Master's thesis

NTNU
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A BBN Risk Analysis of Cruise Ship Groundings in Northern Norway during Winter

Master's thesis in Marine Technology
Supervisor: Jan Erik Vinnem
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Abstract

Northern Norway has gained more focus as a destination for cruise ship tourism the recent years. The number of cruise ship calls has increased for both the summer and winter seasons. A cruise ship grounding in these waters has the potential of many fatalities. The inhospitable weather conditions, long distances, and relatively poor emergency evacuation readiness in the area increase the risk when sailing with many passengers in Northern Norway.

The goal of this thesis is to present the results of a grounding risk analysis for cruise ships sailing in Northern Norway during winter. The analysis is based on a Bayesian belief network constructed from a literature review and quantified by an expert panel through a Delphi process. In addition to constructing a model, several risk-reducing measures are proposed and their effect is investigated with the model.

The individual risk level and group risk level were found by the model. The individual risk found is above what is considered a tolerable level, and the group risk is found to be within a region that calls for risk-reduction if cost-efficient measures are identified.

The results from this thesis indicate that the risk of grounding for cruise ships is within a range that would call for risk-reducing measures to be implemented. When considering that several other hazards exist in addition to the grounding hazard, it is believed that the implementation of risk-reducing measures are imperative if the cruise ship traffic is to continue.

Preface

This thesis report is written as the final work of a five year MSc program in Marine Technology at NTNU. The work with this thesis has lasted throughout the first half of 2020, with a project thesis written in the autumn of 2019 as groundwork and preparation. The thesis presents the results of a study of the risk of grounding for cruise ships in Northern Norway during winter.

To work with this thesis has been a true learning experience. It has been enjoyable to perform this research, but there have been several setbacks and unexpected problems that emerged throughout the process.

I would like to express my sincerest gratitude to my supervisor Professor Jan Erik Vinnem for his guidance and support throughout the work with this thesis. For his help as a co-supervisor, I would also thank Martin Hassel for good discussions and conversations regarding several topics of the thesis. I would also like to thank the experts who spent time and energy on assisting in the Delphi process part of the research.

Some parts of Chapter 2 are reused from the project thesis, as they are relevant for the subject of this thesis.

Contents

List of Tables

List of Figures

Abbreviations

AIBN = Accident Investigation Board Norway
ALARP = As low as reasonable practicable
BBN = Bayesian belief network
CCM = Communication, cooperation & monitoring
CLIA = Cruise Lines International Association
CPT = Conditional probability table
ECDIS = Electronic Chart Display and Information System
FSA = Formal safety assessment
IMO = International Maritime Organization
IR = Individual risk
ISO = International Organization for Standardization
NCA = Norwegian Coastal Administration
nm = Nautical mile(s)
OOW = Officer on watch
PEC = Pilotage exemption certificate
SOLAS = Safety of Life at Sea
STCW = Standards of Training, Certification and Watchkeeping
VTS = Vessel traffic services

Chapter 1

Introduction

1.1 Motivation

Passenger ship traffic is a significant part of the maritime transportation along the Norwegian coastline. Cruise ship tourism has increased in Norway in the last years and is expected to grow further (Dybedal, 2018). Cruise ship traffic is not without risk. With many passengers gathered on one vessel, an accident on the vessel can put many lives in danger. Historical accidents demonstrate how severe the consequences of a big passenger vessel can be. The fire on «Scandinavian Star» in 1990 and the sinking of «MS Estonia» are well-known major accidents with many fatalities. The amount of major accidents is relatively low, yet they do occur. The grounding of a cruise ship can have severe consequences. The grounding and partial sinking of the «Costa Concordia» in 2012 lead to 32 deaths. In March 2019, the cruise ship «Viking Sky» lost propulsion outside Hustadvika for some time and ended up being minutes away from a grounding, and potentially the loss of many lives. Luckily, the crew managed to avoid grounding. This incident highlighted some of the challenges with cruise ship tourism in Norway during winter and revealed that the risk might be too high to continue without introducing risk-reducing measures.

1.2 Objective

The objective of this thesis is to investigate the grounding risk associated with cruise ship tourism in Northern Norway during winter and evaluate potential risk-reducing measures to be implemented by the relevant authorities.

1.3 Scope

In order to achieve the objective of the thesis, a set of tasks have to be performed. These are identified as:

- Review background literature about cruise ship traffic and external conditions in Norway
- Review literature on relevant ship grounding models
- Develop an admissible model that represent the grounding accident scenario in a good way

- Identify potential risk-reducing measures
- Perform a risk analysis with the developed model and assess the proposed risk-reducing measures
- Provide recommendations based on the work done and results obtained in the thesis

1.4 Contribution

This thesis is a study of the grounding risk for cruise ships sailing in Northern Norway during winter. A risk analysis of the kind performed in this thesis for the specific ship type and location has not been realized previously. The Norwegian Government has released a press statement announcing that they will set up a committee to evaluate and discuss the contingency challenges linked to cruise ship traffic in Norway. This thesis is created to be of use for the committee, and set focus on a subject matter that, in the author's opinion, deserves more attention

1.5 Outline

The following describes the outline of the report

Chapter 1 Introduction. Including motivation, objective, scope, contribution, and outline.

Chapter 2 Literature review. Including cruise traffic tendencies, relevant incidents, weather conditions, circumstances specific to Northern Norway, legislation, theory on risk assessment, review of relevant models, theory about Bayesian Belief Networks, and theory about the Delphi method.

Chapter 3 Method. Description of the approach and how the work was performed.

Chapter 4 Results. The results obtained from the developed model with comparison to other models.

Chapter 5 Discussion. Discussion of the work performed, the underlying assumptions, and the developed model.

Chapter 6 Conclusion. Conclusion of the thesis and recommendations for further work.

Chapter 2

Literature Review

2.1 Norwegian Cruise Ship Traffic

With the world's second-longest coastline and exotic nature and wildlife, Norway is a great destination for cruise ships. During the last 20 years, cruise ship tourism has increased rapidly in Norway (Dybedal, 2018). The number of tourists has increased from 200 000 in 2000 to 800 000 in 2018, while the number of calls has increased from 1200 to 2150 in the same period. The tendency seems to be that the ships have been getting bigger with higher passenger capacity.

2.1.1 Port Statistics

The area with the biggest change in the number of calls 2008-2018 is the western part of Norway. But also Trøndelag, Northern Norway, and Svalbard have had an increase in port calls (Dybedal, 2018). The western part of Norway dominates the number of calls, with Northern Norway as the second biggest contributor, with 67.6% and 17.9% in 2018, respectively.

Dybedal's report makes a prognosis for cruise calls to Norway for the period 2022-2060 based on three different estimates. All of these estimates predict an increase in the total number of cruise calls to Norway. The region with the highest prognosis is Western Norway. Svalbard and Northern Norway will see a slight increase in the number of calls, but the total share of cruise calls to these regions will decrease.

2.2 Grounding

A grounding of a ship can cause serious damage and have huge consequences for the ship and the people on board. The damages and consequences of a grounding depend on several factors. The sea bottom, the weather and sea state, the location, the crew skills, and the ship size are all examples of influencing factors. Some factors have an impact on the events leading up to a grounding, some influence the consequences after a grounding, and some influence both before and after the grounding occurs.

2.2.1 Relevant Incidents

2.2.1.1 Costa Concordia

On January 13, 2012, the cruise ship Costa Concordia grounded outside Isola del Giglio (Tikkanen, 2019). At the time of the accident, the ship had 3206 passengers and 1023 crew members on board. The ship deviated from its original route, and when the collision course was detected, language issues on the bridge caused the ship to steer in the wrong direction. The 13 seconds it took to correct the maneuver was too long, and the ship collided with the reef resulting in a 53 meters long tear.

The accident resulted in 32 deaths and a total loss of the vessel. In the aftermath, five crew members were convicted on various charges, including manslaughter. The captain received the strictest penalty with more than 16 years in prison.

2.2.1.2 Viking Sky

On Saturday 23 March 2019 a mayday signal regarding engine stop was sent out from the cruise ship Viking Sky (Accident Investigation Board Norway [AIBN], 2019). The ship was located outside Hustadvika, Norway, with 1373 people on board. Heavy weather with big waves and wind speed up towards strong gale was recorded. Within 15 minutes, the ship had lost power from all four diesel generators and drifted towards shore. The ship dropped both anchors, but they did not hold the ship. The crew managed to restore power from two generators providing sufficient propulsion power to maintain a steady speed ahead. The evacuation was carried out by helicopters during the day and the following night. 470 people were evacuated by helicopter. The following day, the ship was towed to Molde. In the interim report from AIBN (AIBN, 2019), a low level of lubrication oil caused to the stopping of the diesel generators.

The accident resulted in no casualties and no severe consequences for the ship. But the potential of this incident leading to a major accident was present. What if the crew had not managed to restore power in such a short time? A grounding would be imminent. The low evacuation rate is also something to be considered. Because of the weather, the crew found it too dangerous to evacuate by lifeboats, and only helicopters were used.

This incident is of significant interest for this report, as the work will investigate the grounding scenario for a cruise ship along the Norwegian coastline.

2.3 Weather

The weather along the Norwegian coastline can be challenging for ships sailing there. Both regular shipping traffic and cruise ships have to be prepared for, and able to handle bad weather when sailing. The mean frequency of winds above 11 m/s is around 20-25%, and for winds stronger than 21 m/s around 1.5-2.5% for exposed locations along the Norwegian shore (Dannevig & Harstveit, 2019).

During winter in Northern Norway and the Arctic areas, the sea and air temperature are low. Snow and ice may cause challenges for visibility, and the weather can change fast. During the winter of 2019, Bodø port had a total of eight cruise ship call cancellations as a result of bad weather. The ships did not risk maneuvering in the narrow port during the strong winds, so the call was canceled.

2.3.1 Polar Low

An important weather phenomenon in Arctic waters is the polar low. A polar low is a small, intense low created in Arctic air north of the polar front during winter (Noer, 2018). Polar lows occur where cold air meets the relatively warm sea. The Gulf stream and the proximity to the Arctic Ocean make the Norwegian sea a favorable area for polar low formation.

During a normal year, 5-20 polar lows will hit the Norwegian coast. The wind force can increase from breeze to storm in a matter of minutes. The rapid increase in wind speed combined with heavy snowfall and generally bad visibility may pose an increased risk for ships exposed to this phenomenon.

Historically, the forecasting of polar lows has been difficult. In recent years, the forecasting has improved, and today, most polar lows are picked up 12-24 hours before they occur. Beyond 24 hours, the prognoses become more uncertain. However, the large-scale conditions that give favorable conditions for polar lows can be predicted more than a week in advance. Given favorable conditions, a polar low is not certain, but heavy snowfall and changing weather conditions can be assumed with good certainty.

A chart of the average occurrence of polar lows per day per month in the years 2000-2017 can be seen in Figure 2.1 (Noer, 2018). The figure shows quite clearly how the phenomenon mainly occurs between October and April, with a few exceptions. Only polar lows recorded in the Norwegian Sea and the Barents sea are included in the figure.

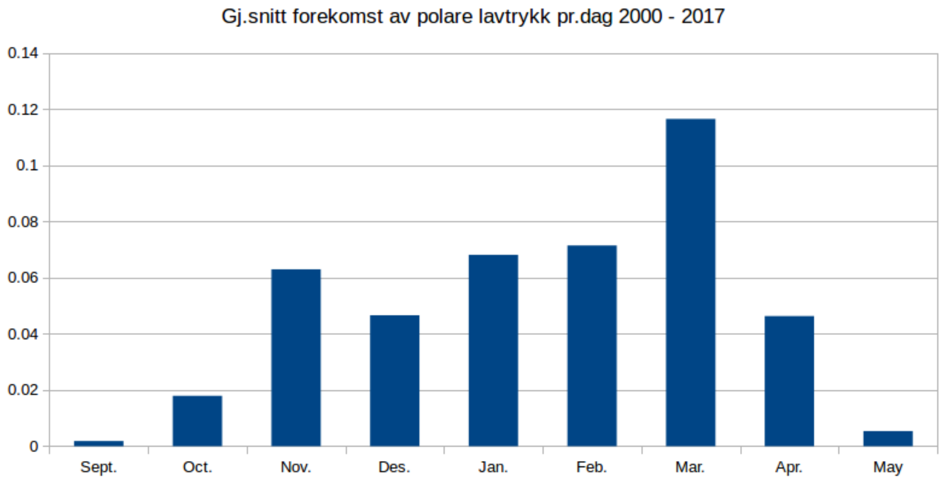


Figure 2.1: Statistics on polar lows in the Norwegian sea and the Barents sea. Average occurrence per day, 2000-2017.Reprinted from *polart lavtrykk* by G. Noer, 2018, Store norske leksikon. Retrieved from https://snl.no/polart_lavtrykk. Copyright 2018 by Gunnar Noer.

2.4 Northern Norway

2.4.1 Vessel Traffic Services

Vessel Traffic Services (VTS) is an international service for the improvement of safety at sea. The service is managed by the Norwegian Coastal Administration (NCA) in Norway. There are five maritime traffic control centers in Norway, only one north of Bergen, see Figure 2.2. The control center in Vardø, NOR VTS, is responsible for vessel control within the Norwegian extended economic zone, outside the baseline (Norwegian Coastal Administration [NCA], 2011c). The primary role of the VTS is to discover irregularities in the ship traffic within its designated zone. The goal of this service is to avoid accidents through better communication and detection of hazardous situations.

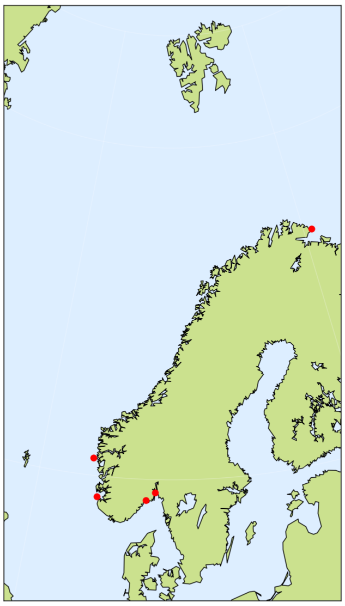
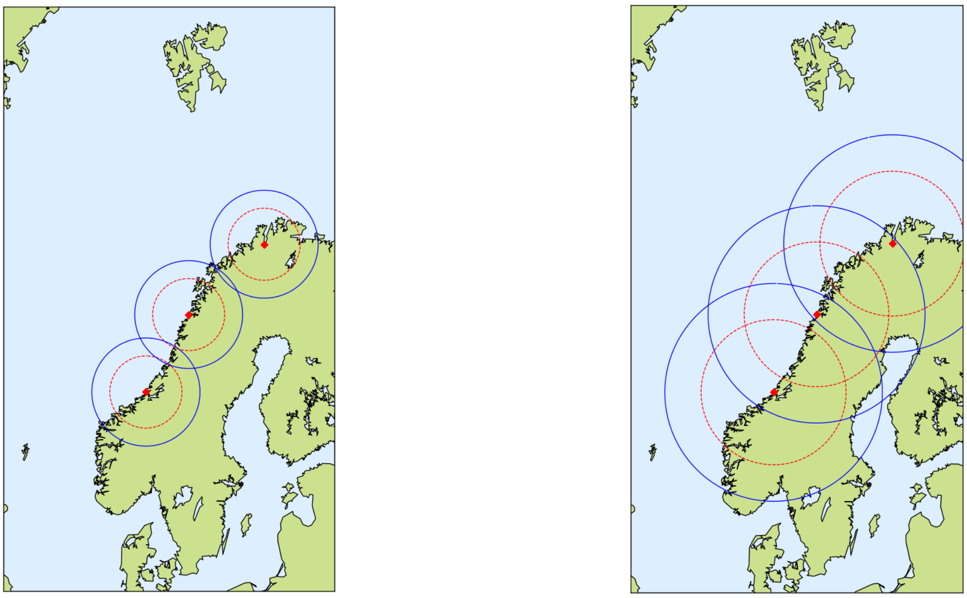


Figure 2.2: The location of the five VTS centres in Norway



(a) The reachable area for the rescue helicopters within one hour. The outer circle is for the new AW101 helicopters (150 nm), while the dashed, inner circle is for the existing Sea-King helicopters (100 nm).

(b) The reachable area for the rescue helicopters within two hours. The outer circle is for the new AW101 helicopters (300 nm), while the dashed, inner circle is for the existing Sea-King helicopters (200nm).

Figure 2.3: Maps showing the reachable area for each of the three northernmost mainland rescue helicopter bases.

2.4.2 Rescue Helicopter Services

There are six rescue helicopter bases on the Norwegian mainland (Luftambulansetjenesten, n.d.). The helicopters are serviced by the Norwegian Air Force 330 Squadron. The average cruising speed of the Sea-King rescue helicopters is 100 knots (Norwegian Armed Forces, 2014). With this speed, it would take around two hours for a rescue helicopter to reach an accident 200 nm away. In Figure 2.3, the 200 nm (two hours) and 100 nm (one hour) range for the three northernmost mainland rescue helicopter bases are drawn (red dotted lines).

The Sea-King helicopters are in the process of being replaced by a more modern helicopter: AgustaWestland AW101 (Dalløkken, 2019). This helicopter has a maximum speed of 150 knots, meaning that the readiness and reachable area will be improved. The difference in reach within one and two hours is illustrated with the blue circles in Figure 2.3a and Figure 2.3b.

The helicopter upgrade in action is a great improvement, and it is easy to see from Figure 2.3 that the readiness is well improved. There are two helicopters ready on each base implying that within the outer circles in Figure 2.3a and Figure 2.3b at least two helicopters are able to assist in emergency situations within one and two hours, respectively. From Figure 2.3a, it is clear that the helicopter upgrade is influential. The one hour coverage of the coast from Trondheim to the Russian border goes from roughly 67% to 100%.

2.4.3 Hospitals

In the case of a cruise ship grounding (or any other incident involving a great number of people) in Northern Norway, there would be a need for medical services. Including the hospital in Trondheim, there are only two hospitals with more than 400 hospital beds (Statistisk sentralbyrå [SSB], 2019). The situation with the hospitals and the long distances will not be subject to any analysis in this thesis but is included to give the reader a more holistic view of the examined case.

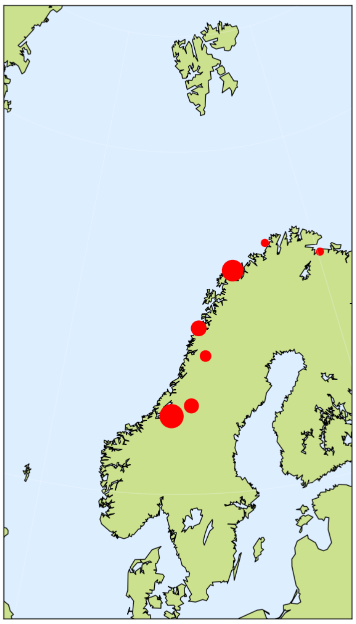


Figure 2.4: Hospitals in Mid- and Northern Norway. Bigger marker means a higher number of hospital beds. (Finnmarkssykehuset's capacity is split into two between the two main hospitals; Hammerfest and Kirkenes.)

2.5 Legislation

2.5.1 Compulsory Pilotage Regulations

According to the Compulsory Pilotage Regulations (NCA, 2011a), all passenger ships with a length above 50 meters are subject to compulsory pilotage within the baseline. The pilotage requirement can be met either by employing a pilot or by the use of a Pilotage Exemption Certificate (PEC). The NCA has the opportunity, in special cases, to make the use of a pilot compulsory for a specific sailing, also sailings outside the baseline (NCA, 2011a). Similarly, the NCA may grant dispensation from the use of a pilot if certain requirements are met.

2.5.2 SOLAS

The International Convention for the Safety of Life at Sea (SOLAS) from the International Maritime Organization (IMO) is a convention to ensure safety at sea, (International Maritime Organization [IMO], 2019). SOLAS's main objective is to establish the minimum standards for construction, equipment, and operation of ships. It is up to the flag state of each ship to make sure that the convention is adhered to.

Safe Return to Port

A package of SOLAS amendments adopted in 2006 entered into force in 2010. The amendments affect all passenger ships being built after July 2010 (IMO, n.d.-b). The amendments enhanced attention on reducing accident probability and increasing the survivability of the ships. The *safe return to port* philosophy and the idea that the ship is *its own best lifeboat* were the background for the amendments.

2.5.2.1 Ch. III - Life-Saving Appliances and Arrangements

Chapter III of the SOLAS convention specifies requirements for life-saving appliances and arrangements, here-under, lifeboats, rescue boats, and life jackets. These requirements are dependent on the type of ship. The requirements from this chapter are critical for the survivability of passengers on a damaged ship.

According to IMO, 2019, the requirement for survival crafts on a passenger ship is to have a total capacity of 125%. This requirement applies to both lifeboats and life rafts. The requirement is for lifeboats on each side with a capacity of 50% of the total number of persons on board, and life rafts with a capacity of 25%, summing up to a total of 125%. The government of the state to which the ship is flagged may permit ships to replace some lifeboats with life rafts with the same capacity, as long as the capacity of lifeboats on each side is no less than 37.5% of the total number of persons on board.

2.5.2.2 International Code for Ships Operating in Polar Waters (the Polar Code)

Ships operating in the unfavorable waters surrounding the two poles have to comply with the Polar Code (IMO, 2017). The code entered into force in January 2017 and was introduced to protect the polar environment and improve the safety of crew and passengers on ships operating in the polar waters. Standards for design, construction, equipment, etc. are specified by the Polar Code, making the ships more suited to overcome challenges that follow operations in polar waters.

