,000
Bockstigen (Gotland)	Sweden	1998	2.5 MW / cluster , 5 turbines	3 - 4 km	6	41.5	Drilled monopile	8,300,000
Utgrunden (Kalmar Sound)	Sweden	2000	10.5 MW / cluster, 7 turbines of 1.5 MW	12 km	7 - 10		Driven monopile	36,900,000
Blyth	U.K.	2000	3.8 MW, 2 turbines	1 km	6	58	Drilled monopile	
Middelgrunden	Denmark	2001	40 MW, curved line, 20 turbines	2 – 3 km	3 - 6	60	Concrete caisson "Gravity"	88,760,000
Yttre Stengrund (Kalmar Sound)	Sweden	2001	10 MW / line, 5 turbines	5 km	8	60	Drilled monopile	30,000,000
Horns Rev	Denmark	2002	160 MW, 80 turbines	14 - 20 km	6 – 14	70	Drilled monopile	629,966,000
Rønland	Denmark	2003	17.2 MW, 8 turbines total			78 - 78.8		66,244,000
Samsø	Denmark	2003	23 MW, line, 10 turbines	3.5 km	11 – 18	61	Monopile	78,906,000
Frederikshavn	Denmark	2003	7.6 MW, 3 turbines	500 m	1		Monopile	21,131,000
Nysted	Denmark	2003	165.6 MW, 72 turbines	9 km	5 - 10	69	Concrete caisson "Gravity",	547,145,000
Arklow Bank	Ireland	2003	25.2 MW, 7 turbines	10 km	5	73.5	Monopile	95,000,000
North Hoyle [2]	U.K.	2003	60 MW, 30 turbines	7 km (closest)	7 - 11	67	Monopile	200,000,000
Hokkaido	Japan	2004	1.2 MW, 2 turbines	700 m		47		
Scroby Sands	U.K.	2004	60 MW, 30 turbines	2.3 km	4 - 8	68	Monopile	284,000,000 [3]
Emden	Dollard/ Germany	2004	4.5 MW, 1 turbine	30 m	2	100	Like land-based	15,000,000
Kentish Flats	U.K.	2005	90 MW, 30 turbines	8 - 10 km	5 (average)	70	Monopile	231,144,000 [3]
Breitling	Rostock/ Germany	2006	2.5 MW, 1 turbine	500 m	2	80	Like land-based	
Barrow [4]	U.K.	2006	90 MW, 30 turbines in 4 rows	7 km	15 - 20	75	Monopile	305,000,000 (expected)

Egmond Aan Zee [5]	Netherlands	2007	108 MW, 36 turbines	10 - 18 km	18	70	Monopile	400,000,000 (expected – operation began in 2007)
Burbo Bank [6]	U.K.	2007	90 MW, 25 turbines	7 km	2 - 8	83.5	Monopile	315,000,000 (expected – operation began in 2007)
Beatrice Wind Farm Demonstrator, Moray Firth	U.K.	2007	10 MW, 2 turbines	25 km	45	88	Lattice tower	Under construction
Lillgrund	Sweden	2007 - 2008	110 MW, 48 turbines	7 km		115 to tip		330,000,000 (expected to be operational in March 2008)
Windpark Q7 [7]	Netherlands	2008	120 MW, 60 turbines	23 km	19 - 24 m	59	Monopile	Construction nearing completion. Expected to be operational in 2008
Lynn & Inner Dowsing	U.K.	End of 2008	180 MW, 54 turbines (2 adjacent windfarms with 27 turbines each)	5 km		80	Monopile	Under construction
Thornton Bank [8]	Belgium	2008	300 MW, 60 turbines	30 km				Phase 1 start-up expected in 2008
Robin Rigg	U.K.	2009	180 MW, 60 turbines	9 km		80		Construction begun, expected to begin operation 2009

Key:
- (dark grey) Offshore Wind Farms that have begun Operations as of November 2007
- (light grey) Offshore Wind Farms under construction as of November 2007

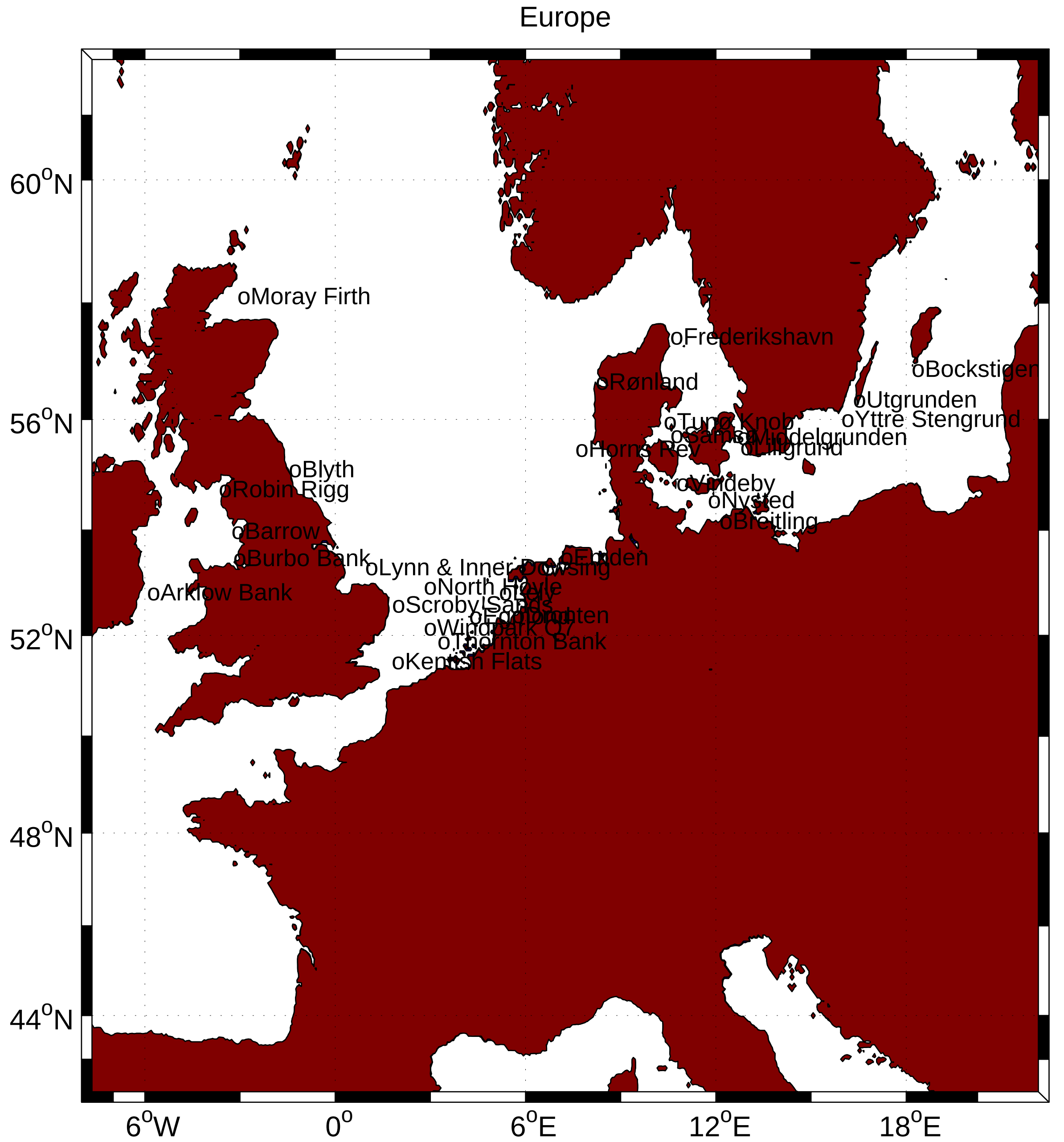
Data compiled from the following sources:
http://www.offshorecenter.dk/offshorewindfarms/
http://www.bwea.com/offshore/worldwide.html
http://www.offshorewindenergy.org/
http://home.wxs.nl/~windsh/offshoreplans.html
www.offshore-wind.de/page/index.php?id=4765&L=1

Notes:

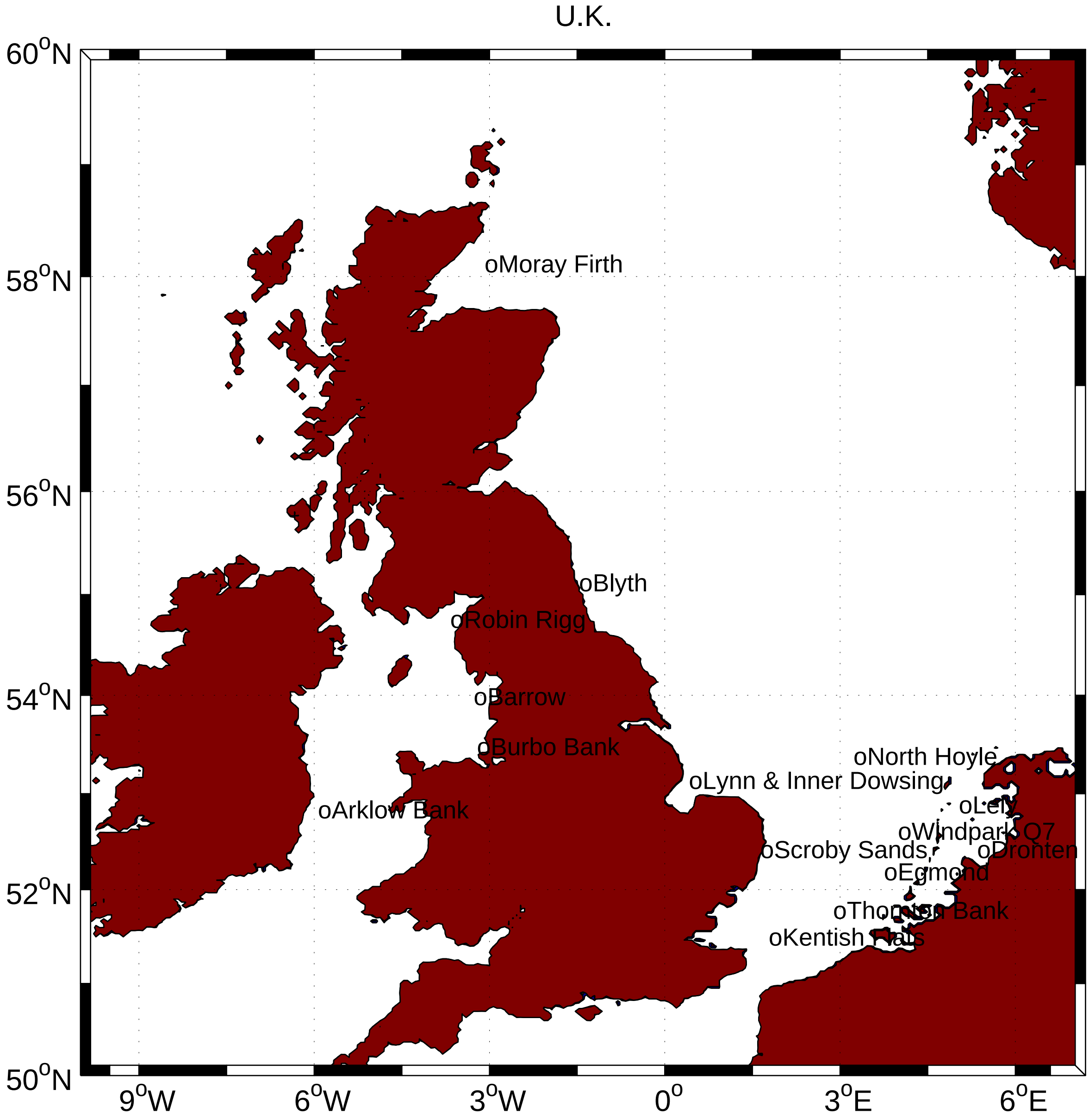
1. **Annual production figures for Danish offshore wind farms are from 2005 and were obtained from: Faktablad P4 Vindmøller på havet. May 2006, Dansk Vindmølleforening**
2. **Information on North Hoyle from www.natwindpower.co.uk/northhoyle/statistics.asp**
3. **Annual operating data for Scroby Sands and Kentish Flats are for the year 2006 and were obtained from www.berr.gov.uk/files/file41543.pdf, "Capital Grant Scheme for Offshore Wind Annual Report – January 2006 – December 2006 Executive Summary"**

4. **Information on Barrow Offshore Wind from: www.bowind.co.uk/keyfacts.htm**
5. **Information on Egmond Aan Zee from: www.noordzeewind.nl/**
6. **Information on Burbo Bank from: www.dongenergy.com/burbo/project/technology.htm**
7. **Information on Windpark Q7 from: www.q7wind.nl**
8. **Information on Thornton Bank from: www.c-power.be/**

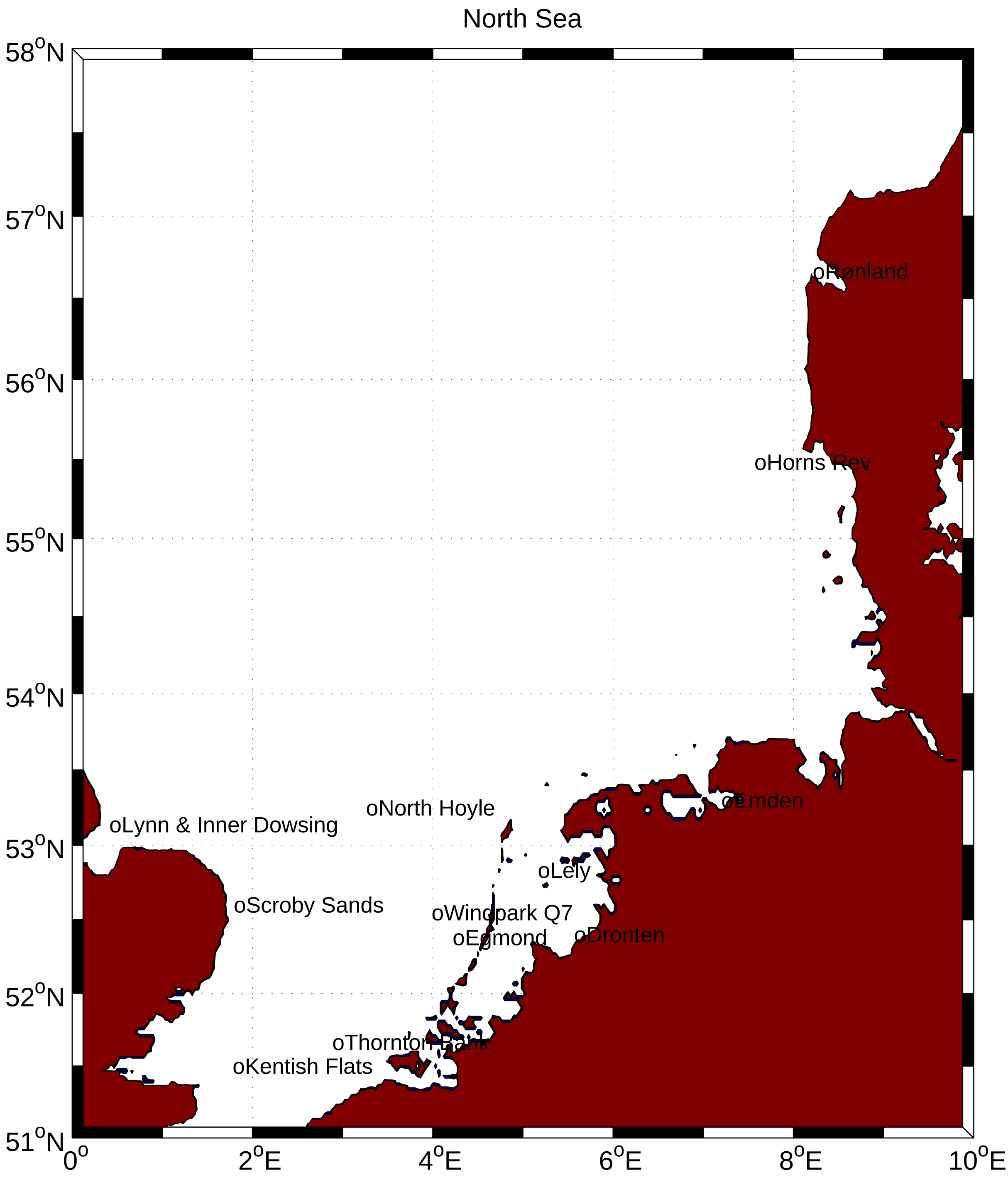
	Wind farms in the world Existing wind farms Name of park	Appendix A Figur 2.1 Report 2005 4028



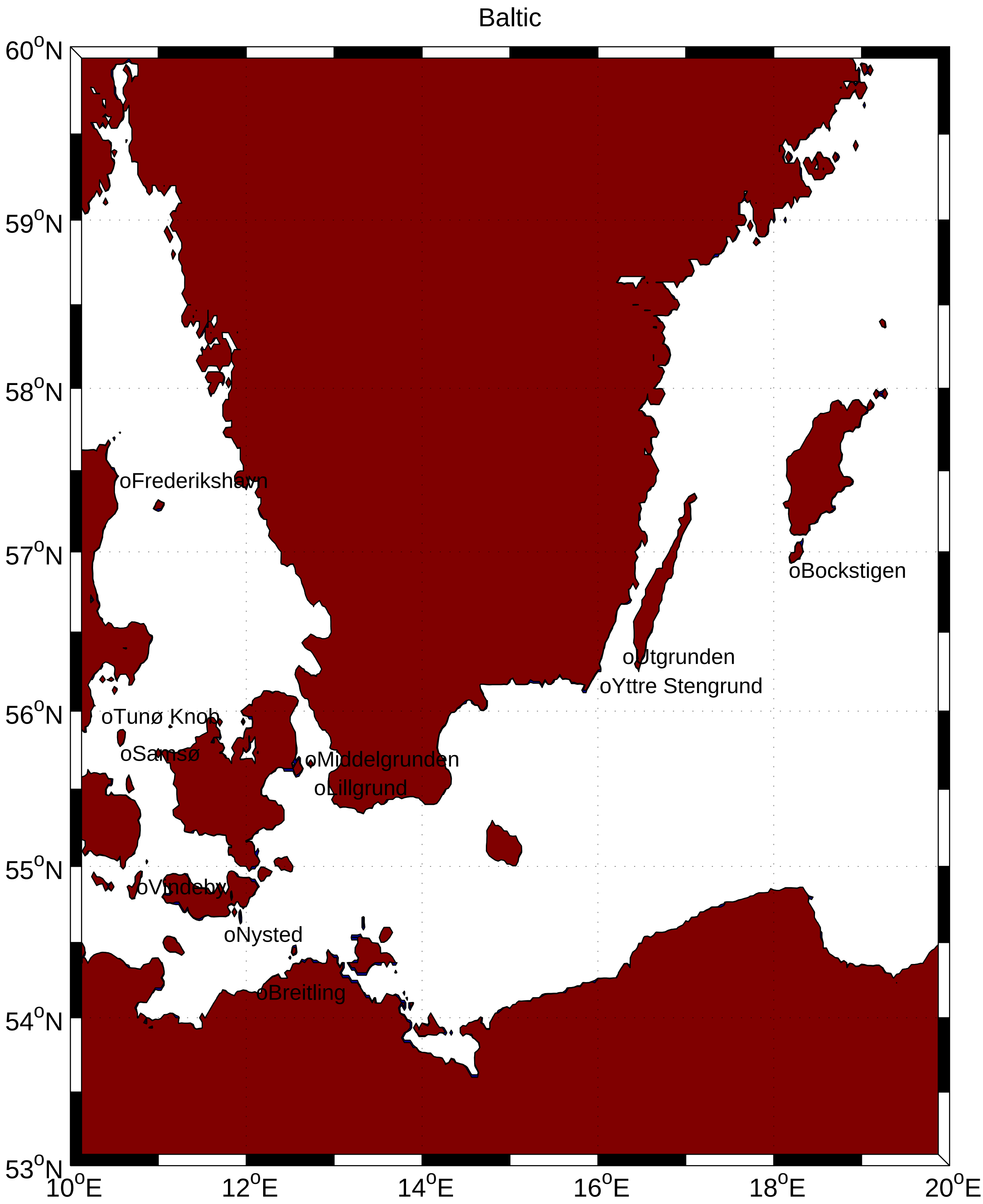
SSPA	Wind farms in the world Existing wind farms Name of park	Appendix A Figur 2.2 Report 2005 4028