Figure 2.5 indicates the maximum extent of Arctic waters. From the figure, it can be seen that the Norwegian mainland is located outside of Arctic waters. Thus, ships sailing along the Norwegian shore, are not required to adhere to the Polar Code unless their voyage takes them into Arctic waters.

Figure 2.5: Maximum extent of Arctic waters. Adapted from *International Code for Ships Operating in Polar Waters* (p. 9) by IMO, 2017. Retrieved from http://www.imo.org/en/MediaCentre/HotTopics/polar/Documents/POLAR%20CODE%20TEXT%20AS%20ADOPTED.pdf. Copyright 2019 by IMO

2.5.3 International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW)

The STCW convention establishes international standards for training, certification, and watchkeeping for seafarers. The goal of the convention is "*...to promote safety of life and property at sea and the protection of the marine environment*" (IMO, n.d.-a). Requirements on hours of work and rest, requirements on training in modern technology, ECDIS, etc., and requirements for leadership and teamwork are some of the topics covered by the convention. It is the responsibility of each member government who is a part of the STCW convention to follow up on the training of seafarers. The Convention requires that training and assessment of seafarers are administered, supervised, and monitored in accordance with the provisions of the code (IMO, n.d.-a).

2.5.4 Act Relating the Harbors and Fairways (2020)

On the 1st of January 2020, a new act relating the harbors and fairways took effect in Norway. The act gives the municipalities a legal basis to regulate the use of the municipality's waters concerning safe traffic. The former regulations regarding measures towards accidents and other events are continued in the new act.

2.5.5 Government Press Releases

2.5.5.1 October 3rd 2019

In a press release from the Norwegian government released on the 3rd of October 2019, the government notified that they will map out the challenges of the cruise tourism around Svalbard (Ministry of Justice & Public Security, 2019). The ministry will look at the challenges tied to safety and readiness and consider if there is a need for further preventive measures. One measure can be regulation of the cruise traffic.

The geographical location, vast distances, and inhospitable weather conditions pose a challenge for the safety and readiness of the region. Even though the readiness and the rescue service on Svalbard has improved, there are limits to what the rescue service can accomplish. The existing emergency preparedness on Svalbard is not designed to handle large and/or simultaneous occurring events over time. Preventive measures might be the most efficient approach to reduce the risk of accidents. Regulation of the cruise traffic can, therefore, be an important measure to maintain the safety of the area (Ministry of Justice & Public Security, 2019).

Even though the government's press release only discusses the challenges on Svalbard, the same arguments can, to some extent, be applied to the northern part of Norway. After the Viking Sky incident (subsubsection 2.2.1.2), experienced professors from the Department of Marine Technology at NTNU wrote a posting in the Norwegian newspaper Dagens Næringsliv (Utne & Vinnem, 2019). The authors posed the question: *"... but what could the consequences have been if this had happened in Finnmark or Svalbard?"*

The professors conclude that a grounding of Viking Sky would have lead to multiple fatalities of the people on board, as a result of the extreme weather, the ship's movements, severe listing, and the low evacuation rate (Utne & Vinnem, 2019).

2.5.5.2 December 14th 2019

On Saturday 14th of December 2019, a new press release from the Norwegian government regarding the challenges with emergency preparedness for the cruise traffic was released. The government has decided that a committee will be set up to map and describe the extent of today's cruise traffic and discuss the contingency challenges related to this traffic.

The Viking Sky incident illustrated the risk involved with big passenger ships sailing in Norwegian waters and is one of the reasons for the press release from the Norwegian government. The potential consequences of these accidents demonstrate why it is important to do a thorough risk analysis of the cruise traffic in Norwegian waters.

2.5.6 Government Committee

The committee announced by the Norwegian government has yet to be pointed out. It is believed that this delay is caused by several political factors in Norway in 2020, with one party leaving the government and the virus pandemic as the most important ones. Upon writing this thesis, no news has come regarding the committee. It is, however, believed that the committee will be appointed and that this thesis can be of use for the committee.

2.6 Risk Assessment

In everything humans take part in, there is some level of risk involved. According to the international standard ISO 31000 Risk Management - Guidelines, risk is defined as *the effect of uncertainty on objectives* (International Organization for Standardization [ISO], 2018). An effect is defined as a deviation from the expected and can be both positive and negative. It is common to include some more details when evaluating risks. Risk sources, potential events, their consequences, and their likelihood are common terms used to express risk.

There are different types of risk with different levels of severity. Financial risk and societal risk are two important risk types. The first one involves a risk of losing or, in the definition from ISO 31000, gaining money, while the other involves a risk of losing lives. There is no way of gaining life, so the definition from ISO 31000 can only be used with negative consequences when it comes to human life. It can be argued that human life is of the most precious entities, and that losing human lives involve the greatest level of severity.

Risk analyses and assessments are widely used in many different fields. The key aspects of a risk assessment are to identify potential hazards and evaluate their consequences. The knowledge from this analysis is used to make decisions to make sure the obtained level of risk can be tolerated. It is important in this work to consider all the factors that are influencing the risk to make well-informed decisions.

When analyzing risk, it is crucial to consider the uncertainty of likelihoods and consequences. This uncertainty must be accounted for for both estimation uncertainty and model uncertainty in the risk analysis.

2.6.1 IMO Formal Safety Assessment

Modeling of risk in the maritime sector (offshore and marine) is widely used. In the offshore industry, the safety case is often used, required in the UK, while the Formal Safety Assessment (FSA) introduced by IMO is used in the marine industry. The FSA methodology consists of five steps:

1. Identification of Hazards	What might go wrong?
2. Risk Analysis	How bad and how frequent/likely?
3. Risk Control Options	Can circumstances be improved?
4. Cost-Benefit Assessment	What would it cost and how much will it improve?
5. Recommendations for Decision-Making	What actions should be taken?

This thesis report will mainly focus on steps 2 and 3 in the FSA methodology. IMO has performed numerous FSA's, and several of them are of interest to this report. Especially "MSC 85/INF.2. FSA – Cruise ships. Details of the Formal Safety Assessment" (IMO, 2008) is relevant for this thesis.

2.7 Bayesian Belief Network

A Bayesian belief network (BBN) is a model consisting of nodes and arcs which illustrates causal relationships between causes and outcomes in a system (Rausand, 2011). The nodes in the network represent states or conditions, while the arcs represent direct influences.

2.7.1 Introduction

In decision-making processes, uncertainty plays an important role. In most cases, there will be some level of uncertainty tied to possible events or outcomes. When modeling uncertain events, there are often some incidents that are dependant on each other, and the outcome of one incident might influence other outcomes. In a model for prediction of uncertain events, it is useful that the model can show dependencies and present the correlation between influencing events.

The most used method for dealing with uncertainty is probability theory and probabilistic networks are a recommended method for handling parental dependencies in analyses subject to uncertainty. Probabilistic networks can be used both quantitatively and qualitatively. BBNs is a developed method for probabilistic networks. A BBN is an acyclic directed graph presenting a set of variables and their conditional dependencies (Kjærulff & Madsen, 2008). BBN's are well suited for representing the probabilistic dependencies between causal or influencing nodes, and the state of the outcome node. The following sections will describe the BBN method further.

2.7.2 Bayes Theorem

BBN is named after the man who formulated what is now known as Bayes theorem, Thomas Bayes. The theorem, which is the basis for calculation in BBN's, is shown in Equation 2.1.

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{2.1}$$

Where,

$P(A)$ = Probability of A occurring
$P(B)$ = Probability of B occurring
$P(A|B)$ = Probability of A occurring given that B is true
$P(B|A)$ = Probability of B occurring given that A is true

2.7.3 Method

A BBN is a network consisting of nodes, representing events, and arcs, connecting the events and showing their dependencies. The graph presents the qualitative side of the model, while the quantitative calculations are handled by the probabilistic properties of the network. The acyclic feature of the network means that a cycle within the network is not allowed.

The nodes in a network do not have a limited number of possible states. However, the model complexity increases significantly with an increasing number of states. The same applies to the number of arcs(dependencies) between the nodes. A simple example of a BBN is shown in Figure 2.6. In this example node A influence both node B and C, while node B only influence node C.

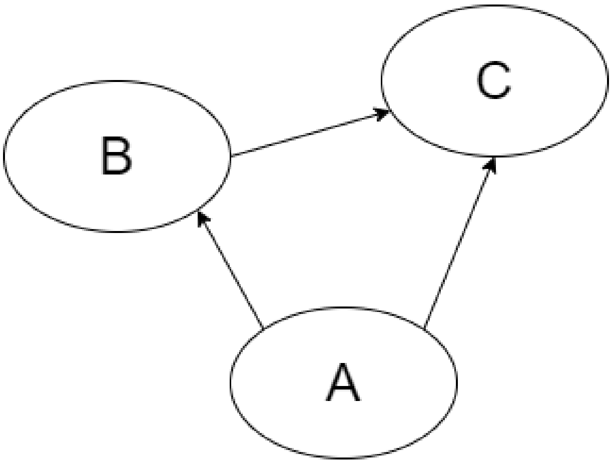


Figure 2.6: Example of a simple BBN

2.8 Literature on Risk Modeling of Grounding Accidents

The grounding of a passenger ship can have critical consequences for the society, the environment, and the ship. The risk of ship groundings has been explored with a variety of different approaches by many scholars.

In the article *Modeling the risk of ship grounding - A literature review from a risk management perspective*, (Mazaheri, Montewka, & Kujala, 2013), the authors review and discuss the available existing risk models for ship grounding (in 2013). They also highlight the models that are suited for risk management and decision-making and give recommendations to further development of the models (Mazaheri et al., 2013). The model that is of most interest for this thesis is the BBN model from DNV, 2003. This model receives a relatively high rating on the decision-making potential with M/H (Mazaheri et al., 2013). Another model found relevant (not in Mazaheri et al., 2013) is the one from Hänninen et al., 2014. This is a BBN model developed for tankers in the Gulf of Finland.

A couple of years after the literature review of ship grounding models, the same authors published the article *Towards an evidence-based probabilistic risk model for ship-grounding accidents*, where they introduce a new BBN model for ship grounding accidents (Mazaheri, Montewka, & Kujala, 2016). This model is significantly smaller with regard to the number of nodes and edges included than DNV, 2003 and Hänninen et al., 2014. However, the results obtained from the model are similar to the other models. This model by Mazaheri et al. is evidence-based, where most other models identified in Mazaheri et al., 2013 are based on expert opinion.

The models already existing in literature are either very general or very specific, e.g. to a location. Another feature of the existing models is their size in the number of nodes. The model by Mazaheri et al., 2016 only has 33 nodes, whereas DNV, 2003, and Hänninen et al., 2014 has 69 and 75 nodes, respectively. It is also important to note that DNV's model extends to the consequences of the grounding, and does not have grounding as the final event. This would naturally lead to a higher number of nodes. On the other hand, only 17 of the nodes are tied to the consequences part of the model. Because of these differences, it is decided to develop a new model specific for grounding of cruise ships in Northern Norway during winter. The model will be based on the already existing models.

Of the three relevant models identified in this section, the model from DNV, 2003 is deemed most relevant as it is made for large passenger vessels.

2.9 Risk Tolerability Criteria

One of the goals of a risk analysis is to find out if the achieved risk is within a tolerable risk level. To be able to assess the risk level, it is necessary to have a defined level of risk that is tolerable. In this thesis, the ALARP principle together with the risk measures individual risk and group risk will be used for evaluation of the risk level.

Individual Risk

Individual risk is the risk that an individual person is exposed to during a specific time period (Rausand, 2011). The individual risk is commonly represented for a person who is in relation to the analyzed hazard. In this report, the individual risk of a passenger on a cruise ship is used as a benchmark.

Group Risk

Group risk is the risk experienced by a group of people. (...) The group risk is a combination of individual risk levels and the number of people at risk, that is, the population being exposed (Rausand, 2011). The group risk is found and illustrated in this thesis by the use of f-N curves. An f-N curve illustrates the different consequences along with their frequencies. It is common to plot the curve with cumulative frequencies and logarithmic scales. In this report, the consequences are the number of expected fatalities.

2.9.1 ALARP - As Low As Reasonably Practicable

The ALARP principle was introduced in the UK in 1992 for nuclear stations, and was later, in 2001, adapted for general applications (Rausand, 2011). There are two main components that make up the principle:

- The principle provides a framework for analyzing risks
- It is a method to determine if the cost of a risk-reducing measure is disproportionate to the benefits of introducing the measure

The principle splits the risk scale into three regions; the intolerable region, the ALARP region, and the broadly tolerable region. The regions are differentiated by two limits. The upper limit separates the intolerable region and the ALARP region. The lower limit separates the ALARP region and the broadly tolerable region. The regions and limits are illustrated in Figure 2.7.

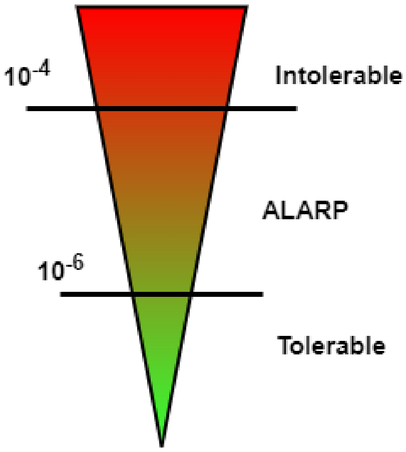


Figure 2.7: Illustration of the ALARP principle with regions and limits for the individual risk

The intolerable region represents a level of risk which under no circumstances is accepted. If the risk is found to be within the intolerable region, measures should be taken to ensure that the risk is lowered to a tolerable level. If the risk level is found to be within the ALARP region, measures should be taken to reduce the risk if the cost of such measures is not grossly disproportionate to the benefit of introducing the measures. The tolerable region represents a risk level where measures to reduce the risk are not required to achieve a tolerable risk level.

2.9.1.1 ALARP Limits

In *Revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process* (IMO, 2018), IMO suggests the following individual risk ALARP limits for passengers:

- **Upper limit:** 1E-04
- **Lower limit:** 1E-06

The numbers represent fatality risk per year.

For the group risk, the document *"MSC 85/INF.2. FSA – Cruise ships. Details of the Formal Safety Assessment"* (IMO, 2008), is used to find the risk tolerability criteria for the f-N curves. This report is found very relevant for the case examined in this thesis.

2.10 Risk-Reducing Measures

Most systems involve some kind of risk towards its environments. Consequently, the systems imposing a risk are often equipped with safety barriers in order to reduce the risk. A safety barrier can be defined as "*physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents.*" (Sklet, 2006).

Safety barriers can be classified into *proactive* and *reactive* barriers. A *proactive*, or preventive, barrier is a barrier installed to prevent or reduce the frequency of a hazardous event. A *reactive*, or mitigating, barrier is a barrier installed to reduce the consequences of a hazardous event after it has occurred.

Safety barriers can be further classified into *active* and *passive* barriers. An active barrier *is dependent on the actions of an operator, a control system, and/or some energy sources to perform its function* (Rausand, 2011). An example of an active barrier can be an alarm signaling that a ship is on collision course with the shore. A passive barrier *is integrated into the design of the workplace and does not require any human actions, energy sources, or information sources to perform its function* (Rausand, 2011). A passive barrier example can be the double bottom of a ship's hull. If the hull is breached, water will not flood into the whole ship because of the double bottom limiting the possible flooded area.

In this thesis, some risk-reducing measures, i.e. barriers, will be proposed and their effects analyzed. The measures will be of both active and passive types, as well as preventive and mitigating.

2.11 Delphi Method

In order to quantify the probabilities in the nodes that cannot be based on historic data, expert judgment is used. As more than one expert is used for quantification, a method to align the experts' opinions is needed. For this thesis, the Delphi method was used. The Delphi method was developed by the RAND organization in the 1950s to estimate the effect of technology on warfare (RAND, n.d.). With this method, a group of experts answers anonymously to a questionnaire. The answers are gathered, and a statistical representation is given as feedback to the experts. The procedure is repeated, and the goal is to arrive at something close to a consensus between the experts.

Chapter 3

Method

3.1 Assumptions

The model is developed based on some main assumptions listed below. There are made several other assumptions in this thesis work, but as they are more specific, they are not listed here.

- Only the winter season, defined as Oct-Apr, is examined
- The model is developed for cruise ships only
- The area examined is the Norwegian mainland coast from Trondheim to the Russian border (Kirkenes)
- One cruise voyage is assumed to be a round trip Trondheim-Kirkenes-Trondheim (roughly 1700nm)

3.1.1 GeNIe Software

To produce and analyze the BBN a software named GeNIe is used. The GeNIe modeler is a graphical editor for the creation of network models. Besides, the software is equipped with tools for sensitivity analyses. The software also includes a lot of features not relevant to this thesis. The main features to be used in this thesis are network creation and sensitivity analysis.

3.2 Influence Diagram

The first step towards the BBN was to construct an influence diagram. An influence diagram is very similar to a BBN. In this thesis, the influence diagram is a more detailed version of the case examined than the resulting BBN will be. The influence diagram is constructed based on relevant models, discussion with the supervisor, and the author's own opinions. The goals of the influence diagram in this work are to get a good comprehension of the matter at hand, a basis for the BBN to be developed, and a way of seeing how the different factors influence each other. The developed influence diagram is attached in Appendix A.

The influence diagram was the starting point for the creation of the BBN. The influence diagram was too large to be suited for quantification by a master thesis, and the diagram was pruned down to a reasonable size without losing too much detail. Further details of the BBN follows in section 3.4.

3.3 Delphi Process

Several people with a background in risk assessment, cruise ships, and other relevant backgrounds were invited to make up an expert panel. The invitations resulted in an expert panel of seven experts. The seven experts had an overweight from academia and risk assessments, and only a few had practical experience from ships. This composition of experts will be further discussed in Chapter 5.

The Delphi process began with sending out the model, with explanations of the model and underlying assumptions, together with a questionnaire to the experts. The experts were asked to answer the questionnaire based on their experiences and beliefs. The questionnaire had a total of 46 questions regarding 18 of the nodes in the BBN. After all the experts had given answers, the replies were gathered and ordered in a way to make them easily comparable. The answers were made anonymous (each expert knew their answers) and then sent out to all the experts.

During the first Delphi meeting, only four of the experts were present. However, all questions were discussed, and several important opinions and beliefs were communicated by the experts. There were quite some differences in the answers before the meeting, and the meeting helped to distinguish uncertainties and make the experts agree on a more common understanding of the nodes and their definitions. After the meeting, the experts received a summary of the numbers with comments from the meeting and were asked to reassess their initial answers based on the discussions from the meeting.

As only four experts were present at the first meeting, it was desirable to arrange a second meeting, hopefully including more of the seven experts. It became clear quite quickly that to arrange a meeting with all experts would be difficult to make happen in the time scheduled for the Delphi process. A decision was made to establish a second meeting, with the experts available. The expert with the most practical experience from the industry was considered as the most important expert to include in this second Delphi round. In the second round, three experts were present, two of them had been present in the first meeting, and the last one was the one with the most hands-on experience.

Before the second meeting, the same procedure as before the first meeting was followed. The experts were provided with the updated answers from all the experts, and the nodes were prioritized to make sure the ones deemed most important were guaranteed a discussion. After the first meeting, the model received some changes; how some nodes were connected and how they were defined were changed. These changes were regarded as improvements to the model and made some of the nodes initially up for expert judgment deterministic or otherwise excluding them from the quantification by experts.

The second Delphi meeting became shorter than the first one. One less expert, as well as fewer nodes up for discussion, are believed to have impacted that outcome. Because of this, it is presumed that all the nodes covered in the second meeting received an adequate amount of discussion. After the meeting, the three experts who had been present were once again asked to reconsider their answers and submit any new answers. All three experts, even the ones who had reviewed their answers once before, did change some of their answers. This outcome implies that a second Delphi meeting was necessary and that a meeting with all, or at least six out of seven, experts present would have been beneficial to further improve the level of consensus between the experts. This will be further discussed in Chapter 5.

3.4 The Model

The following part describes all the nodes in the model, and how their CPT's are quantified. All the CPT's can be found in Appendix D.

3.4.1 Nodes

The BBN model presented in this thesis has a total of 33 nodes, see Figure 4.1. The input to some nodes is decided by stakeholders, historical data, or other external circumstances, while others are quantified by the expert panel.

After the last Delphi meeting, the experts sent in their final revision of the numbers which became the basis for the quantification of the nodes. A method similar to the way ski jumpers are given score was used on the answers; the highest and lowest probability given on each question (excluding the ones with a very high level of consensus) were taken away and a mean value was extracted from the remaining answers.

3.4.1.1 Quantified by Expert Opinion

A number of the nodes in the model were quantified by the use of an expert panel and the Delphi method. Their definitions and states are provided in the following.

Communication, Cooperation, and Monitoring (CCM)

This node is defined as "Bridge management and workflow are/are not in accordance with requirements and expectations". The node is dependant on "Safety culture".
States: - Proper
- Poor
The performance of the bridge crew is important for the vessel, and good safety culture is believed to impact how well trained and familiar the crew is with each other and their tasks. The bridge management and workflow are significant for the situational awareness. The experts reached a very high level of consensus on the probability of "Proper" "CCM" given "Good" "Safety culture", and a medium level of consensus given "Poor" "Safety culture". The spread of answers was between 30% and 75%. After the highest and lowest probabilities were excluded the range became 30%-50%, and a mean value of the remaining answers was judged appropriate.

Unexpected Situational Change

When sailing, there is always a possibility of something unexpected happening, and this factor is included in the node "Unexpected situational change". The node is independent of the other nodes, and defined as "OOW does/does not experience an unexpected change of situation".
States: - Yes
- No
In the first Delphi round, the node was described as a sudden situational change, but was changed to unexpected situational change. This change was made to make it easier for the experts to align their perception of the node. Unexpected change of weather conditions, or a vessel on collision course were described as examples of such a change. The experts generally agreed on the probabilities, with one expert as an outlier, 50%, and the rest within the range 5%-20%. The ski jumping score method and mean value was used to determine the final probabilities.

Situational Awareness

The situational awareness of the bridge crew, and ultimately, the OOW, is important to detect an emerging hazardous situation and act accordingly. The node is defined: "OOW has satisfactory/unsatisfactory situational awareness in accordance with requirements and expectations".
States: - Satisfactory
- Unsatisfactory

The phrase "... in accordance with requirements and expectations" is a vague definition, and was commented on by some experts during the Delphi meetings. However, it is believed that after a short discussion, the experts were of the same understanding, which also is reflected in the low variance in the answers. The node is dependant on three other nodes and has a CPT of 8x2 cells. The probabilities of "Satisfactory" "Situational awareness" given best and worst conditions were found by the ski jumping score method. The rest of the table was interpolated between these values, and it was assumed that the "CCM" node is the most influential node.

Detection of Grounding Course

This node is defined as "Vessel on grounding course detected/not detected at least 15 minutes before potential grounding".

States: - Yes
- No

For the best conditions, the experts were very much aligned in their responses. For the worst conditions, their answers were more wide-spread. Yet, when removing the highest and lowest prediction, the spread is reduced from 65% to 25%, and once again, the mean value of the remaining answers is used in the model.

This node has a CPT of 8x2 cells, and interpolation between the outer points is performed. The dependence from the "Situational awareness" node is the one assumed to have the greatest impact on this node.

Safety Culture

The "Safety culture" node is defined as "The safety culture of the crew is in accordance/not in accordance with requirements and expectations".

States: - Good
- Poor

On this node, the opinions from the experts aligned quite well. However, a span of 35% was considered too high, and a mean value was found from the middle five estimates. The probability of "Good" "Safety culture" found is 86%. When comparing this number to the model from Mazaheri et al., 2016, it is approximately twice as high. This difference is, however, believed to be caused by the fact that Mazaheri et al.'s model is general for all ship types, while the model in this thesis is for cruise ships only. Cruise ships, in general, are assumed to have better safety culture than, e.g., container or bulk ships.

Navigational Error

Defined as "Navigator is/is not making a navigational error". The node is dependant on three other nodes; "Signal quality", "Situational awareness", and "Waterway complexity".

States: - Yes
- No

As mentioned earlier, the compulsory pilotage regulations are present, and it is assumed that there is a pilot on board. One of the experts argued that the waterway complexity might influence in a negative and positive direction. When sailing in a complex waterway, the OOW might be more vigilant, causing a lower chance of a navigational error. The effect of a navigational error is also important. When sailing on the open sea, there is a higher tolerance for being slightly off course without any mentionable consequences, than when sailing narrow passages. This effect is not specifically included in this node, but modeled by the "Successful recovery" and "Distance to shore" nodes.

The experts generally agreed on the probability of a navigational error under the best conditions, but were a bit more out of sync for the worst conditions. After the highest and lowest probabilities were excluded, the difference between the highest and lowest was reduced from 60% to 30%, and a mean value was found from the remaining probabilities. The rest of the 8x2 CPT was filled out with interpolation. It was assumed that "Complex" "Waterway complexity" increased the probability of a navigational error, but not very much, and the "Situational awareness" node was weighted the most in the interpolation.

Waterway Complexity

Definition: "The waterway makes sailing route complex/simple". Dependant on "Visibility" and "Weather conditions".
States: - Complex
- Simple
In the first model presented to the experts, this node was a combination of waterway and traffic complexity. After some discussion, it was decided to change the node to only cover the waterway complexity. The traffic complexity is believed to not be very dependant on weather and visibility, and since only one season is examined, seasonal differences are not contributing.

The geography of the Norwegian coastline is permanent. During discussions about this node in the meetings, it became clear that the "Weather conditions" and "Visibility" nodes are important factors. The answers for best and worst conditions were quite similar, with one outlier on each (from different experts). The highest and lowest estimates were excluded, and mean values were found. The two remaining columns in the CPT were filled out, with "Visibility" assumed to be the most influential factor for "Waterway complexity".

Technical Failure

Definition: "The ship is/is not experiencing some kind of critical technical failure (loss of propulsion, loss of steering, etc.) that lasts longer than 10 minutes". The node is dependant on "Technical redundancy" and "Maintenance routine".
Note: The node was originally dependant on "Technical redundancy" and "Technical condition", more information below.
States: - Yes
- No
In the first Delphi meeting, several of the experts had given quite high probabilities on this node, 40% probability of a critical technical failure given "Poor" "Technical condition" and "Standard" "Technical redundancy". One of the experts argued that all the answers, even the ones the expert had given themselves, were too high. This opinion was based on how rarely such technical failures are heard of and written about. After this opinion was voiced, the experts agreed that the numbers were high, and changed them.

To fill in the CPT, it was decided to use the lowest numbers, which coincided with the numbers given by the expert expressing the important factor that made all the other experts present change their answers. The experts gave answers for three of the four columns in the table, and the last was assumed based on the relations between the other three, with "Maintenance routine" as the most influential node.

It is important to mention that the answers from the experts were given at a point where the node was dependant on "Technical redundancy" and "Technical condition". The "Technical condition" node was later deemed unnecessary, as it was only another link on the line between "Maintenance routine" and "Technical failure", without any other parents or children nodes. This change is believed to not affect the answers given by the experts significantly.

Loss of Control

The node has three states, with definitions given below. "Technical failure" is the only influencing node.

States:
- No - crew has full control of the ship
- Partial - crew has lost full/partial control of the ship up to 15 minutes
- Total - crew has no control of ship movement

For the scenario where there is a technical failure, the answers from the experts were used for quantification. Once again, when removing the highest and lowest estimates, the remaining answers have low variance, and the mean values are found and used in the CPT. For the case with "No" "Technical failure", it is assumed that "No" "Loss of control" will occur.

Successful Recovery

The "Successful recovery" node is defined as: "Action initiated by OOW to avoid grounding is/is not successful", and is dependant on the "Detection of grounding course", "Loss of control", "Escort ship", and "Distance to shore" nodes.

States:
- Yes
- No

Based on the parental node states, it is assumed that in the case where the grounding course is not detected by the crew on the bridge, successful recovery is impossible. The same applies to the case of "Total" "Loss of control", except when there is an escort ship present. In the situation with an escort ship, it is assumed that the escort ship may assist the cruise ship in order to avoid grounding.

The node was further described to the experts as "What is the probability that a successful recovery is performed before a potential grounding occurs?" There is no specific time limit to which the recovery must happen, as there are so many different possible scenarios. In some cases, recovery can be performed within an hour and still be successful, while other situations require a much faster recovery to avoid grounding.

The experts were pretty much aligned on the three different conditions they were asked about. A few answers were a bit deviant, and the same approach as before was used, taking out the highest and lowest and finding the mean value. The network has been changed after the last Delphi meeting, and the experts were asked about the node before the "Escort ship" node was directed to "Successful recovery". In the case without an escort ship, the answers from the experts are used directly, and the remaining columns are filled in using scaling and interpolation. The scaling is performed by using the ratio between short and long for the cases quantified by the experts and utilizing that ratio on the column corresponding. The value in between is interpolated directly.

The presence of an escort ship is assumed to improve the probability of successful recovery in all cases. The improvement is assumed to be higher for the case of "Partial" "Loss of control" than "No" "Loss of control". As mentioned above, the escort ship is assumed to improve the probability of successful recovery given "Total" "Loss of control" of the cruise ship. How much this improvement is, is hard to quantify, but is assumed to help with a maximum of 50% in the case with "Long" "Distance to shore". This effect should be quantified better and is proposed as further work.

Lifeboat Availability

The "Lifeboat availability" node is dependant on the nodes "Heel angle" and "Weather conditions". It has three states, defined below.

States:
- Full - all lifeboats available for use
- Partial - only some lifeboats are available (e.g. one side)
- None - no lifeboats are available (e.g. too high heel angle, decision by master)

In the case where the ship develops a heel angle above 20°, it is assumed that all lifeboats are unavailable. Bad weather is another factor, and as seen from the Viking Sky incident, the master found the risk of using the lifeboats higher than not to use them. The big waves and ship movement would have made it difficult to use the lifeboats in a safe manner.

The same approach as before was used on the numbers, excluding the highest and lowest probabilities and finding the mean. For the scenario with "Good" "Weather conditions" and "Heel angle" below 20°, it is assumed that the probability of "Lifeboat availability" being "None" is zero. This is in line with the answers from the experts. For the "Bad" "Weather conditions", the experts were more divided. This spread in answers is believed to be caused by the way the questions were posed. For the "Good" "Weather conditions", it was asked for the probabilities of "Full" and "Partial" "Lifeboat availability", while for the "Bad" "Weather conditions" the "Full" and "None" lifeboat availabilities were asked for. Some answers were even illegitimate as they would cause the sum of probabilities to be more than 1. Specifically the probability of "None" "Lifeboat availability" given "Bad" "Weather conditions" had a big spread, from 10% to 90%. In spite of these issues, the values used in the CPT are found in the same way as for most of the other nodes. This node is, therefore, suggested to be further worked with.

Immersion Survivability

This node describes how many of the people ending up in the water during a grounding incident that will survive. The node is dependant on the nodes "Weather conditions", "Distance to shore", and "Immersion suits available".

States: - Good - more than 50% of the people in the water survive
- Bad - less than 50% of the people in the water survive

During the discussion about the survivability of people in the water, some experts argued that wind and waves cause drowning even when people are equipped with immersion suits and/or life vests. The cold and inhospitable waters of Northern Norway during winter was also mentioned as an influential factor.

For the best conditions, the experts were split in two, one group estimating high (80-90%) probability of "Good" "Immersion survivability" and the other estimating medium (50%) probability. Even though the experts were divided in their opinions, the difference between them is not considered too high, and the ski jumping score method is once again used. For the worst conditions scenario, all experts agreed that the probability of more than half of the people ending up in the sea, surviving is low. The rest of the CPT was filled out with interpolation based on the outer points and estimations of the most important factors. The "Weather conditions" node is assumed to be most important, and the difference between "Medium" and "Long" "Distance to shore" is assumed not to affect the survivability. For the "Short" "Distance to shore" it is believed that some, very few, passengers might be able to swim to land, and that help will arrive faster.

Emergency Training

The "Emergency training" node is dependant only on "Safety culture". It is defined as "Emergency training of the crew is in accordance/not in accordance with requirements and expectations"

States: - Proper
- Poor

There are minimum requirements for emergency training of the crew set by the STCW convention (IMO, n.d.-a). It is, therefore, assumed that all ships fulfill the minimum requirements. The question or definition should maybe have been phrased differently. A better phrasing of the definition could have been "Emergency training is better than/equal to the minimum requirements". This issue was raised in a Delphi meeting, but not all experts were present at that meeting. Despite this concern, there was a high level of consensus from the experts on both the best and worst state. The resulting CPT is produced the same way as most of the other nodes, i.e. with the ski jumping score method.

Evacuation Rate

The "Evacuation rate" node represents how well the people on board the ship are evacuated. The node is dependant on five other nodes; "Lifeboat availability", "Nearby ship(s)", "Helicopter evacuation possible", "Emergency training" and "Passenger state of health".

States: - Satisfactory (all passengers within 60 minutes)
- Limited (roughly 50% evacuated within 60 minutes)
- None

In *Guidelines for evacuation analysis for new and existing passenger ships*, (IMO, 2007), the requirement for total evacuation time for passenger ships should be less than or equal to 60 minutes if the ship has three vertical zones, and 80 minutes if the ship has more than three vertical zones. The state definitions in this node are based on these requirements.

The experts were given questions that would fill out the best and worst conditions for this node. In the model they received, the nodes "Nearby ship(s)" and "Helicopter evacuation possible" were connected to a node called "Alternative means of evacuation", which again connected to the "Evacuation rate" node. After some further work with the model, it was decided to take away the "Alternative means of evacuation" node, as evacuation by a nearby ship and a helicopter are very different operations.

The CPT of this node is by far the biggest of all the CPT's. It has a size of 3x108 cells. The experts were only asked for the probabilities in the best and worst state conditions, meaning that the remaining 106 columns had to be quantified. The probabilities for the two columns provided by the expert panel are found once again with the ski jumping score method.

In the case with "Full" "Lifeboat availability", it is assumed that helicopter evacuation will have no contribution to the overall achieved evacuation rate. It can be argued that severely injured passengers might prefer helicopter evacuation, but when the node considered only evaluates the evacuation rate, those specific passengers' need for helicopter evacuation will not affect the overall evacuation rate. The injured passengers will be evacuated either way. The possibility of evacuation by helicopter is assumed not to improve the probabilities of "Satisfactory" "Evacuation rate" in any case. This assumption is based on the number of people that can be evacuated by helicopter per hour. As seen from the Viking Sky incident, roughly 24 people per hour were evacuated. It is, therefore, assumed that the helicopter evacuation shifts the probabilities from "None" towards "Limited", and makes no difference on "Satisfactory" for the cases without "Full" "Lifeboat availability".

The rest of the CPT is filled out with interpolation and reasoning based on the above-mentioned assumptions.

Number of fatalities

This node represents the number of people on board that are killed as a result of a ship grounding. The node has five states, describing intervals of the number of fatalities. There are three nodes influencing this node; "Sinking time", "Evacuation rate", and "Immersion survivability".

States: - 75-100%
- 50-74%
- 25-49%
- 0-24%
- No fatalities

The final state, named "No fatalities" is used for the "No sinking" scenario, assuming that there will be no fatalities if the ship does not sink. For all other combinations of parent node states, the experts answered questions related to the best and worst conditions. For the cases where the ship will sink, the state "No fatalities" is excluded, meaning that the top four states' probabilities must add up to 1. There is a possibility of no fatalities even though the ship will sink, and that possibility is included in the 0-24% state. This way, the "No fatalities" state is reserved for the "No sinking" scenario.

"Evacuation rate" "None" does not say anything about the evacuation after e.g. four hours, only after 60 minutes. The number of fatalities in the slow sinking scenario can be assumed not to be as dependant on the evacuation rate as for the rapid sinking scenario. The "Evacuation rate" node is defined based on IMO's guidelines and does not provide explicit information about the evacuation rate after one hour. It is assumed that after six hours of grounding, 50% of the passengers are evacuated in the "None" "Evacuation rate" state. With this assumption, the distribution of fatalities for the slow sinking scenario can be found. For "Satisfactory" and "Limited" "Evacuation rate", 100% probability of "0-24%" fatalities is assumed, because all/almost all passengers will have been evacuated within six hours. For the "None" "Evacuation rate" case, there is assumed some probability of "25-49%" fatalities as well.

The remaining parts of the CPT have been filled out using the experts' opinions. For some of the states, the experts were very aligned, but not all. It was, therefore, decided to use the answers of the expert that overall had the fewest outliers. The answers of this expert were also very similar to the two experts with the second-fewest outliers. The answers from that one expert were used as a basis for the rest of the CPT.

3.4.1.2 Other Nodes

Visibility

This node represents the visibility for the OOW and crew. The node has two states, and in the last Delphi meeting, a distance of 1nm was proposed as the limit.

States: - Good (> 1nm)
- Bad (< 1nm)

There can be different causes of bad visibility; fog, snow, or rain. The node is dependant on "Weather conditions", and the type of precipitation and presence of fog are included in the more general terms of "Good" and "Bad" "Weather conditions". The probabilities used in the node are based on (DNV, 2003), with some adjustments to fit the model.

Voyage Preparation

This node describes the quality of the preparation done before the voyage. The node has two states; "Proper" or "Poor" preparation. "Poor" means that the voyage preparation is not in accordance with requirements and/or expectations and that the ship is subject to higher risk than necessary.

States: - Proper
- Poor

As this node is identical to one from (DNV, 2003), the conditional probabilities are directly adopted from that model.

Signal Quality

The quality of the signal on the electronic display is influenced by the "Weather conditions" node.

States: - Good
- Bad

The conditional probabilities are based on (DNV, 2003). The equivalent node from (DNV, 2003) is also dependant on tuning, which is not considered in this model. DNV's model has more weather states.

When assuming that the tuning of the radar is correct the probabilities for "Good" "Weather conditions" can be applied directly. For the "Bad" "Weather conditions", the probabilities are adjusted. The proposed model's "Bad" "Weather conditions" include wind, rain, snow, fog, storm, etc. DNV's model distinguishes between storm/rain, wind, and fog, with the following probabilities for "Good" "Signal quality": 0.8, 1, and 1, respectively. The conditional probability used for "Good" "Signal quality" during "Bad" "Weather conditions" is set to 0.9.

Technical Redundancy

This node represents the level of redundancy on critical equipment on the ship and is dependant on the "Safety culture" node.

States: - Excellent
- Standard

As there are requirements for redundancy on passenger ships in the Safe Return to Port and SOLAS regulations, it is assumed that all ships fulfill the minimum requirements for redundancy. The node has two states, "Standard" and "Excellent", where "Excellent" represent the ships that have redundancy exceeding what is required by regulations. "Safety culture" is a node including the organizational aspects all the way up to the leadership, and the redundancy on board is believed to be affected by this culture. However, based on the mandatory requirements and the financial view of the cruise lines, the minority of ships are believed to have "Excellent" "Technical redundancy" implemented. The values used in this CPT are assumed by the author based on discussions with the supervisor.

Maintenance Routine

The "Maintenance routine" node describes if the maintenance routines of the ship are followed or not. The "Safety culture" node is the only influencing node.

States: - Followed
- Not followed

This node coincides almost directly to the node in DNV's model. The difference is how the safety culture states are defined. DNV has defined the safety culture as "Standard" or "Excellent", with the probability of "Standard" being 1, as improved safety culture was viewed as an improving measure. In the proposed model, "Safety culture" has the states "Good" and "Poor". As "Good" is defined as above the mean, and "Poor" as below, the conditional probabilities from DNV are decreased to fit the different defined states.

It was pointed out from one of the experts during the last Delphi meeting, that even though the ships and crew are required to perform and document equipment tests, these tests may not always be in accordance with regulations. These deviations may occur as a result of too short time to complete a proper test or other unfortunate circumstances. How well-spread this malpractice is, is hard to say when the documentation does not reveal it. However, the expert contributing with this information has first-hand experience on the matter, and the fact that this kind of rule-bending occurs is not questioned. Such equipment tests are tied to maintenance and maintenance routines, and the probabilities for "Not followed" "Maintenance routine" is deemed significantly higher for the ships with "Poor" "Safety culture" than the ones with "Good".

Being off course

The node is defined as "Ship course is unwillingly deviating from the planned course with at least 30 meters to either side for five minutes or longer. The node is dependant on the "Loss of control" and "Navigational error" nodes.

States: - Yes
- No

The "Being off course" node was originally subject to expert judgment, but after discussion with the experts, it became clear that the way the node and its parent nodes were defined, the CPT would become deterministic. The only combination resulting in the state "No" for the node is "No" "Loss of control" and "No" "Navigational error". All other combinations will logically result in the ship being off course.

Grounding

The "Grounding" node describes whether or not the ship hits the ground. It is dependant on the "Being off course" node and the "Successful recovery" node.

States: - Grounding
- No grounding

The probabilities are deterministic. If a ship is on a grounding course and does not perform a successful recovery, it will hit the ground, and the three other combinations of the two will not lead to a grounding.

Season

This node represents the season.

States: - Summer
- Winter

As mentioned in section 3.1, only the winter season is examined, and the probability of "Winter" is set to 1. This node could have been excluded, but is not in order to make the model more intuitive for a new observer.

Weather Conditions

The "Weather conditions" node describes the weather conditions, and is only dependant on the "Season" node.

States: - Good
- Bad

The node is assumed to be important in the model as it has as much as six children nodes, on both "sides" of the model (before and after grounding). The quantification of the node is performed by the use of meteorological data from four different weather stations during three winters, 2015-2018. The four stations are shown in Figure 3.1

The weather states found to classify the weather as "Good" or "Bad" are the following; wind, precipitation, and temperature. "Bad" is defined as winds above 11 m/s, more than 2 mm precipitation and temperature below 0°, i.e. snow, or both high winds and snow. This definition of "Bad" was decided after the last Delphi meeting and will be discussed in Chapter 5.

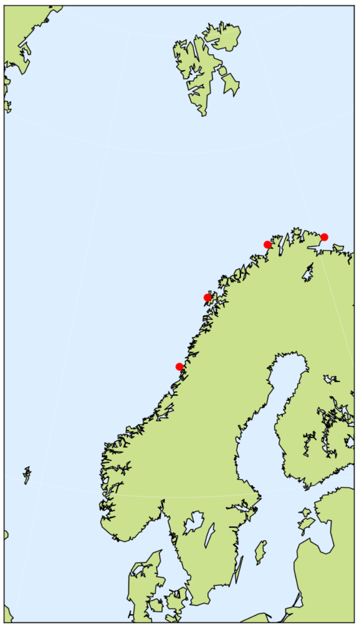


Figure 3.1: The locations of the four weather stations used for collection of weather data

Distance to Shore

This node illustrates how far away from the shore, and hence proximity to grounding possibility, the ship is during its voyage.

States: - Short (<200m)
- Medium (200m-2nm)
- Long (>2nm)

The probabilities in this node are found based on Hurtigruten's sailing plan on the route Trondheim-Kirkenes-Trondheim. The route is split into increments, and the increments are classified into the three categories based on their distance to the closest point on shore.

Ship Damage

This node describes the damage to the ship as a result of the grounding. It is dependant on "Grounding" and "Weather Conditions".