	Wind farms in the world Existing wind farms Name of park	Appendix A Figur 2.3 Report 2005 4028

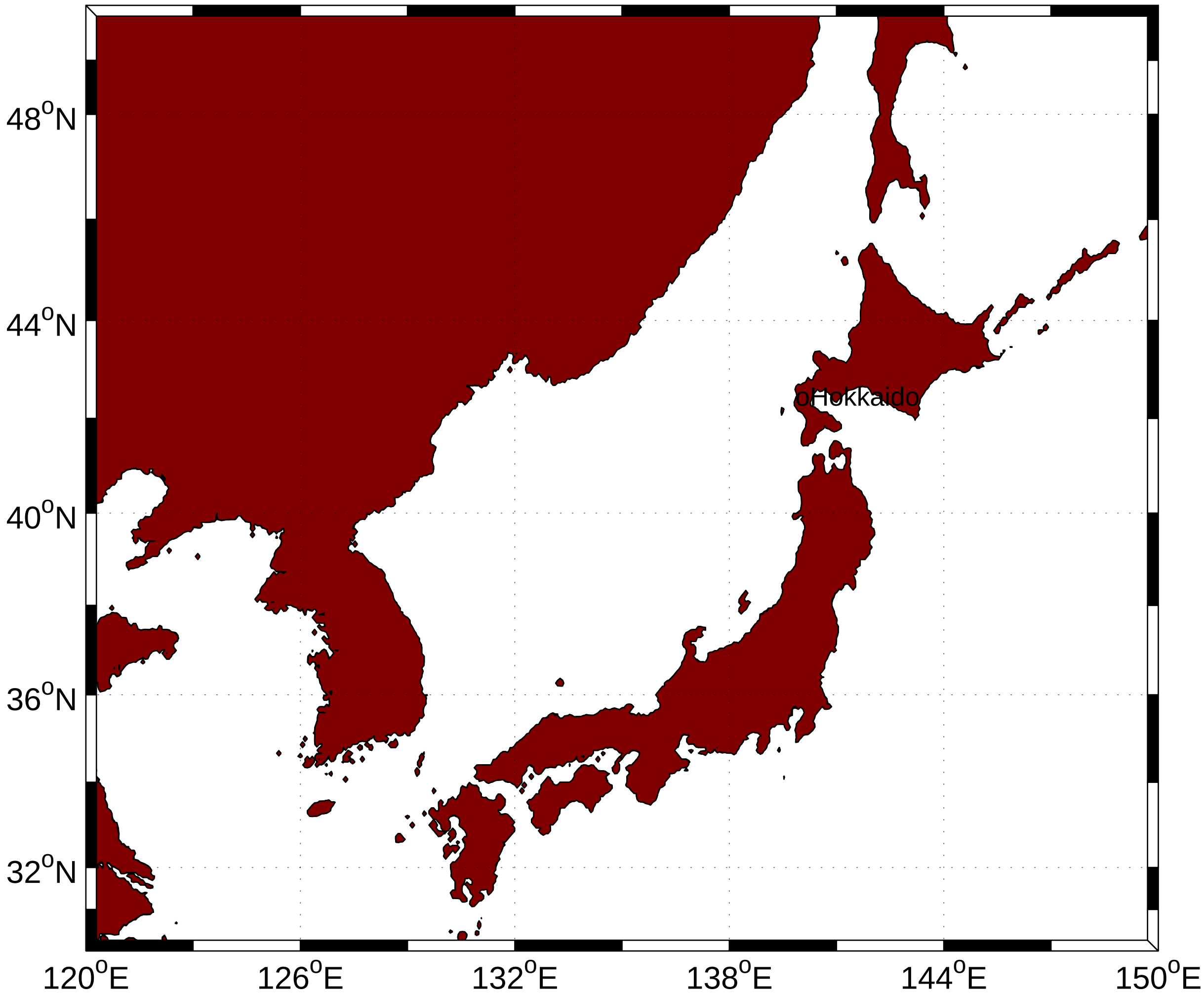


SSPA	Wind farms in the world Existing wind farms Name of park	Appendix A Figur 2.4 Report 2005 4028



SSPA	Wind farms in the world Existing wind farms Name of park	Appendix A Figur 2.5 Report 2005 4028

Japan



Appendix B – Accident Statistics from the Swedish Maritime Safety Inspectorate
(in Swedish).

Valda uppgifter ur olycksrapporteringsmaterial från Sjöfartsinspektionen (2006) i området Sandhammaren-Falsterborev på Skånes sydkust, kompletterat med kategoriseringen gjord i denna studie avseende powered respektive drifting grounding.
Tidsperioden är 1985-01-01—2006-07-13 (dvs ca 21,5 år). OBS: Tabellen fortsätter på nästa sida.

Namn	Typ	Brutto	Avg	Dest	Händelse	Plats	Powered	Drifting	Kommentar
Saga Star	Passagerarfartyg	8226	Trelleborg	Travemuende	Fartyget grundstötte vid inloppet till Trelleborg. Orsaken till grundstötningen var att isdriften p g a tjockan ej rätt kunde uppskattas av befälhavaren.	N55°21,5' E13°9,2'	1		Hamn (Trelleborg)
Götaland	Passagerarfartyg	5159	Sassnitz	Trelleborg	Fartyget grundstötte då det back-manövrerade i rännan in mot Trelleborg. Vid tillfället rådde hård oso-lig vind, tjockdrivande is fanns i rännan och sikten var nedsatt till 50-75 m pga tjockan. Fartyget togs loss kl 11.47 med hjälp av egna maskiner samt isbrytarassistans. Vid efterföljande dockning konstaterades bottenskador och skador på propellerbladen. Det kan dock inte fastslås när dessa skador inträffat. Orsaken torde vara siktförhållandena samt isdriften i rännan.	N55°21,0' E13°09,0'	1		Hamn (Trelleborg)
Annika	Fiskefartyg	20	Kriegers flak	Skåre	Sannolikt felnavigering. Fartyget är utrustat med radar, ap-navigator, ekolod och autopilot. Navigeringen anges dock ha skett på en höft. Skepparen säger sig vara medveten om att det fanns en uppskjutande sten. Båten fick ett hål i fören och tog in vatten men grundsattes för att inte sjunka. Båten bärgades sedermera och hålet i fören reparerades.	N55°21,8' E13°04,4'	1		Fiskefartyg
Sekstant	Fiskefartyg	3147	Tallinn	Indien	Vid bogsering från Tallinn till Indien för upphuggning brast bogserkabeln och SEKSTANT (S) drev på grund. S skall avlägsnas från platsen.	N55°21,80' E13°32,0'		1	Bogserande fartyg är passerande och tappar objekt (fiskefartyg).
Saga Star	Passagerarfartyg	9095	Travemuende	Trelleborg	P g a spänningsbortfall till övervakningssystemet en kort stund slogs detta ut. Alla huvudmaskiner trippade med "black out" som följd. P g a black out förlorades styrningen och fartyget grundstötte. Inga skador kunde upptäckas.	N55°20,20' E13°8,80'		1	Hamn (Trelleborg)
Evita	Fiskefartyg	3	Kåseberga	Skillinge	Fiskebåten var på väg från Kåseberga till Skillinge när en sjö sköljde över däcket, varvid ett nät följde med på utsidan och fångades av propellern. Motorn stannade och fartyget drev upp på sandstranden där fartyget övergavs.	N55°22,70' E14°7,50'		1	Fiskefartyg

Peter Pan	Passagerarfartyg	31356			Det tyska passagerarfartyget fick bottenskador i Trelleborgs hamnområde.	N54°21,0' E13°10,0'	1		Hamn (Trelleborg). Powered antages då inga uppgifter om motorstopp etc uppgetts.
Kattegatt	Fiskefartyg	11			Den danska fiskebåten grundstött och förlist syd om Skåre. Enligt uppgift från Stockholm radio hade en livräddningskryssare observerat båten tjuvfiskande utanför Skåre under dagen. Ärendet redovisat av polisen till åklagarmyndigheten Malmö. Misstanke om brott mot sjölagen och sjötrafikförordningen. Grundstötningsorsak okänd. Anm: Dansk Skibstilsyn informerats om händelsen. Inga åtgärder kommer att vidtagas från deras sida.	N55°21,80' E13°4,0'	?	?	Fiskefartyg
Lobo	Torrlastfartyg	1741	Rostock	Lissabon	Befälhavaren somnade på vakt och fartyget grundstötte. Med hjälp av bogserbåtar kunde fartyget dras av grundet.	N55°22,60' E13°2,0'	1		Passerande
Albakor	Fiskefartyg	1898	Kaliningrad	Nordatlanten	ALBAKOR (A) skulle gå genom Öresund och ut i Atlanten. Bryggan var bemannad av en styrman och utkik. Söder om Trelleborg grundstötte fartyget och tog in vatten. Besättningen evakuerades. Vakthavande styrman var vid tillfället alkoholpåverkad och dömdes senare till två månaders fängelse. Sju veckor efter grundstötningen bärgades fartyget och bogserades till Ystad.	N55°19,4' E013°15,8'	1		Passerande stort fiskefartyg.
Polonia	Passagerarfartyg	29875	Swinoujscie	Ystad	En besättningsman hörde "konstiga" ljud då fartyget passerade Ystad angöring boj. Undersökning utfördes och intryckningar som bedömdes vara gamla, hittades.	N55°23,6' E013°47,5'	1		Hamn (Ystad)
Winland	Torrlastfartyg	2240	Riga	Goole	P.g.a. felnavigering grundstötte fartyget. Sannolikt har trötthet medverkat till händelsen då vakthavande hade arbetat 26 timmar under de två senaste dygnen. Fartyget tog sig loss för egen maskin till hamn.	N55°18,5' E012°48,'	1		Passerande

Referens

Sjöfartsinspektionen. 2006. Rapport från SjöOlycksSystemet. 2006-07-13.