States: - No/Minor - The ship is not significantly affected/no damage
- Major - Damages lead to the need for assistance and repair, does not sink.
- Catastrophic - Total loss, to the sea or scrapyard, will sink

The node is similar to DNV's node, but the same issue as for the "Weather conditions" arise, and DNV's model takes the type of sea ground into account. To adjust for these differences, the mean value for the different cases are used. For "Good" "Weather conditions", the mean of the three different ground types is used. For the "Bad" "Weather conditions", an overall mean value of the three different bad weather conditions; "Storm/rain", "Wind", and "Fog", and the ground types is used.

Heel Angle

This node states whether or not the heel angle of the ship after grounding is above or below 20°. The node is dependant on the "Ship damage" node.

States: - Above 20°
- Below 20°

For the "No/Minor" damage case, the ship is assumed not able to reach heel angle above 20°. The type of grounding is important for the resulting heel angle. A grounding tearing up the side of the ship will result in a higher heel angle than a bottom grounding (Ruponen, Pulkkinen, & Laaksonen, 2017). The different grounding scenarios are not included in the model, and a general probability of high heel angles is desired. It takes some time for a damaged ship to develop a heel angle (Ruponen et al., 2017). Ruponen et al. suggests that a passenger ship with extensive side damage develops a 15°heel angle roughly within 100 minutes. The "Heel angle" node in the model affects the "Lifeboat availability", and a 20°heel angle is assumed too high to be able to use the lifeboats. However, if this threshold angle should be exactly 20°or not is not easy to determine, as other factors may influence as well. With the goal of achieving general probabilities of heel angles above 20°, a probability of 1% for the "Major" damage case and 20% for the "Catastrophic" case are assumed.

Sinking Time

This node represents the time it takes for the ship to sink, and if it sinks at all. It is dependant on "Ship damage" only.
States: - Rapid (<60 min)
- Medium (60 min - 6 h)
- Slow (6 h - 24 h)
- No sinking

The probabilities used are partly based on the model from DNV. For "No/Minor" and "Major", the ship will not sink, directly from DNV and logic. The sinking time increments from DNV are different than the ones used in the developed model. DNV considers sinking before and after 30 minutes as the only two sinking scenarios. In the proposed model, three different time scenarios are introduced. In DNV's model, there is a 75% chance of not sinking given "Catastrophic" damages. In the proposed model, "Catastrophic" damages are defined in such a way that they will lead to the sinking of the ship. The probabilities for the "Catastrophic" damage scenario are based on a uniform distribution between the three sinking states, with a slight increase in probability for the "Medium" state.

Nearby Ships

This node states the number of ships within a 4nm radius.
States: - Multiple
- Single
- None

The numbers used in this node are based on a still picture of AIS data from the route, collected on 23.04.2020. The route was split into increments, and the increments were classified in accordance with the number of ships within a 4nm radius. Pleasure crafts were excluded from the data, as they are deemed non-important for the matter at hand. The AIS still used for this analysis was taken during the Covid-19 pandemic. These abnormal circumstances had a great impact on passenger traffic, and it can, therefore, be argued that the ship traffic during a more normal situation will be higher.

Helicopter Evacuation Possible

This node states whether or not evacuation by helicopter from the ship is possible based on the distance to helicopter bases, and is dependant on the "Sinking time".
States: - 2 helicopters within 2 hours
- >2 helicopters within 2 hours
- Not possible (for the rapid sinking scenario)

As seen from the Viking Sky incident, helicopters may be used for evacuation of a cruise ship. It should be noted that the evacuation rate from helicopters was not especially high. During the incident 460 people were evacuated by helicopter over a period of 19 hours, giving an evacuation rate of 24 people per hour (Jensen, 2019). The helicopter pilots said afterward that to evacuate all onboard Viking Sky would have taken a total of 48-72 hours. With regard to the model and the states of sinking time, helicopter evacuation would definitely help the most in a slow sinking scenario. 24 and 144 would be the maximum number of people to be saved from the ship for the "Rapid" and "Medium" sinking scenarios, respectively.

For the quantification of this node, it is assumed that the new AW101 helicopters, described in subsection 2.4.2, has been deployed on all the rescue helicopter bases. As the states of this node represent two or more helicopters within two hours, Figure 2.3b is used to determine the probabilities. The distance circles overlap all the way up to, approximately, Banak base in Finnmark. This means that it is only the coastline from Banak to the Russian border that is not covered by at least two bases within two hours. This part of the coast makes up about 15% of the voyage. For the scenario where the ship sinks within one hour, it is believed that helicopter evacuation will be of little to no help, and the state "Not possible" is used for this case.

There are other helicopters that can be helpful in addition to the ones from the rescue bases. Helicopters on offshore installations, or otherwise related to the oil and gas industry, can be used, as was the case for Viking Sky. There are a number of factors determining how many helicopters that can be used and how fast the helicopter evacuation can be performed. The distance from the ship to a suited drop-off point for the evacuees is important for the number of helicopters that can be in use. During the Viking Sky incident, it was found that a rotation of three helicopters was optimal when considering the time it took for each helicopter to fill up with passengers (Jensen, 2019). During the Viking Sky incident, there was a short distance from the ship to suited drop-off places. Both Molde and Kristiansund were within 30 km of the ship. This proximity to suited off-loading places is not equal along the shore, and it is believed to be worse the further north you come.

Immersion Suits Available

This node represents whether or not the ship is equipped with immersion suits for all people on board.
States: - Yes
- No

The Polar Code requires that passenger ships sailing in polar waters have *a proper sized immersion suit or a thermal protective aid (...) for each person on board*, (IMO, 2017). This node is present in order to analyze the effect of introducing stricter requirements also for the Norwegian coast not covered by the Polar Code today. For the model, it is assumed that no ships have immersion suits for all people on board.

Passenger State of Health

This node represents the overall health state of the passengers on board.
States: - Good
- Poor

The overall health state of humans is correlated to age. Aging leads to a *...gradual decrease in physical and mental capacity, a growing risk of disease, and ultimately, death* (World Health Organization [WHO], 2018). According to (Cruise Lines International Association [CLIA], 2019), the average age of cruise passengers for the years 2016-2018 has been steady at 46.7 years. For cruise ships in Northern Europe, the average age is roughly 52.5 years. In 2018, 51% of all cruise ship passengers were 50 years or older, and 33% were 60 years or older (CLIA, 2019). With the very general assumption that people older than 60 years have a "Poor" overall state of health, the above-mentioned numbers can be applied with some adjustments. The slight increase in age for Northern Europe is 12.4%. If the age distribution is assumed linear it means that 37.1% of the cruise passengers in Northern Europe are 60 years or older, and in this model, has "Poor" health.

Escort Ship

This node represents whether or not the cruise ship is escorted by another ship, e.g. a tug boat.
States: - Yes
- No
The node is included to be analyzed as a risk-reducing measure, and the state "No" has value 1 in the original model.

3.4.2 Proposed Measures

One of the goals of this thesis is to investigate the need for and the effect of potential risk-reducing measures with regard to cruise ship groundings in Northern Norway. The measures proposed and analyzed in this thesis can be split into two groups; the ones preventing a potential accident and the ones mitigating the consequences after an accident has occurred. Some of the measures contribute as both a preventive and mitigating measure.

The following measures are proposed as potential risk-reducing measures. These measures are taken into consideration during the construction of the model. The measures span from ship specific measures to implementation of national laws and regulations.

Table 3.1: Measures proposed to be analyzed with the model

Preventive Measures	Mitigating Measures
Escort ship/tug boat	
Weather restrictions	
Required sailing distance to shore	Limited number of passengers
Crew familiar to waterway (pilot)	Health requirements for passengers
Improved safety/risk management onboard	Helicopter readiness
Active surveillance from VTS	Immersion suits for all passengers

3.4.2.1 Description of Measures

Escort ship

As a preventive and mitigating risk-reducing measure, it is proposed that each cruise ship has an escort ship. An escort ship, e.g. a tug boat, will follow the cruise ship and can be of need in case the cruise ship loses control. The mitigating effects can be to pick up people from the sea, deploy its own lifeboats, or pull the ship to a safer location after grounding. The probability of "Yes" for the "Escort ship" node is set to 1 when testing the measure.

Weather Restrictions

The other measure regarded as both preventive and mitigating is weather restrictions. Weather restrictions should perhaps be implemented by the authorities with a clear definition of a threshold to where ships should not be allowed to sail/leave port. There are issues when it comes to the implementation of such a measure. What should be the weather threshold for denial? When should a sailing denial be sent out (weather forecast)? Which ships will be affected (size, type of ship)?

The effect of this measure would be that the probability of "Good" is set to 1 for the "Weather conditions" node.

Required Sailing Distance to Shore

The sailing distance to shore is something that can quite easily be adjusted. With increased distance to shore, the crew will have more time to react to navigational errors or technical failures before a potential grounding occurs. The geography of the Norwegian coast is complex, and ships tend to sail inshore to be shielded from the worst weather.

The node representing the distance to shore has three states. Assuming that the number of ports will stay unchanged, there is little to do about the shortest distance state. There are narrow sounds and fjords where the chosen sailing route does not significantly change the distance to shore. This measure is believed to be most influential in the "Medium" distance state. An example of how a change of route to extend the distance to shore is shown in Figure 3.2. In the example, the ship is visiting the same two ports, but the yellow route is slightly longer because of the increase in distance to shore.

Because of the geography of Northern Norway, an increase in sailing distance to shore is mostly relevant for the stretches Trondheim-Bodø and Hammerfest-Kirkenes. Between Bodø and Hammerfest, the ports and fjords make it uncalled-for to sail a route keeping a distance to shore of more than 2 nm over long periods.

The effect of the implementation of this measure is assumed to shift the probabilities somewhat from the state "Medium" to "Long". How much of the route that can be sailed far away from the shore is dependant on how many ports to be visited. In the route used by Hurtigruten, the basis for the original values of the node, a modification is made to model a route complying with a longer distance to shore. The same ports are still visited, and the "Short" state is slightly reduced, while the "Medium" is reduced significantly, and the "Long" increased quite a lot. 7%, 45%, and 48% are the modified probabilities of "Short", "Medium" and "Long" distance to shore.

Figure 3.2: Example of sailing routes with different distances to shore. The red route is Hurtigruten's tour today, and the yellow route is an example of a route with the purpose of sailing further away from the shore.

Improved Safety/Risk Management

The safety culture onboard a cruise ship is believed to be influenced by the safety culture within the cruise line organization the ship belongs to. However, some differences between the ships are assumed. This is not debated further, but an improvement in the safety culture on a cruise ship is assumed to have a positive effect on accidents. The original model had an 86% probability of "Good" "Safety culture". Improved safety culture is modeled by a 9% increase in the probability of "Good" "Safety culture"; 95%.

Active Surveillance from VTS

Active surveillance from a VTS is a potential risk-reducing measure. The VTS centers monitor ship traffic and make contact with ships if trouble is suspected (NCA, 2011b). This service is a good risk-reducing measure at the moment, but it is believed that stricter regulations regarding passenger ships can be useful. Improved surveillance from the VTS is assumed to improve the node "Situational awareness". The quantification of the improvement is assumed to be 20%. This 20% improvement is implemented in such a way that the probability of "Unsatisfactory" "Situational awareness" in each column is multiplied with 0.8. As the node only has two states, the new probability of "Satisfactory" is the complement of the reduced probability of "Unsatisfactory" "Situational awareness".

With this type of modification, the probability of "Satisfactory" "Situational awareness" given the worst conditions is improved more, in absolute value, than the probability given the best conditions. This effect is deemed realistic. A VTS operator is believed to help a badly prepared OOW more than the operator could help a properly prepared OOW.

Crew Familiar to Waterway

The crew's familiarity in the examined area is assumed to be different between the ships. Some ships, and crew, sail the waters often, e.g. Hurtigruten, while others may only sail there once or twice per year. According to the Compulsory Pilotage Regulations, all passenger ships with a length above 50 meters are subject to compulsory pilotage within the baseline. This requirement can be fulfilled by employing a pilot or by the use of PEC (NCA, 2011a).

Even though compulsory pilotage is present, it is assumed that better familiarity with the waters in Northern Norway for the ship's regular crew, ultimately, will improve the safety. The effect of crew familiar to the waterway and conditions is assumed to improve the probabilities in the node "Detection of grounding course". The quantification of this measure is done in a similar way to the improved VTS surveillance, but this measure is assumed to be less effective than the VTS. In this node, a 10% decrease in the worst state is assumed when the ship crew is familiar with the waterway.

It is possible to discuss the pros and cons of better familiarity. If the crew is familiar they might not always agree with the pilot. If they sail seldom in Norway, they might hand all responsibility over on the pilot. These factors can be both positive and negative at the same time, but it is assumed that a good familiarity to the waterway will improve the safety.

Active Surveillance from VTS + Crew Familiar to Waterway

The way the improved VTS surveillance and improved crew familiarity to the waterway are modeled, they are closely related. One affects the "Situational awareness" and the other "Detection of grounding course". These two nodes are directly related in the BBN, and it is therefore decided to also test the effect of both measures introduced at the same time.

Limited Number of Passengers

As a measure to reduce the number of people being affected by a potential grounding, a limitation to the maximum number of people on board is proposed. This constraint will be a mitigating measure as it will likely mean a higher share of passengers evacuated, either by lifeboats, nearby ships, or helicopters and less demanding for the hospital capacity in the region. The end node in the model is "Number of fatalities", which is presented in percentage intervals. The measure will, therefore, not have an effect on the individual risk.

The way the model is constructed, this measure will have an effect on the group risk. This measure is, therefore, not tested by changing probabilities in the model, but by changing the number of people exposed to the grounding risk. The result of this measure will present itself in the resulting f-N curves. The curves will shift leftwards and rightwards with decreasing and increasing the number of passengers, respectively.

Health Requirements for Passengers

Another measure related to the passengers is to introduce some sort of health requirements for the passengers. As described in subsubsection 3.4.1.2, the passengers older than 60 years are defined as passengers with "Poor" health state in the original model. A restriction on the number of passengers above a certain age is easy to implement, but might not be a popular measure for the cruise lines. Another solution is to request some sort of medical license issued by the passenger's doctors to document an adequate health state.

How to implement such a measure will not be discussed further in this thesis. To refuse all people with bad health to come aboard a cruise ship sounds unrealistic. The measure is therefore quantified to a limitation of 10% of the passengers to be "allowed" to have bad health.

Improved Helicopter Readiness

The helicopter readiness in Northern Norway is discussed in subsection 2.4.2 and Figure 3.4.1.2. As almost the whole area under examination in this thesis is covered by at least two rescue helicopter bases, it is decided that an improved helicopter readiness in Northern Norway takes the form of an increased number of helicopters on the northernmost base, Banak. This increase would lead to a 100% coverage of the coast, with the definition three or more helicopters within two hours. To test the effect of this improved readiness, the probability of the state ">2 helicopters within two hours" is set to 100%.

Immersion Suits

Immersion suits are required by the Polar code as mentioned in subsubsection 3.4.1.2. It is assumed that no ships fulfill this requirement from before. The measure is tested by changing the node from "No" to "Yes".

3.4.2.2 Cost Estimates

The proposed measures are classified into three different cost classes; High, Medium, and Low, see Table 3.2. This table is based mainly on the author's own beliefs.

Table 3.2: The proposed measures classified into three cost categories

Cost	**Measure**
High	Escort ship Helicopter readiness
Medium	Number of passenger limitation Passenger health restriction Crew familiar to waterway Active surveillance from VTS Improved safety management Immersion suits for all passengers
Low	Weather restrictions Sailing distance to shore

Chapter 4

Results

4.1 BBN Model

One goal of this thesis was to develop a model that successfully models the events leading up to a ship grounding accident and the potential outcomes. Fault trees and event trees are commonly used for those two purposes with the "bow-tie" method. One disadvantage of this method is that it is difficult to model the factors that influence the outcome in both the events leading up to the hazardous event and the outcomes of the event in a good way.

The final BBN model is shown in Figure 4.1. The model is a result of the work described in the previous chapters.

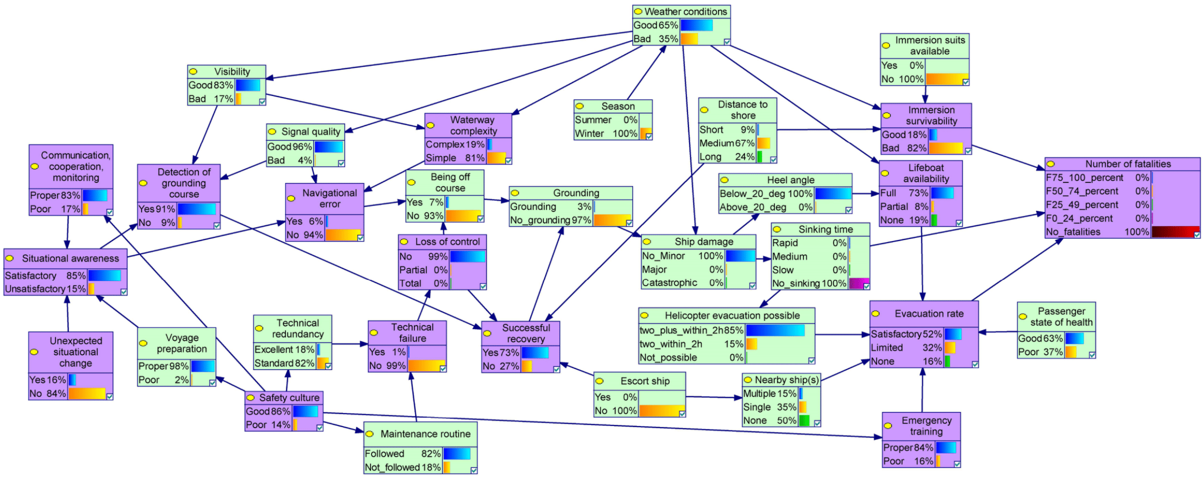


Figure 4.1: The developed BBN model. A bigger figure is attached in Appendix C. The numbers are rounded to zero decimals, i.e. 0% may actually be 1E-04, 100% may be 99.7%, etc.

The model can be viewed as a fast-forward symbol with the end of the first triangle being the grounding event, and the end of the second triangle being the number of fatalities, see Figure 4.2. The dotted lines in the figure are included to illustrate how some factors that influence the outcome of the first event also influence the outcome of the second event.

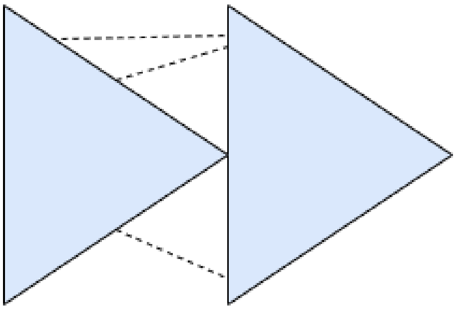


Figure 4.2: Illustration of how the model can be viewed as a fast-forward symbol. The dotted lines represent the factors that influence the outcome of both events.

With this take on the model, it is possible to compare the first part of the model to other models that only look at the events leading up to a grounding, e.g. Mazaheri et al., 2016.

The proposed model is compared with the other models found relevant. The number of nodes for each model is found. Furthermore, the number of nodes in each "triangle" (ref. the fast-forward concept), before and after the grounding, is found. The only other model modeling the consequences of the grounding is the model from DNV, 2003. The comparison in Table 4.1 shows that the number of nodes in the proposed model is in the lower region. It has the same amount of nodes as Mazaheri et al., 2016, but as Mazaheri et al., 2016 does not model the consequences, the number of nodes modeling the grounding accident in the proposed model is lower than Mazaheri et al., 2016. It is, however, reassuring that the number of nodes modeling the consequences of the grounding is roughly the same for the proposed model and the model from DNV, 2003.

Table 4.1: Comparison of the number of nodes between the proposed model and three other relevant models. In the models that also model the consequences of a grounding, some nodes influence both before and after the grounding, which is the reason why the total number of nodes is lower than the sum of the two columns.
*The entire model from Hänninen et al. has not been studied thoroughly, but the simplified version of the BBN structure in the article suggests that the model only examines the events up to a grounding and not the consequences.

Model	Nodes up to and incl. grounding	Nodes after grounding	Total number of nodes
Proposed model	21	16	33
DNV, 2003	55	17	69
Mazaheri et al., 2016	33	-	33
Hänninen et al., 2014	75*	-	75*

4.1.1 Grounding Frequency

In the developed model, the grounding node obtains a probability of grounding of 0.0259 (2.59%) per voyage. Assuming that 20 cruise ships make the voyage Trondheim-Kirkenes-Trondheim each winter, a grounding will occur every second year. This result seems to be high, and a comparison with the other models is desired.

To compare the grounding probability of the four models, a common unit must be found. The proposed model is built for the winter season, so a grounding probability per ship year is thought to possibly induce some unnecessary confusion. A grounding probability per nm is considered more relevant. The round trip Trondheim-Kirkenes-Trondheim along the coast is roughly 1700 nm. With this information, it is easy to convert the grounding probability per voyage, found by the model, to grounding probability per nm. In the report from DNV, the grounding probability per nm is explicitly stated which makes the comparison easy. Mazaheri et al., 2016 compares their results with DNV, 2003 and Hänninen et al., 2014, but use a different unit. As the probability from DNV, 2003 is known in both units, the ratio can be found, and the results from Mazaheri et al., 2016 and Hänninen et al., 2014 are easily converted to grounding probability per nm. See Table 4.2 for the comparison.