Appendix C – Case Study Wind Farm Kriegers Flak: Some detailed information

Power plant coordinates, MARIN

deg north	min north	deg east	min east
54	57.8448	13	5.601
54	58.0272	13	6.2826
54	58.4574	13	6.348
54	58.2102	13	6.9648
54	58.6404	13	7.0302
54	59.0706	13	7.0956
54	58.3926	13	7.6464
54	58.8228	13	7.7118
54	59.253	13	7.7778
54	59.6832	13	7.8432
54	58.1448	13	8.2626
54	58.575	13	8.3286
54	59.0052	13	8.394
54	59.4354	13	8.4594
54	59.8662	13	8.5254
55	0.2964	13	8.5908
54	58.3272	13	8.9448
54	58.7574	13	9.0102
54	59.1882	13	9.0762
54	59.6184	13	9.1416
55	0.0486	13	9.207
55	0.4788	13	9.273
54	58.0794	13	9.561
54	58.5096	13	9.627
54	58.9404	13	9.6924
54	59.3706	13	9.7578
54	59.8008	13	9.8232
55	0.231	13	9.8892
54	57.8316	13	10.1778
54	58.2618	13	10.2432
54	58.6926	13	10.3086
54	59.1228	13	10.374
54	59.553	13	10.44
54	59.9832	13	10.5054
55	0.4134	13	10.5708
54	58.4448	13	10.9248
54	58.875	13	10.9908
54	59.3052	13	11.0562
54	59.7354	13	11.1216
55	0.1656	13	11.1876
55	0.5964	13	11.253
54	58.6272	13	11.607
54	59.0574	13	11.6724
54	59.4876	13	11.7384
54	59.9184	13	11.8038
55	0.3486	13	11.8692
54	59.2398	13	12.3546
54	59.6706	13	12.42
55	0.1008	13	12.4854
55	0.531	13	12.5514
54	59.4228	13	13.0362
54	59.853	13	13.1022

Power plant coordinates, GL

deg north	min north	deg east	min east
54	58.8892	13	7.4020
54	58.6715	13	7.5900
54	58.4542	13	7.7778
54	58.2370	13	7.9653
54	58.0200	13	8.1528
54	59.2712	13	7.9182
54	59.0513	13	8.0982
54	58.8313	13	8.2783
54	58.6115	13	8.4583
54	58.3920	13	8.6380
54	58.1725	13	8.8177
54	59.6980	13	8.4175
54	59.4760	13	8.5895
54	59.2540	13	8.7615
54	59.0320	13	8.9335
54	58.8098	13	9.1053
54	58.5878	13	9.2733
54	58.3662	13	9.4488
54	58.1447	13	9.6203
55	0.1340	13	8.9505
54	59.8967	13	9.1050
54	59.6728	13	9.2688
54	59.4487	13	9.4327
54	59.2247	13	9.5965
54	59.0005	13	9.7602
54	58.7767	13	9.9238
54	58.5525	13	10.0875
54	58.3283	13	10.2512
54	58.1048	13	10.4145
55	0.3888	13	9.5928
55	0.1628	13	9.7485
54	59.9368	13	9.9040
54	59.7108	13	10.0597
54	59.4848	13	10.2152
54	59.2590	13	10.3707
54	59.0330	13	10.5262
54	58.8070	13	10.6815
54	58.5810	13	10.8368
54	58.3555	13	10.9920
54	59.7127	13	10.8627
54	59.4850	13	11.0098
54	59.2572	13	11.1572
54	59.0293	13	11.3042
54	58.8015	13	11.4513
54	58.5737	13	11.5983
54	59.7248	13	11.6225
54	59.4903	13	11.7845
54	59.2660	13	11.9005
54	59.0325	13	12.0420
54	58.8107	13	12.1763
54	59.7357	13	12.4228
54	57.0250	13	5.1917

54	57.4420	13	5.7040
54	57.0833	13	6.0280
54	57.8852	13	6.2922
54	57.6033	13	6.5677
54	57.3213	13	6.8433
54	58.3762	13	6.8683
54	58.0902	13	7.1310
54	57.8043	13	7.3937
54	57.5182	13	7.6563
54	57.6487	13	8.4733
54	57.7425	13	9.3633
54	59.4093	13	12.6068
54	59.1030	13	12.7795
55	0.4558	13	12.8172
55	0.1458	13	12.9795
54	59.8347	13	13.1425
54	59.5273	13	13.3033
55	0.4300	13	13.6667
55	0.1333	13	13.8083
55	0.3962	13	10.4210
55	0.1683	13	10.5683
54	59.9405	13	10.7155
55	0.4133	13	11.2052
55	0.1818	13	11.3117
54	59.9692	13	11.4607
55	0.4292	13	12.0317
55	0.1978	13	12.1622
54	59.9668	13	12.2925

Shipping lanes used for drifting collision, MARIN 2000

No.	Coordinates waypoint 1		Coordinates waypoint 2		No. of ships/year
1	5513	1417	5447.5	1242.3	14940
2	5442.9	1249.6	5512	1421	14858
3	5434.9	1218	5518.8	1307.7	4221
4	5501.4	1313.6	5445.1	1333.3	1227
5	5446.1	1334.3	5501.4	1313.6	1175
6	5518.8	1307.7	5436.8	1214.6	4184
7	5518.8	1307.7	5432.5	1343.8	1768
8	5432.5	1343.8	5518.8	1307.7	1768
9	5513	1417	5446.7	1243.4	99
10	5515	1251.9	5501.4	1313.6	1337
11	5501.4	1313.6	5516	1252.5	1254
12	5446.4	1243.7	5512	1421	95
13	5446.1	1334.3	5447	1258.4	4508
14	5446	1300.3	5445.1	1333.3	4584
15	5501.4	1313.6	5432.5	1343.8	110
16	5432.5	1343.8	5501.4	1313.6	79
17	5523.5	1346.9	5447.5	1242.3	28
18	5515	1251.9	5456.9	1436.7	1865
19	5434.9	1218	5523.5	1346.9	27
20	5515	1251.9	5512	1421	10643

Shipping lanes used for drifting collision, MARIN 2010

No.	Coordinates waypoint 1		Coordinates waypoint 2		No. of ships/year
1	5513	1417	5447.5	1242.3	18402
2	5442.9	1249.6	5512	1421	18360
3	5434.9	1218	5518.8	1307.7	5250
4	5518.8	1307.7	5436.8	1214.6	5193
5	5513	1417	5446.7	1243.4	177
6	5518.8	1307.7	5432.5	1343.8	2141
7	5432.5	1343.8	5518.8	1307.7	2141
8	5501.4	1313.6	5445.1	1333.3	1084
9	5446.1	1334.3	5501.4	1313.6	1038
10	5446.4	1243.7	5512	1421	170
11	5515	1251.9	5501.4	1313.6	1178
12	5501.4	1313.6	5516	1252.5	1108
13	5446.1	1334.3	5447	1258.4	4267
14	5446	1300.3	5445.1	1333.3	4400
15	5501.4	1313.6	5432.5	1343.8	94
16	5432.5	1343.8	5501.4	1313.6	69
17	5515	1251.9	5456.9	1436.7	1739
18	5434.9	1218	5523.5	1346.9	21
19	5523.5	1346.9	5447.5	1242.3	18
20	5515	1251.9	5512	1421	10458

Shipping lanes used for powered collision, MARIN 2000

No.	Coordinates waypoint 1		Coordinates waypoint 2		No. of ships/year
1	5513	1417	5447.5	1242.3	14940
2	5515	1251.9	5501.4	1313.6	1337
3	5446.1	1334.3	5501.4	1313.6	1175
4	5501.4	1313.6	5445.1	1333.3	1227
5	5513	1417	5446.7	1243.4	99
6	5432.5	1343.8	5501.4	1313.6	79
7	5446.4	1243.7	5512	1421	95
8	5501.4	1313.6	5432.5	1343.8	110
9	5434.9	1218	5523.5	1346.9	27
10	5523.5	1346.9	5447.5	1242.3	28
11	5501.4	1313.6	5516	1252.5	1254
12	5518.8	1307.7	5432.5	1343.8	1768
13	5432.5	1343.8	5518.8	1307.7	1768
14	5512	1230.2	5457.4	1304.1	15
15	5446.1	1334.3	5457.4	1304.1	6
16	5456.9	1310.8	5457.4	1304.1	9
17	5432.5	1343.8	5456.9	1310.8	9
18	5442.9	1249.6	5512	1421	14858
19	5457.4	1304.1	5445.1	1333.3	15
20	5442.9	1249.6	5446	1300.3	4557

Shipping lanes used for powered collision, MARIN 2010

No.	Coordinates waypoint 1		Coordinates waypoint 2		No. of ships/year
1	5513	1417	5447.5	1242.3	18402
2	5446.1	1334.3	5501.4	1313.6	1038
3	5515	1251.9	5501.4	1313.6	1178
4	5501.4	1313.6	5445.1	1333.3	1084
5	5513	1417	5446.7	1243.4	177
6	5432.5	1343.8	5501.4	1313.6	69
7	5446.4	1243.7	5512	1421	170
8	5501.4	1313.6	5432.5	1343.8	94
9	5434.9	1218	5523.5	1346.9	21
10	5523.5	1346.9	5447.5	1242.3	18
11	5518.8	1307.7	5432.5	1343.8	2141
12	5432.5	1343.8	5518.8	1307.7	2141
13	5501.4	1313.6	5516	1252.5	1108
14	5512	1230.2	5457.4	1304.1	9
15	5446.1	1334.3	5457.4	1304.1	4
16	5456.9	1310.8	5457.4	1304.1	6
17	5432.5	1343.8	5456.9	1310.8	6
18	5442.9	1249.6	5512	1421	18360
19	5457.4	1304.1	5445.1	1333.3	9
20	5442.9	1249.6	5446	1300.3	4379

Shipping lanes used for drifting collision, GL

No.	Start of Route section	Start of Route section	End of Route section	End of Route section	Traffic on the route per year
1	54°46.26N	12°43.68E	55°12.06N	14°15.96E	17607
2	55°15.36N	14°13.92E	54°46.62N	12°43.56E	14926
3	55°18.384N	12°38.694E	55°25.578N	12°40.692E	18000
4	55°18.384N	12°38.694E	55°15.498N	12°51.864E	19286
5	54°46.62N	12°43.56E	54°35.82N	12°16.602E	21232
6	54°35.82N	12°16.602E	54°46.26N	12°43.68E	21232
7	55°15.498N	12°51.864E	55°15.342N	14°13.938E	17766
8	54°35.82N	12°16.602E	55°20.502N	13°8.502E	9776
9	54°46.272N	12°43.656E	54°50.562N	14°0.558E	9391
10	55°25.578N	12°40.692E	55°31.866N	12°42.54E	18000

Shipping lanes used for powered collision, GL

No.	Start of Route section	Start of Route section	End of Route section	End of Route section	Traffic on the route per year
1	55°15.36N	14°13.92E	54°46.62N	12°43.56E	14926
2	55°15.498N	12°51.864E	55°0.9N	13°15.24E	2240
3	55°0.9N	13°15.24E	54°45.312N	13°33.552E	2240
4	54°46.26N	12°43.68E	55°12.06N	14°15.96E	16187
5	55°13.2N	14°16.02E	54°46.62N	12°43.56E	1420
6	54°45.312N	13°33.552E	55°7.392N	12°30.66E	16

Details from SSPA's simulation of MARIN's calculation for powered collision. Base case.

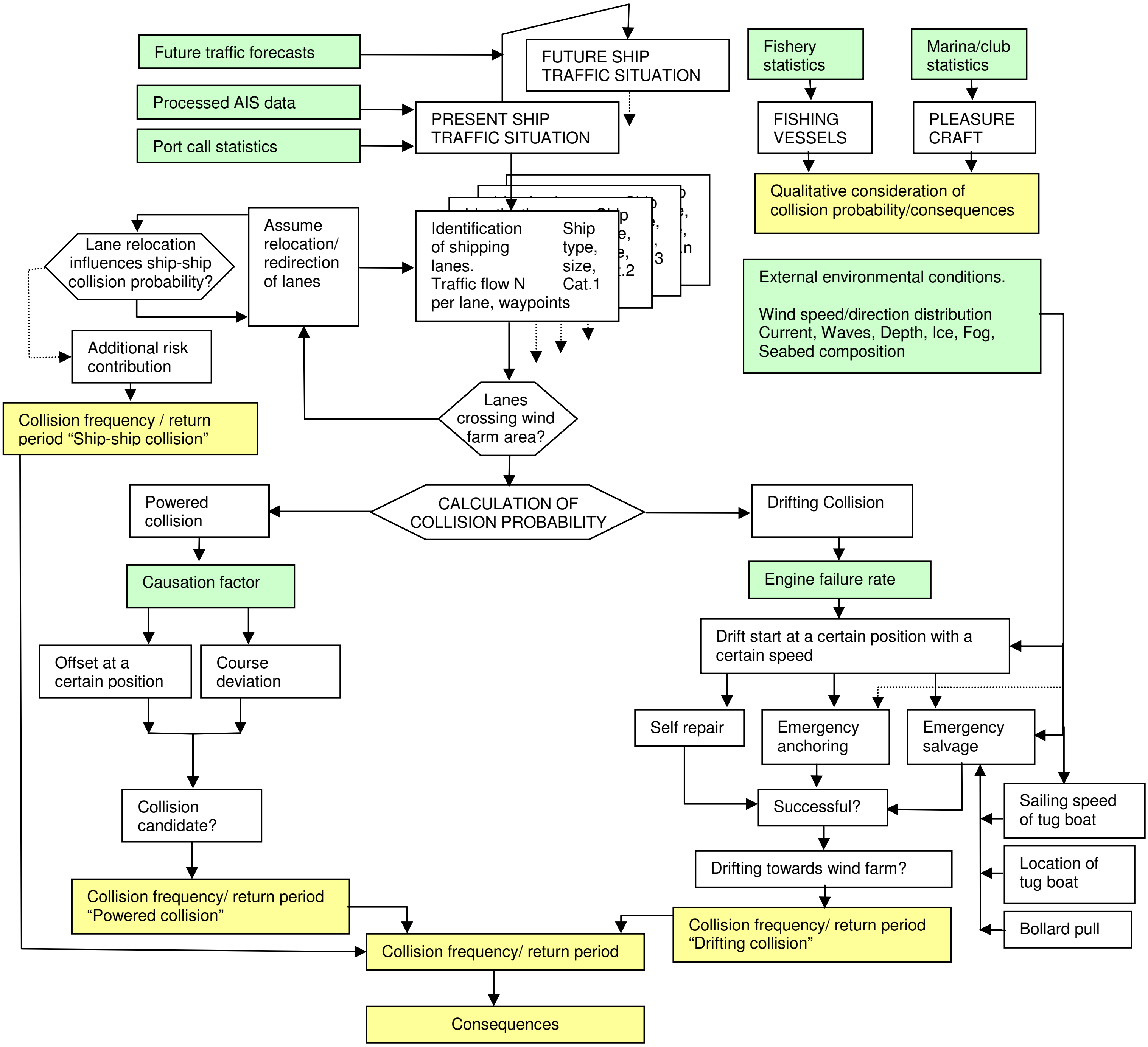
Shipping lane:	Shortest distance to the park [nm]:	Length of shipping lane [nm]:	Assumed standard deviation for course offset [nm]:	Traffic Separation [yes/ no]:
1	2.5854	58.4185	1.23	yes
2	0.97619	20.1962	0.35	no
3	1.0245	19.1475	0.35	no
4	0.95931	20.6587	0.35	no
5	3.2903	58.1576	1.23	no
6	0.9371	35.0682	0.35	no
7	4.1348	59.8115	1.23	no
8	0.9371	35.0682	0.35	no
9	1.8898	68.1982	0.75	no
10	1.4818	49.8748	0.75	no
11	4.8587	52.4619	1.5	no
12	4.8587	52.4619	1.5	no
13	1.0447	19.6906	0.35	no
14	0.94483	25.1808	0.35	no
15	0.818	21.5335	0.35	no
16	0.54863	3.9318	0.35	no
17	1.0275	32.2597	0.35	no
18	7.5258	58.2072	1.23	yes
19	0.8409	21.6649	0.35	no
20	12.0812	6.7433	2	no

Details from SSPA's simulation of GL's calculation for powered collision. Base case.

Shipping lane:	Shortest distance to the park [nm]:	Length of shipping lane [nm]:	Assumed standard deviation for course offset [nm]:	Traffic Separation [yes/ no]:
1	2.5748	57.5041	1.23	yes
2	0.95041	20.5883	0.35	no
3	1.0016	19.574	0.35	no
4	3.9408	57.3038	1.23	yes
5	3.3667	57.6839	1.23	no
6	1.4162	43.8635	0.75	no

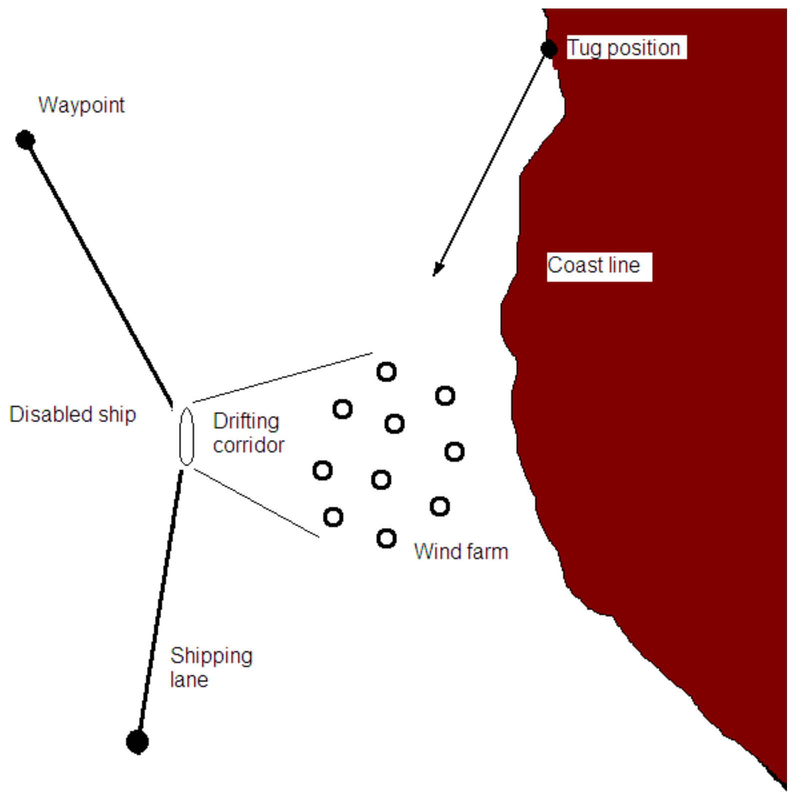
APPENDIX D – SSPA CALCULATION MODEL FOR COLLISION SHIP – OFFSHORE WIND FARM

SSPA Sweden AB conducts an analysis for two cases; drifting collision (with a disabled ship) and powered collision (ramming ship). The schematic diagram below illustrates the components of the risk analysis model used by SSPA. It is worth mentioning that for some locations, distinction in different draughts should be made, because bigger ships may ground before a collision occurs.



1 RISK MODEL FOR "DRIFTING COLLISIONS"

For drifting collisions, SSPA Sweden AB uses a basic method to estimate the probability that ships experiencing a breakdown (i.e. loss of power, propulsion and/or steering) drift into the wind farm. The model includes estimations of frequency of ship breakdown at specific locations and also of effectiveness of mechanisms that help take control of the vessel again. These mechanisms include emergency salvage, self repair, and anchoring.