Table 4.2: Comparison of the grounding probability of the four models

	Proposed model	**DNV, 2003**	**Mazaheri et al., 2016**	**Hänninen et al., 2014**
Probability of grounding per nm	1.524E-05	4.7E-07	7.3E-07	1.52E-06
Factor from proposed model	1	32.4	20.9	10.0

As seen from Table 4.2, the proposed model provides a significantly higher probability of grounding than the other three models in the comparison. The model from DNV, 2003 is the only one of the three dedicated to large passenger ships. Mazaheri et al., 2016 studies what they call "marine transportation systems", which is interpreted as no specific type of ship, and Hänninen et al., 2014 studies tankers. In that way, the comparison with DNV, 2003 is the most interesting one. This is also the one with the biggest difference in grounding probability.

The result from the proposed model is significantly higher than the other models. But the circumstances around the models are not identical. As mentioned, the ship type they are examining differs, and more importantly, the model developed in this thesis examines the case of cruise ship traffic in Northern Norway during winter, which is presumed to be an important difference. In conversations with Professor Jan Erik Vinnem, he has argued that the worsening circumstances in Northern Norway during winter may add up to an increase in accident risks with as much as a factor of ten due to factors such as polar lows, high frequency of severe weather, darkness all day, limited visibility in snow showers, and freezing sea spray (yet to be published). If this argument is applied, the difference between the proposed model and the others is not that significant anymore. There would still be a factor of 3.2 separating the proposed model and DNV, 2003. This is an important difference, but assuming that the argumentation by Professor Vinnem is viable, the results are considered to be within an acceptable range.

4.1.2 Individual Risk

The individual risk is independent of the number of passengers exposed, as the individual risk calculation both multiplies and divides by the total number of passengers. The individual risk for a passenger on a cruise ship in Northern Norway during winter is shown in Table 4.3.

Table 4.3: The individual risk found by the proposed model

Number of fatalities	**Arithmetic mean value**	**Frequency (per voyage)**	**Individual risk (per voyage)**
75-100%	87.5	8.56E-05	7.49E-05
50-74%	62	5.89E-05	3.65E-05
25-49%	37	6.61E-05	2.45E-05
0-24%	12	0.000246	2.95E-05
			1.65E-04

The individual risk displayed in Table 4.3 is found per voyage. It is assumed that a passenger only takes one such cruise per year. That way, the risk per voyage will be identical to the risk per year for the passengers. With an individual risk per year of 1.64E-04, the risk exceeds the upper limit in the ALARP principle.

4.1.3 Group Risk

An f-N curve is provided to illustrate the group risk found with the model, see Figure 4.3. The curve is constructed for a ship with 1300 passengers, approximately the number of people onboard Viking Sky. The f-N curves are constructed using the low end of the fatality intervals from the model. The leftmost point on the curve (outside the edge) represents one fatality, and is used for the 0-24% fatalities. As can be seen easily from Figure 4.3, the f-N curve lies mainly within the ALARP region, suggesting that the risk should be lowered if the cost is not too high.

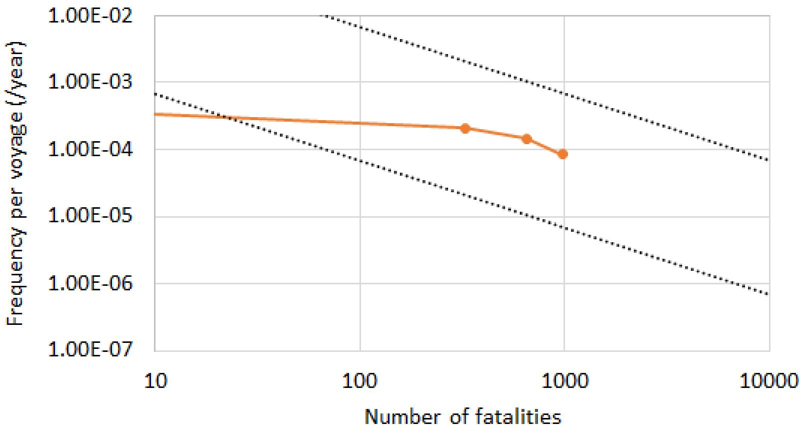


Figure 4.3: f-N curve for the original model with 1300 passengers

The group risk presented in Figure 4.3 lies in the ALARP region. This indicates that the risk should be lowered if it is not too expensive. The f-N curves are dependant on the size of the cruise ships, i.e. number of passengers. Figure 4.3 is constructed for a cruise ship with 1300 passengers. When lowering this number to 500, or even 200, passengers, the f-N curve is still within the ALARP region, see Appendix E

The risk tolerability criteria used for the group risk is found from IMO, 2008. However, another IMO report uses different ALARP limits. The ALARP limits used in IMO, 2000 are 6.9 times lower than the ones from IMO, 2008. These limits would worsen the results, as the ALARP region would shift downwards, and bring the f-N curve closer to the upper tolerability limit. However, the decision to use the limits from IMO, 2008 stands.

4.1.3.1 Comparison with DNV, 2003

In addition to comparing the grounding results, the results for fatalities from the proposed model can be compared to the results from DNV, 2003. The difference in results between the two models is bigger for the fatality risk than it was for the grounding probability, see Table 4.4. If the tenfold increase in risk argument from Professor Vinnem is applied in this scenario as well, which is a reasonable assumption, the difference becomes 8.7, which is almost three times as high as the grounding difference.

Table 4.4: Comparison of the fatality frequency between the proposed model and DNV, 2003

	Proposed model	**DNV, 2003**
Frequency of fatalities per nm	2.43E-08	2.80E-10
Factor	1	87

This increase in the difference between the two models is sensible. Assuming that the circumstances in Northern Norway increase the risk of grounding, they will also cause a higher risk of fatalities given a grounding. To explain this, the fast-forward idea can be used. The model can be split into two parts. In the first triangle, the proposed model predicts an outcome (grounding probability) that is 3.2 times more probable than DNV, 2003. The second triangle is also believed to increase the fatality probability compared to DNV, 2003. The total difference between the fatality risk found by the proposed model and DNV, 2003 is 8.7 (87 if not using Professor Vinnem's argument). When accounting for the increase in grounding probability (3.2), the increase of the fatality risk from the second triangle becomes 2.7. Figure 4.4 illustrates this aggregating effect.

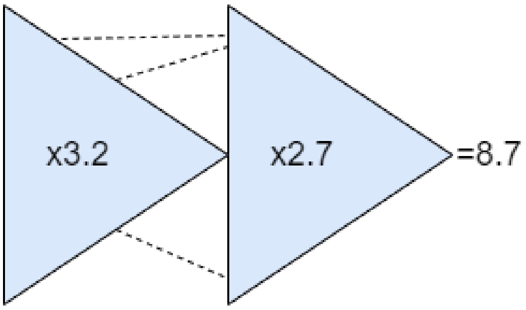


Figure 4.4: The difference between the proposed model and DNV, 2003 in each of the two parts of the model after accounting for the tenfold risk increase argued by Professor Vinnem.

4.2 Risk-Reducing Measures

The risk-reducing measures described in subsection 3.4.2 are applied to the model as specified and the result of their effects are summarized in the following sections.

The BBN network models only one ship, and it is assumed that more cruise ships at risk will worsen the picture even though they might be able to assist each other if needed. This assistance would require a relatively low distance between the ships when the need for assistance is urgent. Hurtigruten in normal operation have ships that sail daily in the region, that could be of assistance. However, it is assumed that more ships at risk increase the risk of fatalities more than the potential reduction from improved assistance possibilities. A potential measure could, therefore, be to limit the number of ships at risk.

4.2.1 Grounding Frequency

The effects on the grounding frequency from the proposed risk-reducing measures are shown in Table 4.5. The escort ship measure is the one with the biggest effect, followed by a combination of both improved VTS surveillance and crew familiar to waterway.

Table 4.5: The effect of the proposed risk-reducing measures on the grounding probability

Measure	Grounding frequency	% of baseline	% improvement
Baseline	0.0259	100	0
Escort ship	0.0215	83.1	16.9
Improved VTS surveillance and Crew familiar to waterway	0.0222	85.6	14.4
Weather restrictions	0.0227	87.6	12.4
Improved VTS surveillance	0.0231	89.0	11.0
Increased sailing distance to shore	0.0235	90.7	9.3
Improved safety culture	0.0248	95.7	4.3
Crew familiar to waterway	0.0249	95.9	4.1

4.2.2 Individual Risk

The effects of the proposed risk-reducing measures on the individual risk are summarized in Table 4.6. One measure stands out as significantly more efficient than the others, weather restrictions.

Table 4.6: The effect of the proposed risk-reducing measures on the individual risk

Measure	Individual risk	% of baseline	% improvement
Baseline	1.653E-04	100	0
Weather restrictions	6.459E-05	39.1	60.9
Escort ship	1.359E-04	82.2	17.8
Improved VTS surveillance and Crew familiar to waterway	1.412E-04	85.4	14.6
Improved VTS surveillance	1.473E-04	89.1	10.9
Increased sailing distance to shore	1.510E-04	91.4	8.6
Crew familiar to waterway	1.581E-04	95.6	4.4
Improved safety culture	1.580E-04	95.6	4.4
Immersion suits available	1.642E-04	99.3	0.7
Health requirements	1.639E-04	99.2	0.8
Improved helicopter readiness	1.650E-04	99.8	0.2

The only measure achieving an individual risk level within the ALARP region is the weather restriction measure.

4.2.3 Group Risk

An f-N curve after the implementation of the weather restrictions measure is provided in Figure 4.5. The curve is now closer to a tolerable risk level, but still within the ALARP region. The other measures did not improve the f-N curve as much as the weather restrictions did. All the f-N curves for the other measures lies between the curves in Figure 4.3 and Figure 4.5, and are not included in this report.

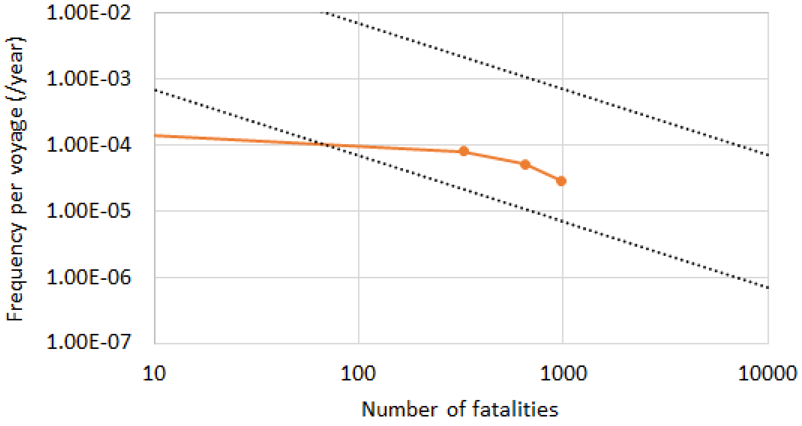


Figure 4.5: f-N curve for the grounding scenario when introducing weather restrictions. The curve represent 1300 passengers at risk

4.2.4 Results of the Proposed Measures

To assess the proposed measures both in terms of effect and cost, Table 4.7 is provided. The different cost classes from Table 3.2 are converted to a score. The rightmost column in Table 4.7 gives the "Implementation score" of each measure. This score is calculated by multiplying the cost score with the relative decrease in individual risk for each measure. The lower the implementation score, the better. It is considered sufficient that this analysis is only performed for the individual risk, and not the grounding case as well.

Table 4.7: The proposed measures ranked by their effect and cost

Measure	Individual risk	% of baseline	Cost class	Cost score	Implementation score
Weather restrictions	6.46E-05	39.1	L	1	39.1
Increased sailing distance to shore	1.51E-04	91.4	L	1	91.4
Improved VTS surveillance	1.47E-04	89.1	M	2	178.2
Crew familiar to waterway	1.58E-04	95.6	M	2	191.2
Improved safety culture	1.58E-04	95.6	M	2	191.2
Health requirements	1.64E-04	99.2	M	2	198.4
Immersion suits available	1.64E-04	99.3	M	2	198.6
Improved VTS surveillance and Crew familiar to waterway	1.41E-04	85.4	M/H	2.5	213.5
Escort ship	1.36E-04	82.2	H	3	246.6
Improved helicopter readiness	1.65E-04	99.8	H	3	299.4

The measure with the best implementation score is, not surprisingly, the weather restrictions measure. This measure is considered to have low cost and found to have the greatest effect on the individual risk. Generally, when reviewing Table 4.7, the relatively low difference in individual risk between most measures, and the relatively big difference in cost score between the different classes result in a table valuing the cost way more than the reduced risk.

The ALARP principle states that *...risk reduction measures are desirable but may not be implemented if their cost is grossly disproportionate to the benefit gained* (Rausand, 2011). With this in mind, most of the measures in Table 4.7 might be beneficial to implement. This cost-benefit assessment deserves more research to determine which risk-reducing measures should be implemented in the future to ensure a tolerable level of risk for the cruise ship traffic in Norway.

The measures could have been classified with more detailed cost classes to obtain more accurate results. However, the cost-benefit assessment performed in Table 4.7 is so trivial that further work is needed to achieve solid results for decision-making in any case.

Chapter 5

Discussion

This chapter includes sensitivity analyses of the model, discussion about model validation, the Delphi process, and the quantification of the nodes and the risk-reducing measures.

5.1 Sensitivity Analyses

The nodes in the model influence the outcome differently. Some nodes are more important than others, meaning that a slight change in a node can give big changes in the outcome. Other nodes might not change the outcome very much even though the node is changed completely from one state to another. It is important to be aware of which nodes the model is most sensitive to. A high sensitivity would call for low uncertainty in the node to increase the quality of the model. Sensitivity analyses are performed for both the "Grounding" node and the "Number of fatalities" node, in accordance with the fast-forward idea.

5.1.1 Grounding

All the nodes that are shown to influence the "Grounding" node from the sensitivity analysis performed in GeNIe, see Figure C.2 in Appendix C, are tested to see how much the result of the "Grounding" is affected. The nodes are tested by setting the values of the node to maximum and minimum and the corresponding result of the "Grounding" node is found. The information uncovered by such an analysis is important. The analysis points to the nodes that influence the model outcome the most. Some nodes do not affect the result significantly, and a higher level of uncertainty can be accepted. Other nodes that influence the model outcome to a greater extent should be subject to thorough quantification and a low level of uncertainty is desirable.

There is a total of 17 nodes important for the "Grounding" node uncovered by the sensitivity analysis. Of those 17, ten are quantified by the expert panel, and seven are quantified by other means. The results of the sensitivity analysis can be seen in Figure 5.1. It is clear from the figure that most nodes have a greater potential for worsening the outcome given worst state than they can improve the outcome given their best state.

The four nodes that affect the result the most are all nodes quantified by the expert panel. The "Technical failure" node is the node the model is most sensitive to. The resulting probability of grounding is worsened from 0.0259 to 0.2878 (+1111%) in the worst state and improved to 0.0241 (-7.3%) in the best state. As a comparison, the second most influential node ("Navigational error") worsen and improve the result to 0.1743 (+673%) and 0.0152 (-41.3%), respectively. These two nodes are the ones with the maximum worsening and improvement of the outcome.

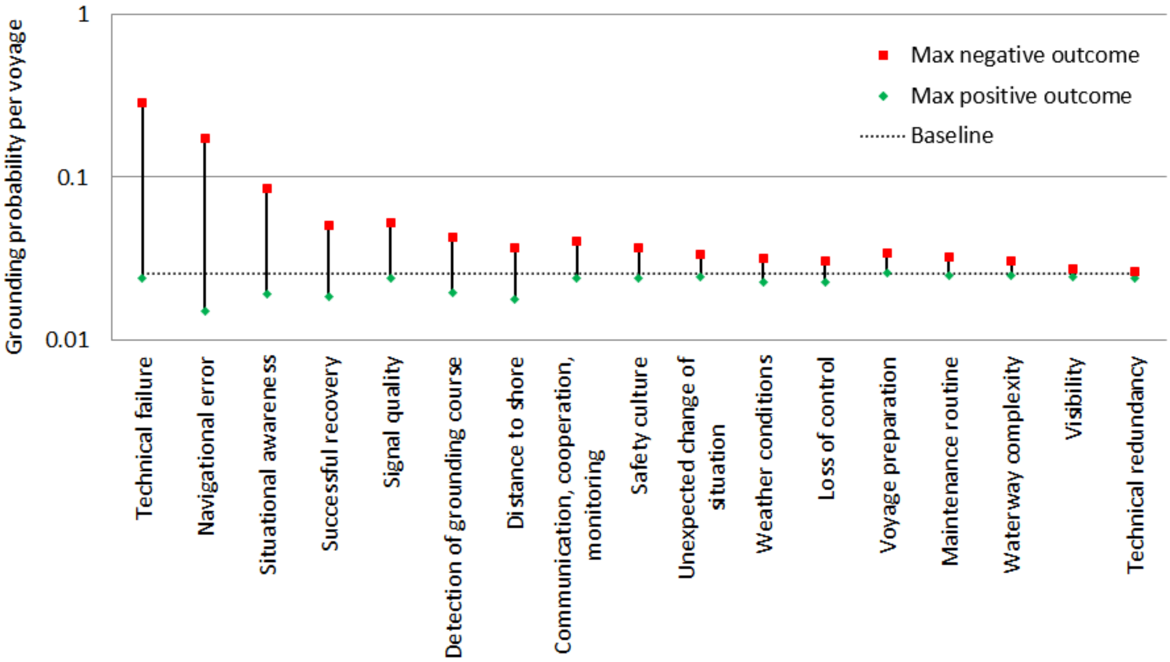


Figure 5.1: Sensitivity analysis of the nodes influencing the "Grounding" node.

5.1.2 Number of Fatalities

A similar sensitivity analysis is performed for the "Number of fatalities" node. The illustration of the GeNIe analysis can be found in Figure C.3 in Appendix C. The node is sensitive to 28 of the 33 nodes in the network, but only the ten most influential nodes are included in Figure 5.2. The analysis of this node is performed for the outcome with 75-100% fatalities. This decision is believed not to impact the results of the sensitivity analysis to any significant extent.

The node with the most impact on the result is the "Ship damage" node. From its worst and best state, the result is changed to 0.0023 (+2687%) and 1.86E-5 (-78.3%), respectively. The node that provides the lowest result is the "Sinking time" node. This node yields end results of 0.0002 (+241%) and 0 (-100%).

The "Technical failure" node should also be addressed in this sensitivity analysis. It is the second most influential node. The fact that this node is important for the "Number of fatalities" node, as well as the "Grounding" node, is as expected. The number of fatalities in a grounding accident is naturally dependant on the occurrence of the grounding. It is, therefore, expected that the node that is most dominant for the grounding result also has a big effect on the number of fatalities. This tendency is again backed up by the succeeding nodes in the analyses.

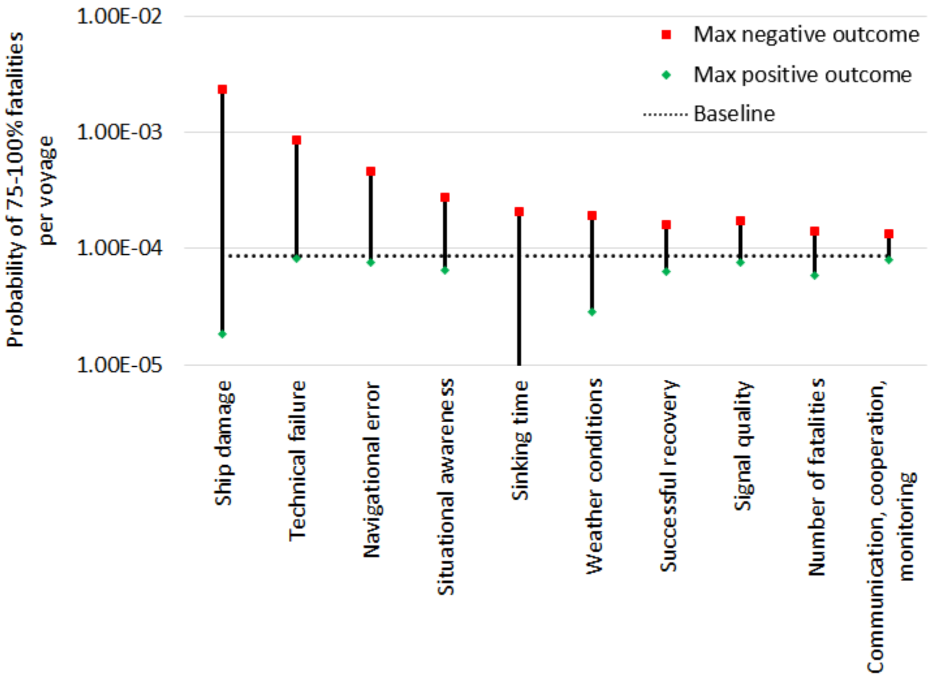


Figure 5.2: Sensitivity analysis of the 10 most influencing nodes on the "Number of fatalities" node. The "Sinking time" element goes to zero, outside the axis.

5.2 Model Validation

The validity of a model is the model's ability to describe a system well by the output and how the output is generated. There are several ways to validate a model. The proposed model is developed mainly through a literature review. The model can be validated by the framework provided by Pitchforth and Mengersen (Pitchforth & Mengersen, 2013). This framework consists of seven types of validity; nomological, face, content, concurrent, convergent, discriminant, and predictive validity. For more information about this, read Pitchforth and Mengersen, 2013.

A proper validation of the proposed model has not been performed in this thesis. However, with the expert panel assisting in the quantification, it is assumed that the model has some face validity. The framework by Pitchforth and Mengersen is how the author would have performed a proper validation test of the model.

Even though a model validation as proposed by Pitchforth and Mengersen, 2013 is not performed, several analyses of the model's behavior are performed.

5.2.1 Strength of Knowledge

Terje Aven propose two methods for assessing the strength of knowledge of a model in "Practical implications of the new risk perspectives" (Aven, 2013). The method used in this thesis is described like this:

The strength of knowledge is weak if at least one of the following conditions are fulfilled (Aven, 2013):

- *The assumptions made represent strong simplifications.*

- *Data are not available or are unreliable.*
- *There is a lack of agreement/consensus among experts.*
- *The phenomena involved are not well understood; models are non-existent or known/believed to give poor predictions.*

Correspondingly, if none of the above-mentioned conditions are true, the strength of knowledge is strong. For the cases in between, the strength of knowledge is considered medium. This classification with three strengths is adopted into the assessment of the strength of knowledge of the developed model. Figure 5.3 visualize the strength of knowledge of the entire model.

Three different features of the model are assessed. The color of the border of each node represents the level of certainty that the node should be present in the model, and the importance of the node in a grounding scenario. The color of the link between the nodes displays the certainty of the model maker on the presence of a parental relationship between the nodes. Finally, the color of the center of each node represents the uncertainty of the conditional probabilities of each node. The terms strength of knowledge and uncertainty have been used about each other, so to avoid any confusion Table 5.1 is provided as an explanation of the colors used in Figure 5.3.

Table 5.1: Explanation of the colors used in Figure 5.3

Strength of knowledge	Level of uncertainty
Strong	Low
Medium	Medium
Weak	High

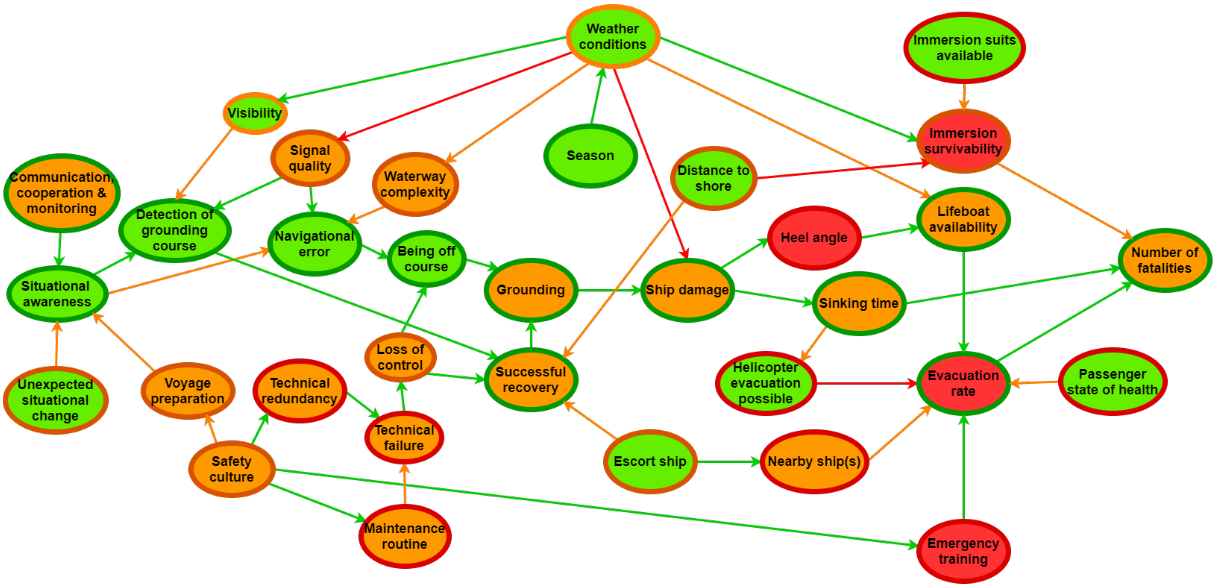


Figure 5.3: Strength of knowledge map of the model showing the uncertainty of each node (as the color of the border of the node), the strength of parental relations (as the color of the link), and the conditional probabilities of each node (as the color of the center of the node). Green color is strong, orange is medium, and red is weak strength of knowledge. The different shades of the three colors are included to ease the differentiation between the centers and the borders of the node, and has no impact on the strength of knowledge.

5.2.2 Model Criticality

When combining the results of the sensitivity analyses with the strength of knowledge map, useful information about the model can be uncovered. The sensitivity analyses point towards the nodes that should be given extra effort to achieve low uncertainty of the model. The strength of knowledge map describes the existing uncertainty in the model.

To further determine the criticality of each node the strength of knowledge is combined with the magnitude of change in state for every node to make the outcome of the "Grounding" node and the "Number of fatalities" node become "No grounding" and "No fatalities", respectively. This is done separately for the two nodes. The amount of change in probabilities of the nodes is found by setting the probability of "No grounding" equal to 1. Subsequently, the difference in probabilities of each node from the original value and the new value is documented. The same procedure is followed for the "Number of fatalities" node when setting the probability of "No fatalities" equal to 1.

The change in probabilities of each node and its state is combined with the strength of knowledge for each node. The nodes are assigned a score determined by the product of their change in state probability and their strength of knowledge. The classes of strength of knowledge are converted to numbers where strong(S) = 1, medium(M) = 2, and weak(W) = 3. The nodes without parent nodes receive a score of 1 on their parental strength of knowledge. The achieved score determines the level of criticality of the node. The criticality can be one of three scores; high - H, medium - M, or low - L. The threshold between the three classes is differently defined for the two cases examined, seen in Table 5.2.

Table 5.2: Threshold for the different criticality classes for the two cases examined

Criticality class	Grounding	Number of fatalities
H-M	1.0E-02	1.0E-03
M-L	1.0E-03	1.0E-04

The results of the criticality analyses are found in Table F.1 and Table F.2 in Appendix F. From the tables, it is easy to spot which of the nodes should be focused on to reduce the risk of grounding (and fatalities). For the "Grounding" node, the three nodes that have the greatest change of probabilities (excluding the "Grounding" node itself) are "Being off course", "Navigational error", and "Successful recovery". The nodes with the highest change in probability are the nodes where risk-reducing measures would achieve the most. This seems to be in accordance with the results in Table 4.5 in section 4.2.

The results in Table 4.5 are not directly transferable to what is uncovered in this section. That is, however, logical, as the change in the values in the CPT's of the nodes are different for each measure tested. The measure improving the grounding frequency the most in Table 4.5 is the escort ship measure. This measure improves the "Successful recovery" node, which was identified as important in the criticality analysis. The other two nodes found in this analysis are not directly changed by any of the proposed measures. They are, nonetheless, influenced by the node "Situational awareness", directly and indirectly, which is improved by the measure "Improved VTS surveillance".

The corresponding three nodes for the "Number of fatalities" node are "Ship damage" in the state "Catastrophic", "Sinking time" in the state "No sinking" and "Ship damage" in the state "No_Minor". This result is in agreement with what could be expected. The outcome "No fatalities" in the "Number of fatalities" node is used only in the case of "No sinking". When setting the probability that "Number of fatalities" is "No fatalities" to 1, that implies that the ship does not sink and the node "Sinking time" obtains a probability of "No sinking" equal to 1. The big change in probability is, therefore, not surprising. It is also reasonable that the "Ship damage" node is critical to the resulting number of fatalities.

It is important to emphasize that the criticality of the node "Number of fatalities" is found only for the state "No fatalities". The results would not have been identical if any of the other four states had been used, but it is believed that the results would have been similar.

5.3 Delphi Method

The Delphi method is an attractive method for graduate research (Skulmoski, Hartman, & Krahn, 2007). It is a flexible research method, and well suited for researching phenomena with incomplete information or phenomena where judgment is required. The decision to use the Delphi method was taken early in the design phase of the thesis. Discussions with supervisor Jan Erik Vinnem and co-supervisor Martin Hassel, who had more experience with the Delphi method together with BBN development, were important to learn about the strengths and weaknesses of the method. In the work developing the model, several aspects of a ship grounding accident seemed appropriate for quantification by expert judgment.

5.3.1 Expert Panel

According to Adler and Ziglio, there are four criteria the Delphi participants should satisfy (Adler & Ziglio, 1996):

- knowledge and experience with the issues under investigation
- capacity and willingness to participate
- sufficient time to participate in the Delphi
- effective communication skills

In graduate research, the student's supervisor is often a helpful resource to colleagues who can qualify as experts (Skulmoski et al., 2007). This thesis is not an exception, and supervisor Jan Erik Vinnem helped propose relevant colleagues for the expert panel.

With the above-mentioned criteria in mind, several experts were asked to participate in the study. The last three criteria on the list were out of the author's control, but it seemed that the experts that gave positive responses at least fulfilled the first two of the three criteria. The expert's fulfillment of the final criteria was assumed to be sufficient for all experts asked to participate.

In addition to known colleagues of supervisor Vinnem, it was discussed several times in guidance meetings that it would be extremely beneficial to have experts in the group with hands-on experience from cruise ship traffic in Northern Norway during winter. Several captains on Hurtigruten's ships were asked to participate as well as a captain on a Royal Caribbean Cruise Line ship. Unfortunately, after some discussion, none of the captains could spare time to participate in the study. It is believed that this response from the captains was impacted by the ongoing pandemic at the time and that a postponement of the Delphi study for one or two months could have provided different responses. However, with a scheduled date of submission of the thesis and a time plan accordingly, the Delphi work continued without postponement.

The resulting expert panel was a set of seven experts. Four of these are directly connected to NTNU as professors. The remaining three have varying experience from risk assessment work, sailing experience, academia, and/or safety work in marine operations. One important setback of the expert panel is the overweight of experts from academia and lack of experts with bridge experience from cruise ships. The effect of this quite homogeneous panel is not easy to determine. Do experts with a lot of theoretical experience give more optimistic or pessimistic answers than more practical experts? It is assumed that they do not. The answers from the experts were sometimes quite different, but in general, all experts were within a range of 30-40% difference from highest to the lowest answer. The four professors from NTNU did not always give the same answer, and the assumption that the most theoretical experts are not biased one way or the other seems to hold.

There is a tradeoff between the quality of the results of a Delphi study (i.e. the number of experts) and the manageability of the expert group (Skulmoski et al., 2007). A high number of experts yields a lower group error, but it also makes the managing of the Delphi process and analyzing the data more tedious. It is believed that the benefit of including one or two cruise ship captains in the expert panel would outweigh the cost of potential additional work related to a bigger panel. For this master thesis, the resulting expert panel was deemed sufficient in terms of the number of experts and their expertise. Nonetheless, the results of the model should be used carefully, considering the lack of cruise ship captains (or other corresponding experts) in the expert panel.

The composition of the panel was not only negative. One advantage of their academic experience was that they were familiar to work with probabilities, which was useful knowledge for the work at hand.

5.3.2 Questionnaire

What questions and how those questions are asked are important decisions to be made early in the research design phase (Skulmoski et al., 2007). The questions can be asked broadly to widely cast a research net to obtain information, or the questions can be asked more direct to guide the panel participants towards a certain goal. In the work presented in this thesis, the second approach was utilized. That decision was made based on the nature of the model subject to quantification. Even though the initial questionnaire focused on specific questions asking for specific probabilities, the experts were allowed to comment on all the parts of the model they were asked about. With that in mind, it can be said that the first questionnaire both asked direct, specific questions, as well as more broad questions to catch the experts' opinions on the first BBN model.

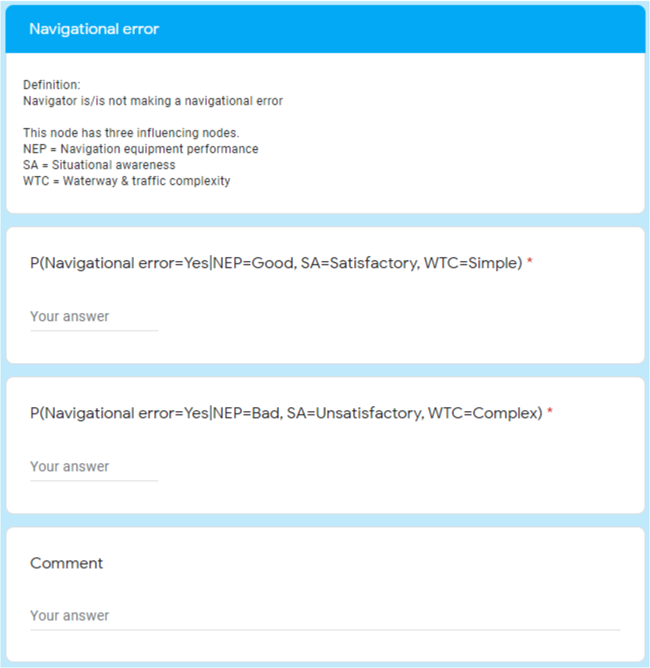
The tradeoff between asking specific questions and more broad questions is that the answers to the broad questions require more time and work to analyze, while the answers to the specific questions are easier to process. In the Delphi process in this thesis, the specific questions asked for a finite probability (quantitative), while the open comment sections were included as a qualitative part of the questionnaire. This was done to both obtain initial probabilities for the model and gain the experts' insight when it comes to how the model was designed in terms of nodes and parental relations.

A quick view of the model and its CPT's in Appendix D, shows that there are several hundred different probabilities to be quantified in the model. To expect the experts to familiarize themselves with each specific scenario for each node and provide probabilities for them is unrealistic as that would require a lot of time and effort from the experts. For the nodes subject to quantification from the expert panel, it was decided to only ask for the probabilities regarding the best and worst conditions of their parent nodes (if any). Based on these end values the remaining columns in each CPT would be interpolated.

When the CPT's were to be filled out after the final Delphi round, it became clear that it would have been beneficial to include a few more questions to some of the nodes. The best example of this is the "Evacuation rate" node which consists of 108 columns, and only two of them are anchored to expert judgment. The benefit of increasing the number of questions for the nodes with the biggest CPT's is assumed to outweigh the potential extra time from experts and analysis work. The reason for this assumption is that the potential expansion of the questionnaire is believed not to have been more than ten questions.

When preparing the questionnaire to a Delphi process, the questionnaire should be developed carefully and tested to avoid ambiguity in the research (Gordon, 1994). The responses from the first Delphi round suggested that the preparation of the questionnaire should have been better. Even though it was attempted to inform the participants well about all aspects of the model, it seemed that the way the information was given and the questions were posed was not completely unambiguous.

The questionnaire was formed in such a way that the participants were presented with the case of one node at a time. To continue, the respondents were obligated to provide an answer for each probability asked for. The format of the probabilities had to be of the format 0.XX. Two decimals were considered sufficient, but if the expert wanted to, answers with three digits were also accepted. The demand to provide an answer was not prompted for the comment opportunity. An example of how a section in the questionnaire looked can be seen in Figure 5.4. As most of the answers to be provided were of the quantitative sort, an online questionnaire tool was utilized. This tool made a transition from the questionnaire to a spreadsheet effortless.


Navigational error

Definition:
Navigator is/is not making a navigational error

This node has three influencing nodes.
NEP = Navigation equipment performance
SA = Situational awareness
WTC = Waterway & traffic complexity

P(Navigational error=Yes|NEP=Good, SA=Satisfactory, WTC=Simple) *

Your answer

P(Navigational error=Yes|NEP=Bad, SA=Unsatisfactory, WTC=Complex) *

Your answer

Comment

Your answer

Figure 5.4: Example screenshot from the first questionnaire sent out to the Delphi participants. The red asterisk symbolize that the question requires an answer in order to continue the questionnaire.

As an effort to make the questionnaire more engaging, some variance was included for a few of the sections. It can best be described with an example. The node "Lifeboat availability" has three possible states: "Full", "Partial", and, "None". Each column in a CPT must add up to 1, and it is, therefore, sufficient to receive probabilities of only two of the three states. The probability of the final state can be calculated from the other two probabilities. For this specific example, the state probabilities asked for were different for the best and worst conditions of the node. For the best conditions, the probabilities of the states "Full" and "Partial" were asked for. For the worst conditions, the probabilities of the states "Full" and "None" were asked for. The difference is illustrated in Table 5.3.

Table 5.3: Table illustrating an example of how some probabilities were found in different ways. The blue colored cells indicate probabilities provided by the experts, and the pink cells indicate the probabilities calculated from the blue cells.

State	Best conditions	Worst conditions
Full	Requested	Requested
Partial	Requested	Calculated
None	Calculated	Requested

Despite the good intentions behind this maneuver, it is suspected that it caused more harm than good. The consequence of this difference is hard to quantify. It is assumed that the difference in questions may have been contributing to misunderstanding or unnecessary confusion for the experts. Maybe it would have been better to ask for all three probabilities for the two cases and emphasize that the sum of the answers must add up to 1. The potential positive and negative effects of this inconsistency in the questionnaire should have been more thoroughly considered before the first Delphi round. In general, the questionnaire should have been given more effort in terms of preparation and testing before sending it out to the experts.

5.3.3 Workshop Meetings

The panel of seven experts was invited to the first Delphi meeting after all experts had responded to the questionnaire. The invitation proposed only one meeting time with two weeks notice, but advised the experts to speak out if they had any collisions in their schedule. The responses were not great, and eventually, only four experts were able to attend the first meeting. In addition to the low attendance, all four of the attending experts were the professors from NTNU. This shortcoming was also pointed out by one of the experts at the beginning of the meeting. Ideally, at least one of the other experts should have been present. Despite the relatively homogeneous group of experts and a tight meeting schedule to cover all the nodes, the meeting was productive.

Before the meeting, all the experts received a summary of all the responses in a spreadsheet. This summary included all the answers from the experts made anonymous, as well as summaries of the comments deemed most relevant. The experts were informed about which of the columns in the spreadsheet their answers belonged to.

There were held two Delphi meetings, with four and three experts present at each meeting. Ideally, all seven experts should have been present at both meetings. This was, unfortunately, not achieved. The Delphi process in general, is subject to uncertainties because of this lack of participation from some of the experts.

5.4 Model

5.4.1 Quantification of Nodes

When determining the value from the expert judgment to be used in the CPT's, a few different methods were used. The main method is what is previously called the ski jumping score method. The highest and lowest estimate from all experts were excluded and the mean value of the remaining five answers was found. The mean value from the whole panel is not desirable as an outlier in either end would have a big impact on the result. With only seven experts, this effect could become quite significant.

One way to work around this issue is to use the median value, instead of the mean. In this thesis, it was, however, decided to utilize the ski jumping score method. That way, single outliers were excluded, but when the panel was more split in its opinions, the same result might not have been obtained by using the median. Especially for cases where three and four experts were clustered on two different values, the median value would not describe the expert judgment in the best way. This median value sensitivity is related to the number of experts, and a higher number of participants in the study could advocate a more extensive use of the median value.

In addition to the ski jumping score method, one other method was used for two specific cases. For the nodes "Technical failure" and "Number of fatalities" it was decided to use the numbers from only one of the experts. When discussing the "Technical failure" node in the first Delphi meeting, one of the experts argued that all numbers were very high, and eventually, the other experts agreed to lower their estimates. A critical technical failure is not something that happens very often on a cruise ship. Based on the discussion and evaluation of the new answers it was determined that the estimates from the expert who had voiced the opinion that made the other experts present change their minds were used directly in the CPT.

The other case where a similar approach was taken is the "Number of fatalities" node. For the worst conditions, it was decided to use the estimates from the most conservative expert. The expert who provided these estimates was the one who had the least estimates that were either the highest or lowest. The number of end values for each expert was in the range between 12 and 28. The decision to use the estimates from the expert with the lowest amount of end estimates was backed up by the two experts with the second least end values in their estimates (15), as their estimates were very much alike.

The approach used for the two nodes described above could have been used for more of the nodes. If so, the nodes would be more dependant on the different experts that their numbers originated from. In some Delphi processes, a self-rating system can be included in the questionnaire to assign scores to the experts in the different fields of the study, and give more weight to the specialist experts (Gordon, 1994). This technique was not used to any significant extent, as the difference in expertise between the experts was assumed to not be very big. The lack of diversity in the expert panel has already been discussed and is the main reason that a self-rating system not was included. The nodes of the model could have been classified into different topics, such as human factors on the bridge, ship technical issues, evacuation procedures, and survivability. The experts invited would rate their expertise in each area, and the final composition of experts should cover all the topics in the model. This would call for a great amount of work in locating experts on different fields, and still be dependant on their willingness and time to participate. This method was, therefore, considered to not fit the circumstances of this thesis work.

As mentioned, the questionnaire only posed questions regarding the worst and best conditions for each node. This decision caused the need for some kind of interpolation to fill the remaining columns of the CPT's. The interpolation performed varied a bit between the different nodes. Some CPT's were interpolated directly, assuming that the parental dependencies contributed the same. Others were interpolated with some adjustment based on differently weighted parental relations, and in some cases, a combination of the two approaches was used. For the biggest CPT, "Evacuation rate", several assumptions were made to make the interpolation process more manageable. The assumptions made are not believed to lessen the certainty of the node as they are well documented and have reasonable ties to the definitions in the model.

The nodes that were quantified by other means than the expert panel, are all described in subsubsection 3.4.1.2. The equivalent nodes, or almost equivalent, to the nodes in the model from DNV, 2003, are quantified directly or with some adjustment from that model. The remaining nodes are quantified with different levels of certainties. The "Technical redundancy" and "Heel angle" nodes are the two nodes with the least certain CPT's. The values in the "Technical redundancy" node are assumptions based on discussions with the supervisor and deserve more attention to lower its uncertainty. The "Heel angle" node also has a CPT with values assumed without a desirable amount of attention. These two nodes should be granted more treatment in further work. Despite the high uncertainties of these nodes, their effect on the model is not very serious. For the "Grounding" criticality analysis, the "Heel angle" node is classified with medium and the "Technical redundancy" node with low criticality (Table F.1). Correspondingly, for the "Number of fatalities" criticality analysis both are classified with medium criticality (Table F.2). The sensitivity analysis of the "Grounding" node suggests that the "Technical redundancy" node is the least important node, and for the "Number of fatalities" analysis, none of the two nodes are within the ten most important nodes.