The frequency of vessels drifting from a shipping lane and colliding with an object near the lane can be written as:

$$F_{CD} = \sum_i N_i \cdot F_{drift} \cdot T_i \cdot P_{D1} P_{D2} P_{D3}$$

where

F_{CD}=	Collision frequency of drifting vessels (per year)
N_i =	Number of vessels of ship type *i* in the area around the object (vessels/year)
F_{drift}=	Frequency of breakdown (per hour)
T_i =	Average time a vessel of ship type *i* spends in the area to be considered for the calculation of the collision frequency (hours)
P_{D1}=	Probability of the ship drifting towards the object
P_{D2}=	Probability of not receiving any effective external help before a collision occurs
P_{D3}=	Probability of no collision avoidance by the ship before a collision occurs (i.e. the crew is unable to stop the drifting through self-repair, anchoring, etc.)

If there are several shipping lanes, the total collision frequency is the sum of the collision frequencies of each lane.

The model is not applicable for estimating collisions during war situations, or due to terrorist attacks or volitional/ targeted ramming.

1.1 Number of vessels and main shipping lanes

Maps with information from the Automatic Identification System (AIS) are used to identify the main shipping lanes in the area around the object. Histograms are used to estimate the number of vessels that sail on each identified shipping lane. The data are also used to estimate the breakdown of different ship types and ship sizes. For cases where data are not available for the ship classes, statistics from harbours and authorities are used.

The model is based on corresponding models for oil platforms. The frequency of drifting collisions is calculated as a total for an area of typically 20 nautical miles radius around the platform. The dimensions of a wind farm are much bigger than those of an oil platform, which implies that a larger radius could be required. However, for a single wind power plant this is not true.

It has been agreed on by a group of experts (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005) that the length of the shipping lanes to be considered to contribute to the collision frequency corresponds to a drifting time of 24 hours.

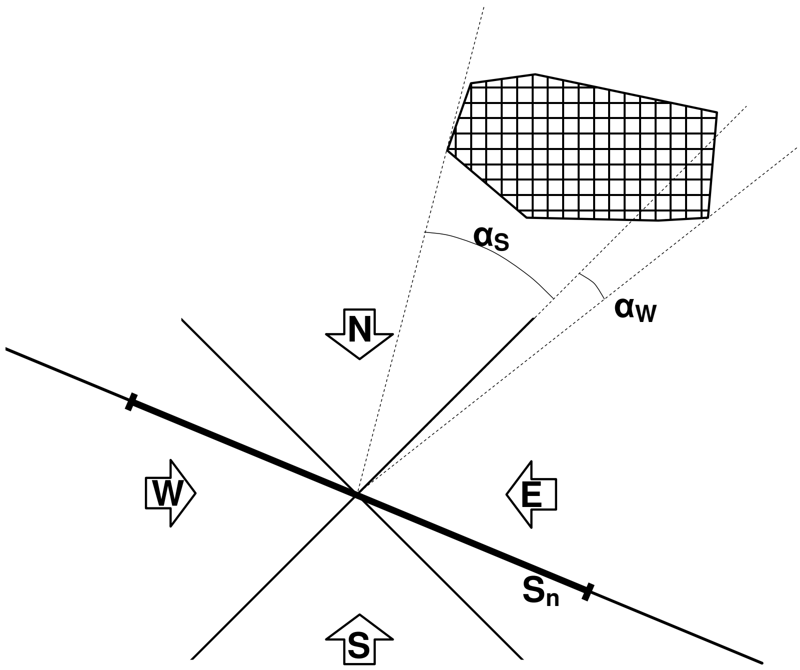
In SSPA’s model no such limits are introduced as described above. Geographical limitations of the length of the shipping lanes are used instead, e.g. land areas located between the wind farm and the lane.

1.2 Average time

The average time a specific vessel sails in the area to be considered for the calculation of the collision frequency depends on the length of the lane the ship is sailing on and on the speed of the vessel on this lane. Average speeds are taken for the vessels on the different lanes.

1.3 Probability of drifting towards the object

The probability of drifting towards the object under consideration varies with position on the shipping lane and the course of the shipping lanes. For each point on the lane the wind farm is covered by an angle which overlaps with the wind directions as shown in the example in the figure below (division in 4 wind directions):



The probability is therefore dependent on the size of the angle, the distance from the wind farm to the shipping lane and the frequency of the wind blowing from the different directions. The factor P_{D1} is calculated as follows:

$$P_{D1} = \sum_{w=1}^{N_{wd}} \left(\frac{R_w \text{ x } \alpha_w}{360 / N_{wd}} \right)$$

where:

N_{wd} =	number of divisions in different wind directions
α_w=	angle which is covered by the wind farm in the wind direction *w*
R_w=	frequency for wind from direction *w*

(For the figure above, the angle is measured at the centre of S_n. In SSPA's calculation program, it is measured at the endpoints of S_n. This approximation will most probably not have an influence on the calculated results.)

1.4 External help (salvage tug)

External help for drifting vessels is assumed to be by emergency salvage. This help depends on certain factors:

- The salvage tug needs a certain time to respond, i.e. there needs to be an available tug and it requires time to leave the harbour/ position.
- The time for the salvage tug to reach the vessel depends on the salvage tug position, vessel position, drift speed and salvage tug speed. The sailing speed of the salvage tug depends on the sea state and the wind velocity.
- The time for the crews to connect a line. This time is strongly dependent on the equipment of the two vessels involved as well as the training of their crews.
- The time to take control of the drifting vessel.
- The performance of the tug, which is measured in tonnes of bollard pull. The required power depends on the size and type of the drifting vessel and the wind conditions.

When salvage tugs with different capabilities can reach the drifting vessel in time, the one with the best performance is assumed to tow it. It is assumed that a collision is avoided once the tug takes control of the disabled vessel.

1.5 Self-repair, emergency anchoring, etc.

The frequency of breakdown (engine failure rate) for a single engine ship is taken as $F_{drift} = 2.5x10^{-4}$ per hour (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005). It is assumed that the engine failure rate is independent of the ship type and propulsion system.

One part of P_{D3} is the probability of no successful self-repair. This probability depends on time it takes for the crew to repair the engine failure without external help. A function has been derived based on statistics from Dutch waters (additional details published in: SAFESHIP 2005 and Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005), which depends on the time to repair:

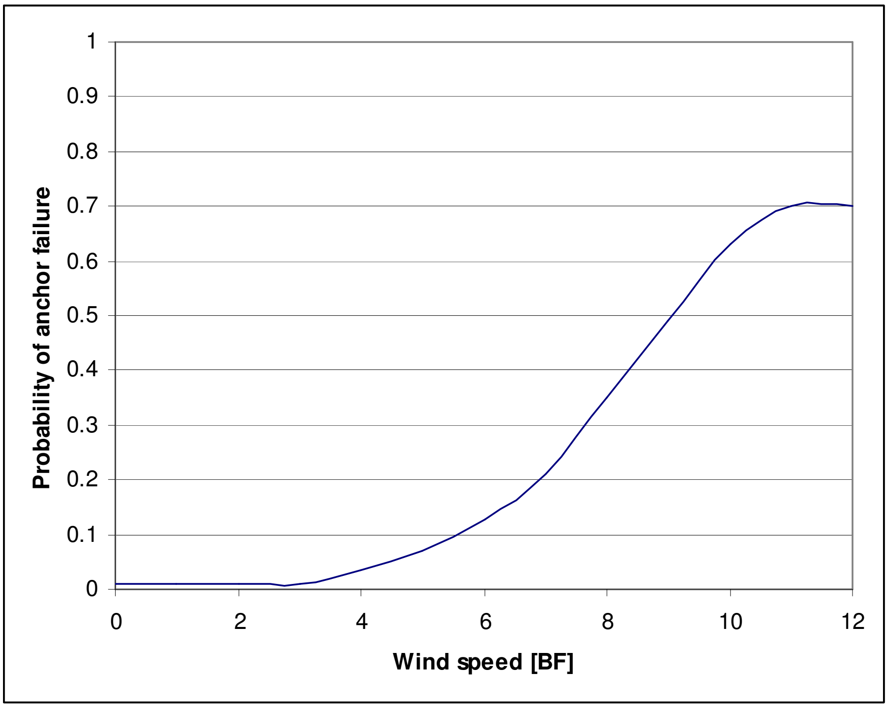
$$f(t) = 1 \qquad \text{for } t < 0.25 \text{ h}$$

$$f(t) = \frac{1}{(1.5 \cdot (t - 0.25) + 1)} \qquad \text{for } t > 0.25 \text{ h.}$$

where t = time after the engine failure occurred (hours)

P_{D3} therefore varies with the distance to the wind farm and the drift speed of a certain vessel.

Another part of P_{D3} accounts for the cases when the crew is unable to stop the ship with emergency anchoring. The probability for this is connected to the water depth, the type of sea bottom, the wind velocity, the drift speed, the distance from the wind farm and the ship size. The figure below shows the probability of anchor failure for different wind speeds for typical sea bottom characteristics of the Baltic Sea, which has been agreed on of a group of experts (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005). If the anchor holds, the anchor prevents the drifting ship from reaching the wind farm.