The quantification of the "Weather conditions" node is important for the model. As mentioned, the node has six children nodes, which makes the node influential. The weather conditions used for the quantification of the node were winds above 11m/s, snow, or both high winds and snow. This definition of "Bad" weather conditions is probably too wide and resulting in a higher probability of "Bad" weather conditions than in reality. Another issue with the definition is the link to the "Visibility" node. "Bad" weather conditions will increase the probability of "Bad" visibility, but the link is circumstantial as "Bad" weather conditions might only mean high winds, which do not change the visibility with any significance. The "Weather conditions" node was quantified after the last Delphi meeting. The experts were, therefore, not informed of how the "Bad" weather conditions were going to be defined. The author believes that most of the experts had worse weather in mind when imagining the "Bad" weather conditions. This has not been rechecked with the experts, and the main argument of this paragraph is that the "Weather conditions" node should have been properly researched and defined in advance of the Delphi meetings.

A vital aspect of the work done in this thesis that should be taken into account when reviewing and interpreting the results is the influence of the analyst/author. As concluded by Aven and Guikema, 2011, the results of a risk analysis will represent both the experts' and the analyst's knowledge.

5.4.2 Number of Passengers

The number of passengers is a factor that influences a great deal of the nodes in the model. There is no node in the model that represent the number of passengers, or even the ship size. To include the number of passengers as a node with discrete, and, probably, large intervals was considered to be a troublesome task with regard to classification, quantification, and parental relations. It was therefore decided to take the number of passengers out of the model, and calculate the influence from the number of passengers from the results of the model. It can be argued that the model would have been more accurate if the number of passengers, or ship size, had been included in the model.

5.5 Risk-Reducing Measures

5.5.1 Implementation of the Proposed Measures

In a similar way to how the quantification of the nodes was discussed in subsection 5.4.1, the way the measures are modeled and implemented in the model will be discussed here.

The measures improved VTS surveillance and crew familiar to waterway are modeled by changing the nodes "Situational awareness" and "Detection of grounding course". Regardless of their effect on the model as a whole, the improved VTS surveillance is assumed to have a bigger effect on "Situational awareness" than crew familiar to waterway will have on "Detection of grounding course". Their improvement is applied by multiplying the worst state outcome probability with 0.8 and 0.9, respectively. This approach suggests that the measures will have a greater effect in the cases where the worst state outcome has a high probability. Table 5.4 shows the effect.

Table 5.4: Example CPT's illustrating the relative difference in probabilities when the worst state outcome probability is multiplied by 0.8 (-20%).

	Original value		**Measure implemented**	
	Best conditions	Worst conditions	Best conditions	Worst conditions
Best outcome state	0.9	0.5	0.92	0.6
Worst outcome state	0.1	0.5	0.08	0.4

It seems reasonable that the effect of improved VTS surveillance will have a bigger effect on the case with the worst circumstances than with the best. With "Proper" "Communication, cooperation & monitoring", "Proper" "Voyage preparation", and "No" "Unexpected situational change" improved VTS surveillance might not be able to improve the "Situational awareness" very much. But in the case of "Poor" "Communication, cooperation & monitoring", "Poor" "Voyage preparation", and "Yes" in "Unexpected situational change" improved VTS surveillance is believed to improve the "Situational awareness" significantly. The same reasoning can be applied to the crew familiar to the waterway measure.

This way to implement a measure would not work as well for nodes with more than two states. In those cases, two (or more) of the states would have to receive some predefined change.

The weather restrictions measure is identified by the model as the best measure to implement. This result is a consequence of the way the measure is implemented. When introducing the weather restrictions measure, it is assumed that no cruise ship will be allowed to sail in bad weather conditions, and the "Weather conditions" node is set to "Good" with 100% probability. A 100% probability might be too optimistic, and a somewhat reduced probability could be more realistic. To deny all cruise ships from sailing in bad weather might be too strict, and difficult to establish and oversee for the relevant authorities. The threshold to determine when the weather is bad enough for a sailing denial will be difficult to decide, and should maybe be different for different types of ships.

The cost of the weather restrictions measure is assumed to be low. But the cost is dependant on the stakeholder. The costs for a cruise ship to be detained in a port due to bad weather can be high. Depending on the circumstances, they might have to drop other ports or even shorten the entire journey to avoid costly delays. The low cost assumed for the measure in this thesis is considered for the relevant authorities. It is assumed that the work and necessary infrastructure to establish and maintain such a measure is relatively low.

The implementation of some of the measures is not reinforced by low uncertainty. It is believed that some of the measures would have benefited from being included in the Delphi process for quantification.

5.6 Total Risk

The risk tolerability criteria from section 2.9 are given for all types of hazards a person can be exposed to. They are not specific to the grounding hazard. When the risk level is found for only this one hazard, the total risk level must be higher than this. The two types of maritime accidents that contribute to the most fatalities are grounding and collision accidents. These two contribute with 93% of the fatalities (IMO, 2008). Collision contributes to 57% and grounding with 36% of the total fatalities.

Knowing that the risk level found in this report is only a part of the total risk, the findings suggest that the total risk level is outside the ALARP region and that measures have to be implemented to continue the cruise traffic.

5.6.1 Crew Risk

In this thesis, the risk that the passengers are exposed to is examined. The risk for crew members has differently defined tolerability criteria for the individual risk (IMO, 2008). The risk level the crew is exposed to is not calculated in this thesis, but it is expected to be in the high/unacceptable region considering the findings in this report.

Chapter 6

Conclusion

6.1 Conclusion

This thesis investigates the grounding risk for cruise ships in Northern Norway during the winter season. A literature review covering case-specific subjects has been performed. Some of these subjects are risk analysis, weather conditions, relevant accidents, emergency preparedness in Northern Norway, and legislation. A BBN model for the grounding accident scenario was developed, and quantified by the use of relevant data and expert judgment from a Delphi process. In addition to developing the model, several risk-reducing measures are proposed and assessed by the model.

The results obtained by the model are a bit high concerning the grounding probability, but considered to be within a reasonable range. The individual risk found is above the upper tolerability limit and the societal (group) risk found is within the ALARP region defined by IMO, 2018 and IMO, 2008. This result indicates that measures should be implemented to reduce the risk.

The proposed measures are assessed with regard to their effect on the grounding probability (preventive) and the number of fatalities (preventive and mitigating). The measure identified with the best risk-reducing effect is weather restrictions.

The thesis only examines the grounding risk, and when the risk level from only one hazard is this high, the total risk will be well above what is tolerable. Based on the findings presented in this report, the risk associated with cruise ship traffic in Northern Norway during winter is too high, and measures to reduce the risk should be realized by the Norwegian authorities to achieve a tolerable risk level.

It is recommended that future research on the model and the proposed measures in continuation of this report is performed to validate the model and verify the results.

6.2 Recommendations

The results of this thesis are considered to be significantly influenced by the numerous assumptions made. Several efforts can be done to improve the work done in this thesis. The BBN model as a whole could benefit from a slight increase in nodes to model relevant aspects of a grounding accident with more detail. Specifically, the first part of the model, leading up to the grounding node, could deserve some more detail.

More work on the quantification of some nodes as well as improved quantification of the measures is believed to reduce the uncertainty of the model, and, especially, the results regarding the risk-reducing measures. A thorough validation of the model should be performed, e.g. by the framework proposed by Pitchforth and Mengersen, 2013.

In addition to the actions mentioned above, more work should be performed on the cost estimates of the different measures. This part of the report is devoted the least amount of work because it is not part of the main objective of the thesis. To make a well-informed decision about which of the measures should be implemented, detailed cost calculations must be performed.

References

Accident Investigation Board Norway. (2019). *Interim report 12 November 2019 on the investigation into the loss of propulsion and near grounding of Viking Sky, 23 March 2019.*

Adler, M., & Ziglio, E. (1996). *Gazing into the oracle: The delphi method and its application to social policy and public health.* London: Jessica Kingsley Publishers.

Aven, T. (2013). Practical implications of the new risk perspectives. *Reliability Engineering & System Safety*, *115*, 136–145. doi:https://doi.org/10.1016/j.ress.2013.02.020

Aven, T., & Guikema, S. (2011). Whose uncertainty assessments (probability distributions) does a risk assessment report: The analysts or the experts? *Reliability Engineering & System Safety - RELIAB ENG SYST SAFETY*, *96*, 1257–1262. doi:10.1016/j.ress.2011.05.001

Cruise Lines International Association. (2019). *2018 Global Passenger Report.*

Dalløkken, P. E. (2019). AW101-helikoptrene kan bli tatt i bruk i Norge 20 måneder forsinket. Retrieved May 7, 2020, from https://www.tu.no/artikler/aw101-helikoptrene-kan-bli-tatt-i-bruk-i-norge-20-maneder-forsinket/462636

Dannevig, P., & Harstveit, K. (2019). Klima i Norge. Store norske leksikon. Retrieved February 20, 2020, from http://snl.no/klima_i_Norge

DNV. (2003). FSA Navigation Large Passenger ships.

Dybedal, P. (2018). *Cruisetrafikk til norske havner - oversikt, utvikling og prognoser 2018-2060.* Transportøkonomisk Institutt, TIØ.

Gordon, T. J. (1994). The delphi method. *Futures research methodology*, *2*(3), 1–30.

Hänninen, M., Mazaheri, A., Kujala, P., Montewka, J., Laaksonen, P., Salmiovirta, M., & Klang, M. (2014). Expert elicitation of a navigation service implementation effects on ship groundings and collisions in the gulf of finland. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *228*(1), 19–28. doi:10.1177/1748006X13494533. eprint: https://doi.org/10.1177/1748006X13494533

International Maritime Organization. (n.d.-a). International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978. Retrieved May 15, 2020, from http://www.imo.org/en/OurWork/HumanElement/TrainingCertification/Pages/STCW-Convention.aspx

International Maritime Organization. (n.d.-b). Safety and environmental standards on passenger ships. Retrieved February 18, 2020, from http://www.imo.org/en/MediaCentre/HotTopics/passengership/Pages/default.aspx

International Maritime Organization. (2000). Formal safety assessment, MSC 72/16.

International Maritime Organization. (2007). Guidelines for evacuation analysis for new and existing passenger ships, MSC.1/Circ.1238.

International Maritime Organization. (2008). MSC 85/INF.2. FSA – Cruise ships. Details of the Formal Safety Assessment.

International Maritime Organization. (2017). International Code for Ships Operating in Polar Waters (Polar Code), MEPC 68/21/Add.1.

International Maritime Organization. (2018). Revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process, MSC-MEPC.2/Circ.12/Rev.2.

International Maritime Organization. (2019). International Convention for the Safety of Life at Sea (SOLAS). Retrieved February 18, 2020, from http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx

International Organization for Standardization. (2018). ISO 31000 risk management - guidelines. Retrieved April 12, 2020, from https://www.iso.org/obp/ui/#iso:std:iso:31000:ed-2:v1:en

Jensen, A. B. (2019). Pilotene forteller: Slik gjennomførte vi Viking Sky-evakueringen. Library Catalog: www.tu.no. Retrieved April 24, 2020, from https://www.tu.no/artikler/pilotene-forteller-slik-gjennomforte-vi-viking-sky-evakueringen/463578

Kjærulff, U. B., & Madsen, A. L. (2008). *Bayesian Networks and Influence Diagrams: A Guide to Construction and Analysis*. Springer-Verlag New York.

Luftambulansetjenesten. (n.d.). Våre baser. Retrieved May 7, 2020, from http://www.luftambulanse.no/v%5C%C3%5C%A5re-baser

Mazaheri, A., Montewka, J., & Kujala, P. (2013). Modeling the risk of ship grounding - A literature review from a risk management perspective. *WMU Journal of Maritime Affairs*. doi:10.1007/s13437-013-0056-3

Mazaheri, A., Montewka, J., & Kujala, P. (2016). Towards an evidence-based probabilistic risk model for ship-grounding accidents. *Safety Science*, *86*, 195–210. doi:10.1016/j.ssci.2016.03.002

Ministry of Justice & Public Security. (2019). Regjeringen vil kartlegge utfordringer med cruiseturisme på Svalbard. Press release. Retrieved January 28, 2020, from https://www.regjeringen.no/no/aktuelt/regjeringen-vil-kartlegge-utfordringer-med-cruiseturisme-pa-svalbard/id2671552/

Noer, G. (2018). polart lavtrykk in Store norske leksikon. Store norske leksikon. Retrieved February 20, 2020, from http://snl.no/polart_lavtrykk

Norwegian Armed Forces. (2014). Sea-King. Retrieved May 7, 2020, from https://forsvaret.no/fakta/utstyr/Luft/Sea-King

Norwegian Coastal Administration. (2011a). Compulsory pilotage. Retrieved May 4, 2020, from https://www.kystverket.no/en/EN_Maritime-Services/Pilot-Services/Compulsory-pilotage/

Norwegian Coastal Administration. (2011b). Om sjøtrafikkovervåking. Retrieved May 12, 2020, from https://www.kystverket.no/Maritime-tjenester/Sjotrafikkovervaking/Maritim-trafikkovervaking-langs-norskekysten/

Norwegian Coastal Administration. (2011c). The Vardø Vessel Traffic Service.

Pitchforth, J., & Mengersen, K. (2013). A proposed validation framework for expert elicited bayesian networks. *Expert Systems with Applications*, *40*(1), 162–167. doi:https://doi.org/10.1016/j.eswa.2012.07.026

RAND. (n.d.). Delphi Method. Retrieved March 14, 2020, from https://www.rand.org/topics/delphi-method.html

Rausand, M. (2011). *Risk Assessment - Theory, Methods, and Applicatons*. John Wiley & Sons.

Ruponen, P., Pulkkinen, A., & Laaksonen, J. (2017). A method for breach assessment onboard a damaged passenger ship. *Applied Ocean Research*, *64*, 236–248. doi:10.1016/j.apor.2017.01.017

Sklet, S. (2006). Safety barriers: Definition, classification, and performance. *Journal of Loss Prevention in the Process Industries*, *19*, 494–506.

Skulmoski, G. J., Hartman, F. T., & Krahn, J. (2007). The delphi method for graduate research. *Journal of Information Technology Education: Research*, *6*(1), 1–21. Retrieved from https://www.learntechlib.org/p/111405

Statistisk sentralbyrå. (2019). Statistikkbanken - spesialisthelsetjenesten. 04434: Sykehus og øvrige somatiske institusjoner, etter region, statistikkvariabel og år. Retrieved April 30, 2020, from https://www.ssb.no/statbank/table/04434/

Tikkanen, A. (2019). Costa Concordia disaster. *Encyclopedia Britannica*. Retrieved February 17, 2020, from https://www.britannica.com/event/Costa-Concordia-disaster

Utne, I. B., & Vinnem, J. E. (2019). Innlegg: Risikoen ved cruisetrafikken i nordområdene er uakseptabel. Retrieved February 10, 2020, from https://www.dn.no/innlegg/skipsfart/shipping/cruise/innlegg-risikoen-ved-cruisetrafikken-i-nordomradene-er-uakseptabel/2-1-572696

World Health Organization. (2018). Ageing and health. Retrieved April 28, 2020, from https://www.who.int/news-room/fact-sheets/detail/ageing-and-health

Appendix

A Influence Diagram

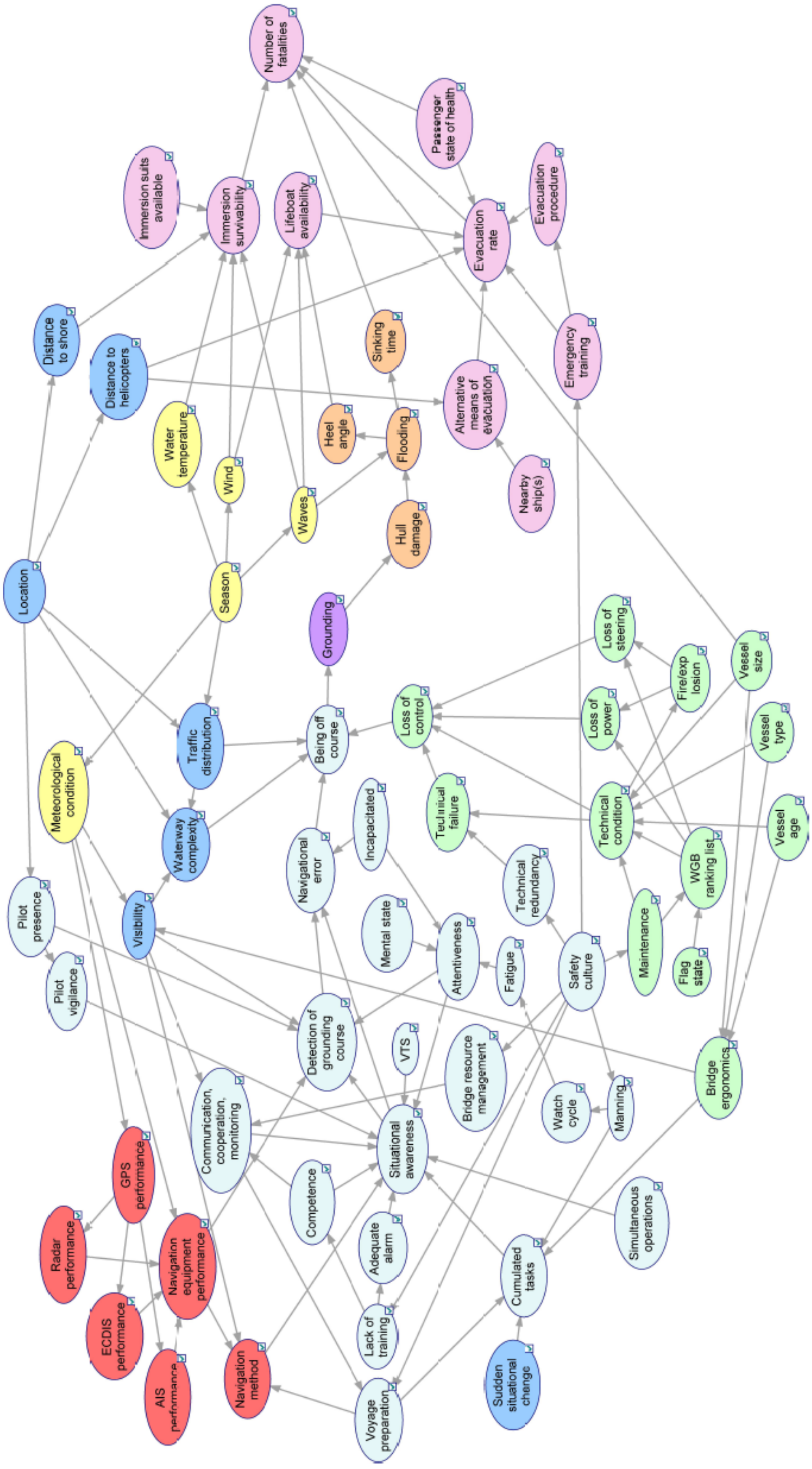


Figure A.1: Influence diagram

B Expert Panel

The expert panel was comprised by the following persons:

- Jan Erik Vinnem
- Ingrid B. Utne
- Martin Hassel
- Terje Rødahl
- Svein Kristiansen
- Stein Haugen
- Emil Aall Dahle

C BBN Model

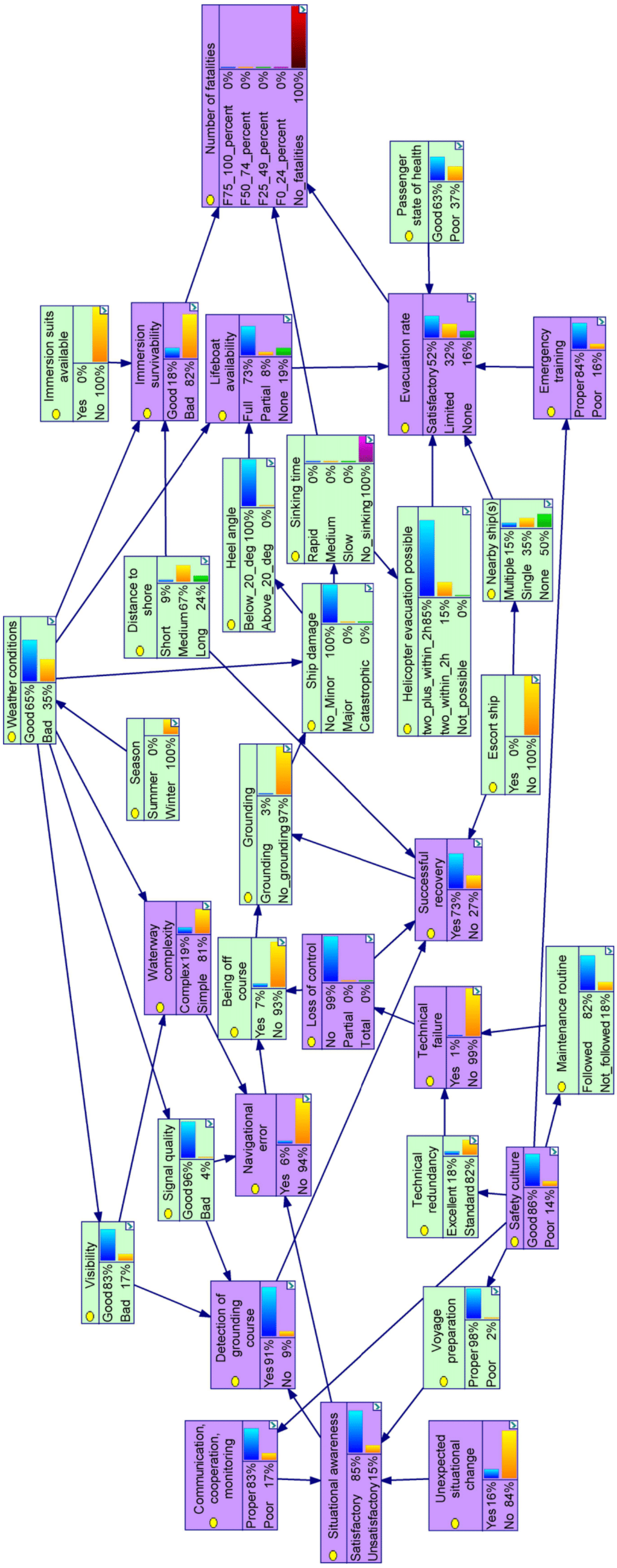


Figure C.1: The developed BBN model. The numbers are rounded to zero decimals, i.e. 0% may actually be 1E-04, 100% may be 99.7%, etc.