1.6 Drift velocity

The drift velocity of the disabled vessel is assumed to be constant for the calculations. It is modelled by the energy equation that shows the sum of all forces acting on the ship to be equal to zero.

$$F_{\text{Resistance}} + F_{Wind} + F_{Wave} + F_{Current} = 0$$

where

$F_{Resistance}$= Resistance of the ship through the water

$$\left|F_{\text{Resistance}}\right| = \frac{1}{2}\rho_{water} L_i T_{il} C_{d\_i} v_{drift\_il}^2$$

F_{Wind}= wind force acting on the ship

$$\left|F_{Wind}\right| = \frac{1}{2}\rho_{air} A_{L\_il} C_{dWind\_i} v_{Wind}^2$$

F_{Wave}= wave force acting on the ship (assumed to be F_{Wave}=½ F_{Wind})

$F_{Current}$= force acting on the ship due to current

v_{drift_il} = drift velocity of ship of type *i* in loading condition *l* in wind and waves at different wind velocities
v_{wind} = wind velocity
ρ_{air} = density of air (1.35 [kg/m^3])
ρ_{water} = density of water (1025 [kg/m^3])
A_{Lil} = lateral wind surface of ship of type *i* in loading condition *l*
T_{il} = draught of the ship of type *i* in loading condition *l*
L_i = length of the ship of type *i*
C_{dWind_i} = lateral wind resistance coefficient of the ship of type *i*
C_{d_i} = lateral resistance coefficient of the underwater body of the ship of type *i*

The coefficients and parameters are based on data from SSPA Sweden AB and on published approximations. The force acting on the ship due to current is most of the time assumed to be negligible for the Baltic Sea. The drift direction is assumed to be the same as the wind direction.

1.7 Sailing into the park versus hitting a wind power plant

The model described above calculates the frequency of disabled ships drifting into the wind farm area. It is also possible to calculate the frequency of collisions of disabled ships with the single power plants. For this case, the results calculated for reaching the park area should be multiplied by the following expression:

$(1-(1-(L+D)/b)^r)$

where
L = ship length
D = power plant diameter
b = distance between power plants
r = number of rows of power plants

2 RISK MODEL FOR "POWERED COLLISIONS"

The model used at SSPA Sweden AB estimates the probability of ships being navigated incorrectly into the wind farm. The incorrect navigation can be caused by human, technical and/or watch keeping failure.

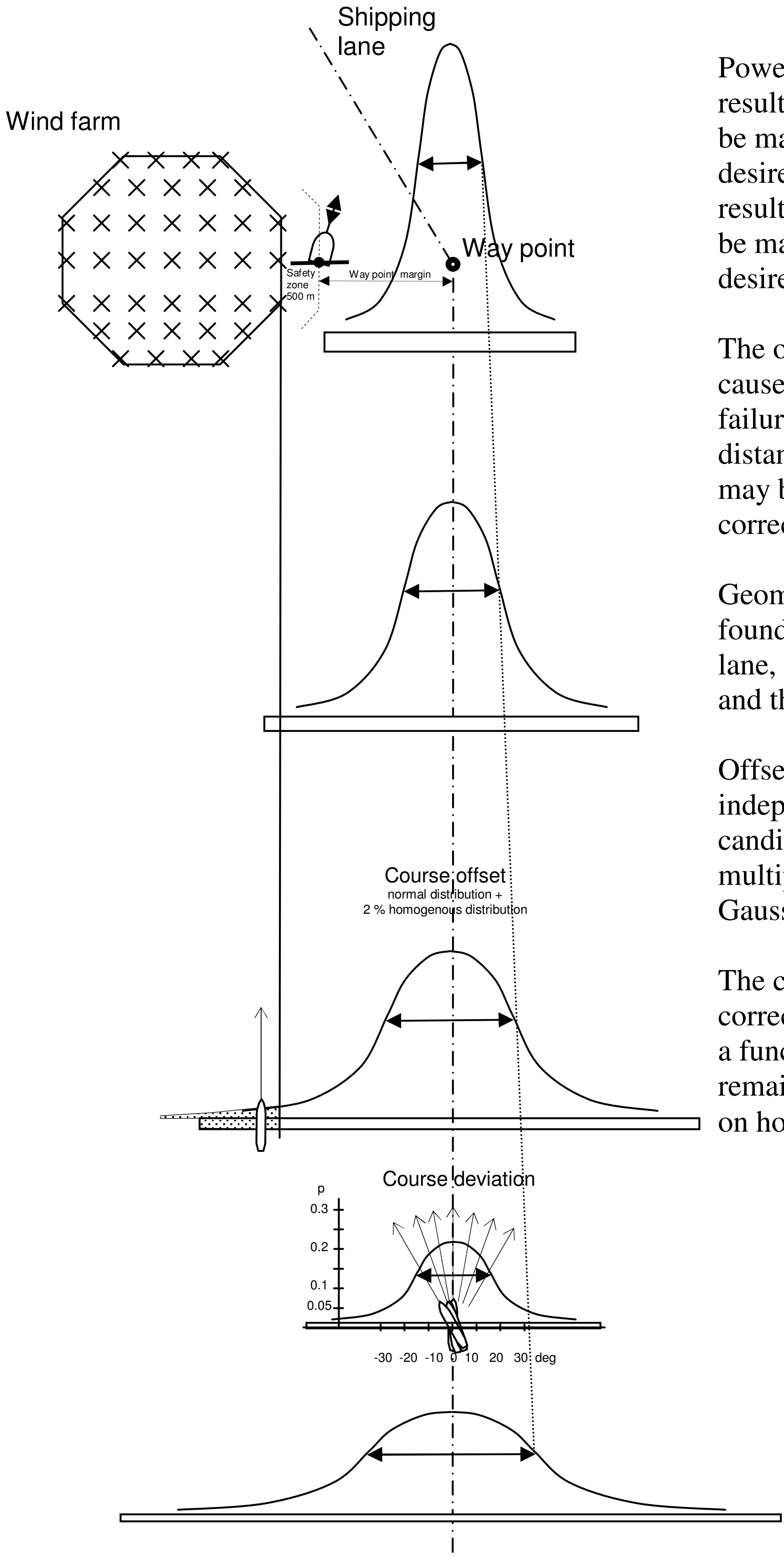
The collision frequency for powered collisions on a shipping lane is calculated using the following equation:

$$F_{CP} = \sum_{x} \sum_{offset} \sum_{course} N \cdot P_x \cdot P_{offset} \cdot P_{course} \cdot P_{C1} \cdot P_{C2} \cdot P_{C3} \cdot P_{react}(x)$$

where

F_{CP}=	Frequency of a passing ship colliding under power (per year)
N=	Total traffic on the shipping lane (vessels/ year)
x =	Position on the shipping lane
P_x =	Probability of being on position *x* on the shipping lane
P_{offset} =	Probability of having a certain offset on the current x-position (Gaussian distribution + uniform distribution)
P_{course} =	Probability of following a certain course heading towards the object (Course deviations are assumed to follow a Gaussian distribution.)
P_{C1} =	Probability of human failure during planning and execution of the passage of an object
P_{C2} =	Probability of technical failure of navigational equipment or of watch keeping failure due to factors such as lack of attention during lookout on the bridge or bad visibility
P_{C3} =	Probability of failure of the wind farm safety equipment/ crew or a potential stand-by boat to warn the passing ship in time to avoid a collision
P_{react}(x) =	Probability of the crew onboard being unable to react in time to correct the navigational error (dependent on *x*)

If there are several shipping lanes, the total collision frequency is the sum of the collision frequencies of each lane.
The model is not applicable for estimating collisions during war situations, or due to terrorist attacks or volitional/ targeted ramming.



Risk model Powered collision (/grounding)

Powered collision/grounding is a result of mistaken position that will be manifested as an offset from desired track on lane and or a result of mistaken heading that will be manifested as a deviation from desired course direction.

The offset and deviations may be caused by human and/or technical failures. Depending on the distance to the obstacle, the crew may be able to detect the error and to correct the mistake.

Geometric collision candidates are found by their position on the shipping lane, their offset from the shipping lane and their course over ground.

Offset and deviations vary independently and collision candidates are identified by multiplying the two independent Gaussian distributed variables.

The chance of detection and correction of the collision course is a function of the time/distance remaining to the collision position and on how often the position is checked.

2.1 Number of vessels and main shipping lanes

It is assumed that parts of the shipping traffic follow certain routes. This is modelled by shipping lanes on which the ships sail. To identify the main shipping lanes in the wind farm surroundings and to estimate the traffic on these lanes, AIS plots and histograms are used in the same way as for drifting collisions (see previous chapter). If the current traffic sails through the area of a future wind farm, the traffic is moved according to certain assumptions. The length of the shipping lanes are suggested to correspond to a traffic area that measures about 15 nautical miles (or 20 nautical miles) from the outer corners of the wind farm, which has been agreed on by a group of experts (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005). In SSPA’s model no such limit is introduced. Geographical limitations of the length of the shipping lanes are used instead, e.g. land areas located between the wind farm and the lane.

2.2 Position on shipping lane

The shipping lanes are split into a number of parts and the calculations for each part is summarised. This is an approximation to integrating over the whole lane. The probability of being on position x on the shipping lane (P_x) is assumed to be equally distributed over the shipping lane as follows:

$$P_x = 1/\ n_{split}$$

where n_{split} is the number of parts the lane has been split into in the calculation. This assumption presupposes that the sailing speed is constant over the shipping lane and that each part of the lane has the same length. The original function is

$$P_x = t_x\ /\ t_{tot}$$

where t_{tot} is the total time it takes to travel from the start to the end of the shipping lane and t_x is the time it takes to travel from the start to the end of the part of the shipping lane representing the position x.

2.3 Course offset

The lateral distribution on the lanes is assumed to usually follow a Gaussian distribution. The standard deviation (σ) for the Gaussian distribution is estimated from histograms. If the standard deviation cannot be estimated from histograms because, for example, the lane has been moved or certain parts of the shipping lane have special distributions, reference values from the table below have been used. The source of the table is: Bundesministerium für Verkehr-, Bau und Wohnungswesen (2005).

Description	**Standard deviation for Gaussian distribution [nm]**
Port approach	0.2 to 0.3
Conspicuous navigational points, e.g. navigational marks, buoys	0.3 to 0.4
Navigational channel with traffic separation	0.5
Waypoints in wider shipping lanes	0.5 to 1.0
Waypoints in open sea areas	2.0

The mean value (μ) of the Gaussian distribution is usually assumed to be zero. If no further information is available, SSPA assumes that the width of the Gaussian distribution used in the calculations is taken as 12 times the standard deviation (i.e. 12σ).

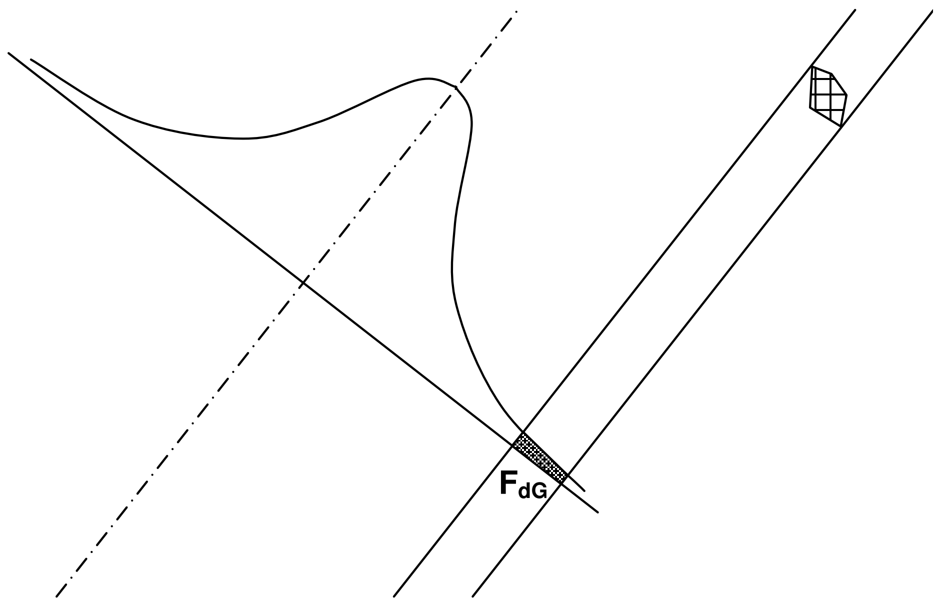
Part of the shipping traffic does not follow a Gaussian distribution. For this part of the traffic a uniform distribution is assumed. If no further information is available, the width of the uniform distribution is taken as 6 times the standard deviation (i.e. 6σ). The uniform distribution is then taken as 2% of the normal distribution (Bundesministerium für Verkehr-, Bau und Wohnungswesen 2005).

Accordingly, the Gaussian distribution only partly describes the probability of having a certain course offset along an axis perpendicular to the shipping lane, here called $P_{offsetG}$. The other part, the uniform distribution, of P_{offset} is $P_{offsetU}$, i.e.

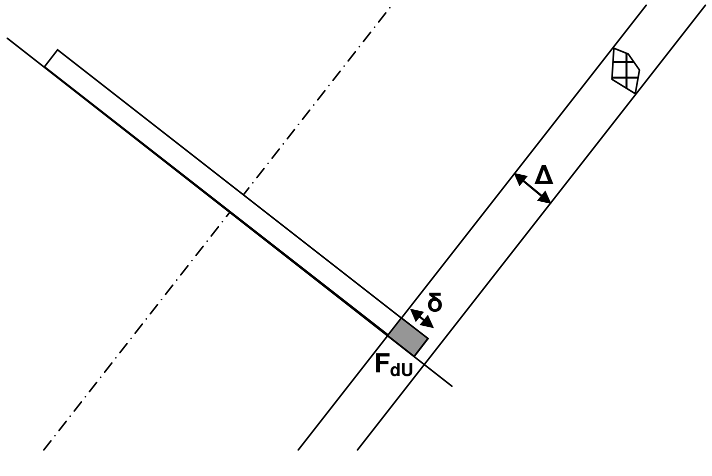
$$P_{offset} = P_{offsetG} + P_{offsetU}$$

As an example, the two figures below illustrate $P_{offsetG}$ and $P_{offsetU}$, respectively, for a special interval instead of for a certain point along the axis. The probability of having an offset in this interval is called F_d in this model description.

The first figure shows the Gaussian distribution on the shipping lane and the possible collision candidates who are at risk of a collision with an object (F_{dG}), if they continue their course straight ahead (i.e. if the course deviation is zero degrees). As the figure shows, the distance between the lane and the object also influences F_{dG}.



The second figure shows the uniform distribution on the shipping lane and the possible collision candidates who at risk of a collision with an object (F_{dU}), if they continue to sail on their course straight ahead (i.e. if the course deviation is zero degrees). As the figure shows, the distance between the lane and the object also influences F_{dU}.



The total proportion of vessels that are in the part of the lane directed towards the wind farm if the course deviation is zero degrees is assumed to be:

$F_d = F_{dG} + F_{dU}$

where $F_{dU} = 0.02 \cdot \delta / 6\sigma$

and $\delta \leq \Delta$

2.4 Course deviation

In SSPA's model it is assumed that the course deviation of a ship can vary between -90 and 90 degrees, i.e. no course deviations leading to ships sailing in the opposite direction are possible.

The course deviation is assumed to usually follow a Gaussian distribution. The standard deviation (σ) for the Gaussian distribution is difficult to estimate. Further studies of AIS data are needed. To date, figures from MARIN have been used in SSPA's model as a base for estimation. MARIN does not use a Gaussian distribution for the course deviation. They use a distribution where the courses -30, -20, -10, 0, 10, 20, 30 have the probability of 0.05, 0.1, 0.2, 0.3, 0.2, 0.1 and 0.05 respectively (van der Tak and Rudolph 2003). Fitting a Gaussian distribution to these values, with the mean value (μ) assumed to be zero, gives a standard deviation of about 15 degrees.

2.5 Causation factor

Different values of P_{C1}, P_{C2} and P_{C3} are presented in the literature (see e.g. Spouge 1999). A combined factor P_C is often used. P_C (Causation probability, i.e. probability of failure to avoid an obstacle on the navigation route) has been discussed extensively in the literature since the seventies. Most estimates of P_C have been based on data available for groundings and ship-ship collisions. Two approaches published in 1974 constitute the basis for most of the other estimations: Fujii's or MacDuff's (Larsen 1993). The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) also refers to Fujii for the value of P_C (IALA 2007). Ramböll (2000) suggests $P_C = 2 \times 10^{-4}$ be used based on Fujii's estimations. GL and DNV have agreed to use the causation factor of $P_C = 3 \times 10^{-4}$ for a ship not taking corrective action when on collision course (SAFESHIP 2005). In SSPA

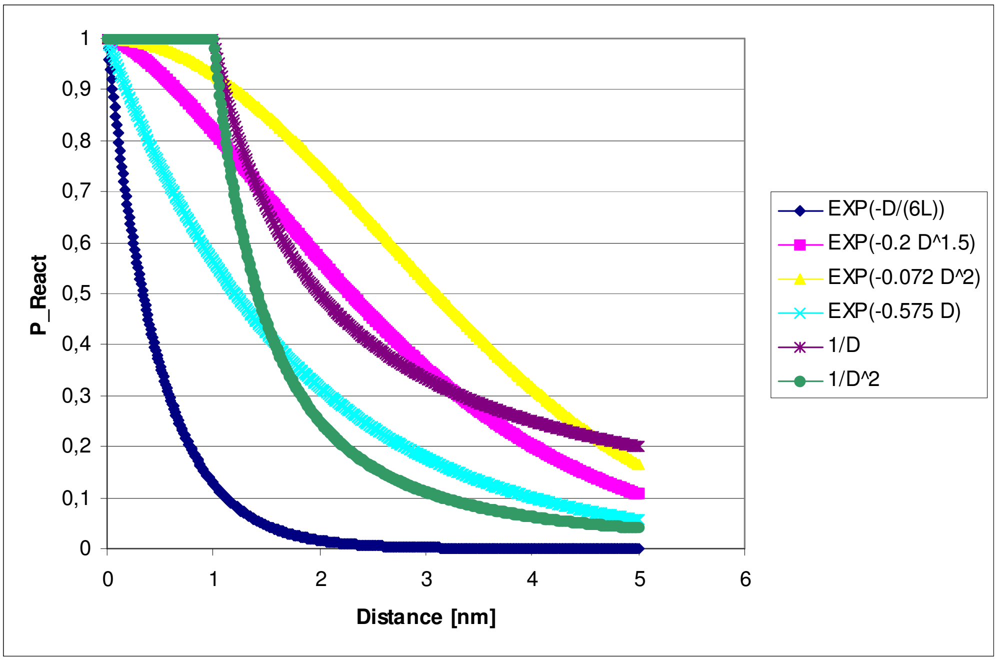
Sweden AB's risk model for powered collisions this factor is assumed to be valid ($P_C = 3 \times 10^{-4}$).

There are also other factors influencing P_C, such as bad visibility. Larsen (1993) and Spouge (1999) illustrate such factors.

2.6 Onboard crew reaction

In SSPA's model, the probability that the crew onboard is not able to react in time to correct the navigational error is called $P_{react}(x)$. It is dependent on the distance between the wind farm and the position of the ship (D), and is therefore modelled as dependent on the x-position on the shipping lane. The figure below shows weightings for offshore platforms presented by MARIN (all curves except for exp(-D/(6L))) (van der Tak and Glansdorp (Year unknown)). As already mentioned, MARIN uses the Navigational Error Rate (NER) instead of the causation factor. $P_{react}(x) = \exp(-D/(6L))$, where L = ship length, is suggested in the literature to be used together with the causation factor (Fujii and Mizuki 1998). The function is, however, derived for navigation on lanes with a bend passing bridge piers. The parameter D in the formula stands for distance from bend to bridge. In the SSPA model, it is assumed that this function could be used for offshore wind farms with D equal to the distance between the wind farm and the position of the ship. In the figure below the ship length (L) is assumed to be 150 m.

A more conservative approach is to use for example $P_{react}(x) = \exp(-0.2D^{1.5})$ together with the causation factor instead of using $P_{react}(x) = \exp(-D/(6L))$.



2.7 Sailing into the park versus hitting a wind power plant

The model described above calculates the frequency of ships sailing into the wind farm area as the result of an error. It is also possible to calculate the frequency of ships colliding (under power) with the single power plants. For this case, the results calculated for reaching the park area should be multiplied by the following expression:

$(1-(1-(B+D)/b)^{r})$

where
B = ship breadth
D = power plant diameter
b = distance between power plants
r = number of rows of power plants

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