Sensitivity Analysis

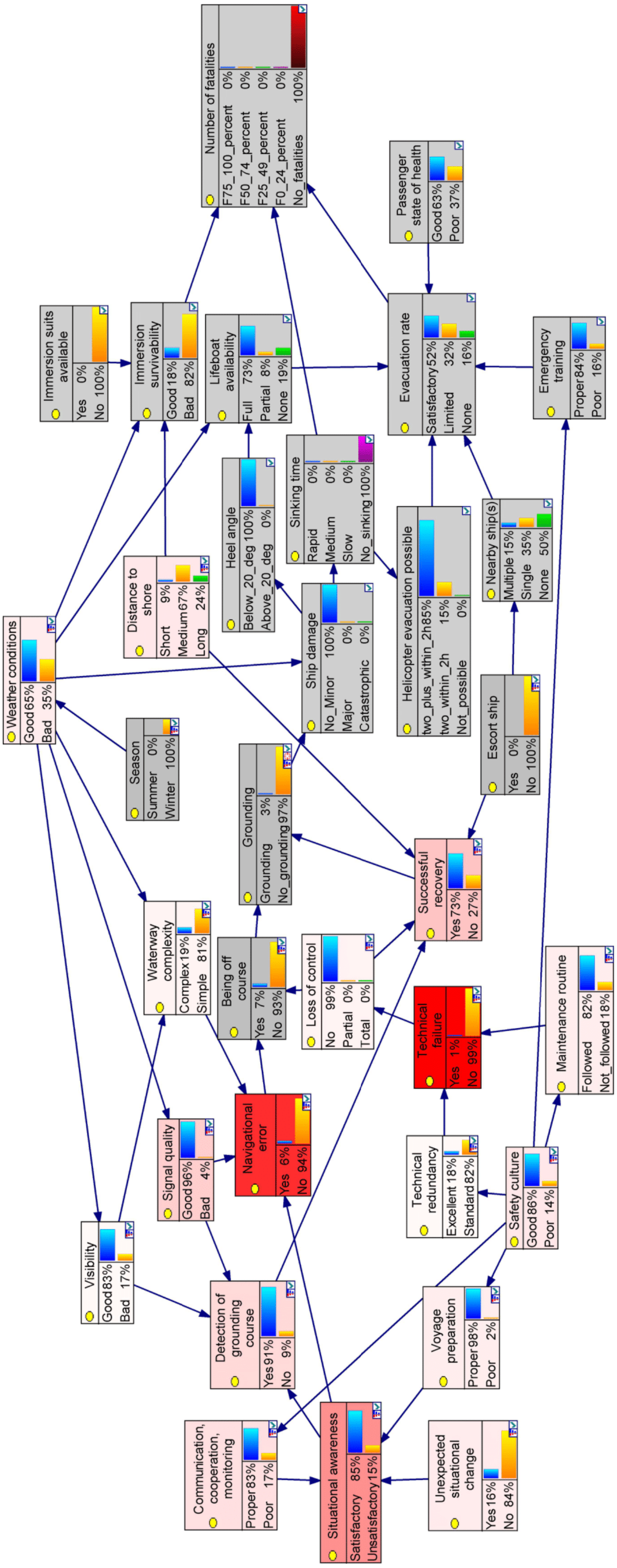


Figure C.2: Sensitivity analysis of the BBN with the node "Grounding" set as target

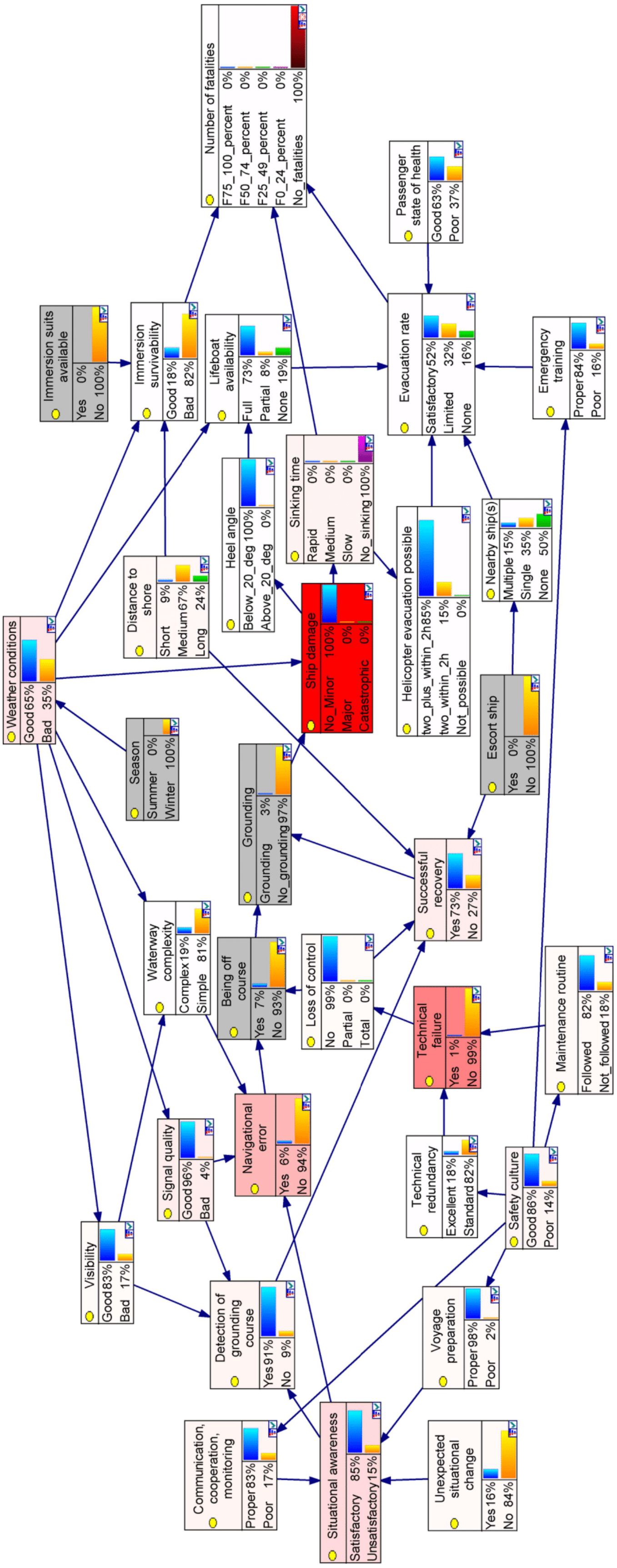


Figure C.3: Sensitivity analysis of the BBN with the node "Number of Fatalities" set as target

D Conditional Probability Tables

D.1 Expert Nodes

Table D.1: Explanation for the symbols used in the following tables

Source	Sign
Expert judgement, ski jumping score	⚒
One expert’s opinion	☢
Logical, from definitions or the nature of the node	☽

Communication, Cooperation & Monitoring

Safety culture	Good	Poor
Proper	0.9⚒	0.41⚒
Poor	0.1⚒	0.59⚒

Unexpected Situational Change

Yes	0.16⚒
No	0.84⚒

Situational Awareness

Communication, cooperation & monitoring	Proper				Poor			
Voyage preparation	Proper		Poor		Proper		Poor	
Unexpected situational change	Yes	No	Yes	No	Yes	No	Yes	No
Satisfactory	0.8	0.9⚒	0.7	0.8	0.6	0.7	0.47⚒	0.6
Unsatisfactory	0.2	0.1⚒	0.3	0.2	0.4	0.3	0.53⚒	0.4

Values used for analysis of the measure "Active surveillance from VTS":

Communication, cooperation & monitoring	Proper				Poor			
Voyage preparation	Proper		Poor		Proper		Poor	
Unexpected situational change	Yes	No	Yes	No	Yes	No	Yes	No
Satisfactory	0.84	0.92	0.76	0.84	0.68	0.76	0.576	0.68
Unsatisfactory	0.16	0.08	0.24	0.16	0.32	0.24	0.424	0.32

Detection of Grounding Course

Visibility	Good				Bad			
Situational awareness	Satisfactory		Unsatisfactory		Satisfactory		Unsatisfactory	
Signal quality	Good	Bad	Good	Bad	Good	Bad	Good	Bad
Yes	0.964⚒	0.85	0.7	0.4	0.95	0.75	0.5	0.27⚒
No	0.036⚒	0.15	0.3	0.6	0.05	0.25	0.5	0.73⚒

Values used for the analysis of the measure "Improved crew familiarity to waterway":

Visibility	Good				Bad			
Situational awareness	Satisfactory		Unsatisfactory		Satisfactory		Unsatisfactory	
Signal quality	Good	Bad	Good	Bad	Good	Bad	Good	Bad
Yes	0.9676	0.865	0.73	0.46	0.955	0.775	0.55	0.343
No	0.0324	0.135	0.27	0.54	0.045	0.225	0.45	0.657

Safety Culture

Good	0.86⚒
Poor	0.14⚒

Values used for the analysis of the measure "Improved safety culture":

Good	0.95
Poor	0.05

Navigational Error

Situational awareness	Satisfactory				Unsatisfactory			
Signal quality	Good		Bad		Good		Bad	
Waterway complexity	Complex	Simple	Complex	Simple	Complex	Simple	Complex	Simple
Yes	0.05	0.026⚒	0.15	0.1	0.25	0.2	0.33⚒	0.3
No	0.95	0.974⚒	0.85	0.9	0.75	0.8	0.67⚒	0.7

Waterway Complexity

Weather conditions	Good		Bad	
Visibility	Good	Bad	Good	Bad
Complex	0.12⚒	0.4	0.2	0.46⚒
Simple	0.88⚒	0.6	0.8	0.54⚒

Technical Failure

Technical redundancy	Excellent		Standard	
Maintenance routine	Followed	Not followed	Followed	Not followed
Yes	0.001☢	0.01	0.005☢	0.03☢
No	0.999☢	0.99	0.995☢	0.97☢

Loss of Control

Technical failure	Yes	No
No	0.3⚒	1
Partial	0.48⚒	0
Total	0.22⚒	0

Successful Recovery

Escort ship	No								
Detection of grounding course	Yes								
Loss of control	No			Partial			Total		
Distance to shore	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long
Yes	0.582	0.77	0.958⚒	0.48⚒	0.635	0.79⚒	0	0	0
No	0.418	0.23	0.042⚒	0.52⚒	0.365	0.21⚒	1☽	1☽	1☽

Escort ship	No								
Detection of grounding course	No								
Loss of control	No			Partial			Total		
Distance to shore	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long
Yes	0	0	0	0	0	0	0	0	0
No	1☽	1☽	1☽	1☽	1☽	1☽	1☽	1☽	1☽

Escort ship	Yes								
Detection of grounding course	Yes								
Loss of control	No			Partial			Total		
Distance to shore	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long
Yes	0.7	0.845	0.99	0.6	0.775	0.95	0.2	0.35	0.5
No	0.3	0.155	0.01	0.4	0.225	0.05	0.8	0.65	0.5

Escort ship	Yes								
Detection of grounding course	No								
Loss of control	No			Partial			Total		
Distance to shore	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long
Yes	0	0	0	0	0	0	0	0	0
No	1☽	1☽	1☽	1☽	1☽	1☽	1☽	1☽	1☽

Lifeboat Availability

Heel angle	Below 20°		Above 20°	
Weather conditions	Good	Bad	Good	Bad
Full	0.93⚒	0.36⚒	0	0
Partial	0.07	0.1⚒	0	0
None	0	0.54⚒	1☽	1☽

Immersion Survivability

Distance to shore	Short				Medium			
Immersion suits available	Yes		No		Yes		No	
Weather conditions	Good	Bad	Good	Bad	Good	Bad	Good	Bad
Good	0.69⚒	0.4	0.5	0.3	0.3	0.15	0.2	0.09
Bad	0.31⚒	0.6	0.5	0.7	0.7	0.85	0.8	0.91

Distance to shore	Long			
Immersion suits available	Yes		No	
Weather conditions	Good	Bad	Good	Bad
Good	0.3	0.15	0.2	0.09⚒
Bad	0.7	0.85	0.8	0.91⚒

Emergency Training

Safety culture	Good	Poor
Proper	0.9⚒	0.5⚒
Poor	0.1⚒	0.5⚒

Evacuation Rate

Lifeboat availability	Full											
Nearby ships	Multiple											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0.84⚒	0.75	0.7	0.6	0.84	0.75	0.7	0.6	0.84	0.75	0.7	0.6
Limited	0.13⚒	0.2	0.2	0.35	0.13	0.2	0.2	0.35	0.13	0.2	0.2	0.35
None	0.03⚒	0.05	0.1	0.05	0.03	0.05	0.1	0.05	0.03	0.05	0.1	0.05

Lifeboat availability	Full											
Nearby ships	Single											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0.77	0.675	0.6	0.525	0.77	0.675	0.6	0.525	0.77	0.675	0.6	0.525
Limited	0.19	0.275	0.3	0.425	0.19	0.275	0.3	0.425	0.19	0.275	0.3	0.425
None	0.04	0.05	0.1	0.05	0.04	0.05	0.1	0.05	0.04	0.05	0.1	0.05

Lifeboat availability	Full											
Nearby ships	None											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0.7	0.6	0.5	0.45	0.7	0.6	0.5	0.45	0.7	0.6	0.5	0.45
Limited	0.25	0.35	0.4	0.5	0.25	0.35	0.4	0.5	0.25	0.35	0.4	0.5
None	0.05	0.05	0.1	0.05	0.05	0.05	0.1	0.05	0.05	0.05	0.1	0.05

Lifeboat availability	Partial											
Nearby ships	Multiple											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0.7	0.5	0.2	0.1	0.7	0.5	0.2	0.1	0.7	0.5	0.2	0.1
Limited	0.2	0.3	0.65	0.6	0.15	0.25	0.6	0.55	0.1	0.2	0.55	0.5
None	0.1	0.2	0.15	0.3	0.15	0.25	0.2	0.35	0.2	0.3	0.25	0.4

Lifeboat availability	Partial											
Nearby ships	Single											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0.425	0.3	0.15	0.075	0.425	0.3	0.15	0.075	0.425	0.3	0.15	0.075
Limited	0.5	0.45	0.625	0.575	0.45	0.4	0.575	0.525	0.4	0.35	0.525	0.475
None	0.075	0.25	0.225	0.35	0.125	0.3	0.275	0.4	0.175	0.35	0.325	0.45

Lifeboat availability	Partial											
Nearby ships	None											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0.15	0.1	0.1	0.05	0.15	0.1	0.1	0.05	0.15	0.1	0.1	0.05
Limited	0.8	0.6	0.6	0.55	0.75	0.55	0.55	0.5	0.7	0.5	0.5	0.45
None	0.05	0.3	0.3	0.4	0.1	0.35	0.35	0.45	0.15	0.4	0.4	0.5

Lifeboat availability	None											
Nearby ships	Multiple											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0	0	0	0	0	0	0	0	0	0	0	0
Limited	0.6	0.5	0.5	0.4	0.55	0.45	0.45	0.35	0.5	0.4	0.4	0.3
None	0.4	0.5	0.5	0.6	0.45	0.55	0.55	0.65	0.5	0.6	0.6	0.7

Lifeboat availability	None											
Nearby ships	Single											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0	0	0	0	0	0	0	0	0	0	0	0
Limited	0.5	0.4	0.4	0.3	0.425	0.35	0.35	0.2875	0.35	0.3	0.3	0.275
None	0.5	0.6	0.6	0.7	0.575	0.65	0.65	0.7125	0.65	0.7	0.7	0.725

Lifeboat availability	None											
Nearby ships	None											
Helicopter evacuation	2+ within 2h				2 within 2h				Not possible			
Emergency training	Proper		Poor		Proper		Poor		Proper		Poor	
Passenger state of health	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Satisfactory	0	0	0	0	0	0	0	0	0	0	0	0⚒
Limited	0.4	0.35	0.35	0.3	0.35	0.3	0.3	0.275	0.3	0.26	0.26	0.24⚒
None	0.6	0.65	0.65	0.7	0.65	0.7	0.7	0.725	0.7	0.74	0.74	0.76⚒

Number of Fatalities

Sinking time	Rapid					
Evacuation rate	Satisfactory		Limited		None	
Immersion survivability	Good	Bad	Good	Bad	Good	Bad
75-100%	0.2	0.25	0.4	0.5	0.55	0.6☢
50-74%	0.2	0.3	0.2	0.3	0.3	0.28☢
25-49%	0.4	0.35	0.3	0.12	0.1	0.1☢
0-24%	0.2	0.1	0.1	0.08	0.05	0.02☢
None	0	0	0	0	0	0

Sinking time	Medium					
Evacuation rate	Satisfactory		Limited		None	
Immersion survivability	Good	Bad	Good	Bad	Good	Bad
75-100%	0	0	0.01	0.05	0.3	0.35
50-74%	0	0	0.05	0.08	0.25	0.25
25-49%	0.05	0.1	0.235	0.2	0.25	0.2
0-24%	0.95	0.9	0.705	0.67	0.2	0.2
None	0	0	0	0	0	0

Sinking time			Slow			
Evacuation rate	Satisfactory		Limited		None	
Immersion survivability	Good	Bad	Good	Bad	Good	Bad
75-100%	0	0	0	0	0	0
50-74%	0	0	0	0	0	0
25-49%	0	0	0	0	0.1	0.2
0-24%	1	1	1	1	0.9	0.8
None	0	0	0	0	0	0

Sinking time			No sinking			
Evacuation rate	Satisfactory		Limited		None	
Immersion survivability	Good	Bad	Good	Bad	Good	Bad
75-100%	0	0	0	0	0	0
50-74%	0	0	0	0	0	0
25-49%	0	0	0	0	0	0
0-24%	0	0	0	0	0	0
None	1☽	1☽	1☽	1☽	1☽	1☽

D.2 Other Nodes

Table D.2: Explanation for the symbols used in the following tables

Source	Sign
(DNV, 2003)	†
(DNV, 2003) with adjustment	♡
Logical, from definitions or the nature of the node	☽

Visibility

Weather conditions	Good	Bad
Good	1†	0.5♡
Bad	0†	0.5♡

Voyage Preparation

Safety culture	Good	Poor
Good	0.99†	0.95†
Bad	0.01†	0.05†

Signal Quality

Weather conditions	Good	Bad
Good	0.999†	0.9♡
Bad	0.001†	0.1♡

Technical Redundancy

Safety culture	Good	Poor
Good	0.2	0.05
Bad	0.8	0.95

Maintenance Routine

Safety culture	Good	Poor
Good	$0.85^{\heartsuit}$	$0.6^{\heartsuit}$
Bad	$0.15^{\heartsuit}$	$0.4^{\heartsuit}$

Being off Course

Loss of control	No		Partial		Total	
Navigational error	Yes	No	Yes	No	Yes	No
Yes	$1^{\rightmoon}$	$0^{\rightmoon}$	$1^{\rightmoon}$	$1^{\rightmoon}$	$1^{\rightmoon}$	$1^{\rightmoon}$
No	$0^{\rightmoon}$	$1^{\rightmoon}$	$0^{\rightmoon}$	$0^{\rightmoon}$	$0^{\rightmoon}$	$0^{\rightmoon}$

Grounding

Being off course	Yes		No	
Successful recovery	Yes	No	Yes	No
Grounding	$0^{\rightmoon}$	$1^{\rightmoon}$	$0^{\rightmoon}$	$0^{\rightmoon}$
No grounding	$1^{\rightmoon}$	$0^{\rightmoon}$	$1^{\rightmoon}$	$1^{\rightmoon}$

Season

Summer	0
Winter	1

Weather Conditions

Season	Summer	Winter
Good	1	0.651
Bad	0	0.349

Values used for the analysis of the measure "Weather restrictions":

Season	Summer	Winter
Good	1	1
Bad	0	0

Distance to Shore

Short	0.0856
Medium	0.6726
Long	0.2418

Values used for the analysis of the measure "Increased sailing distance to shore":

Short	0.07
Medium	0.45
Long	0.48

Ship Damage

Grounding	Grounding		No grounding	
Weather conditions	Good	Bad	Good	Bad
No/Minor	$0.883^{\heartsuit}$	$0.807^{\heartsuit}$	$1^{\rightmoon}$	$1^{\rightmoon}$
Major	$0.108^{\heartsuit}$	$0.164^{\heartsuit}$	$0^{\rightmoon}$	$0^{\rightmoon}$
Catastrophic	$0.009^{\heartsuit}$	$0.029^{\heartsuit}$	$0^{\rightmoon}$	$0^{\rightmoon}$

Heel Angle

Ship damage	No/Minor	Major	Catastrophic
Below 20°	$1^{\rightmoon}$	0.99	0.8
Above 20°	$0^{\rightmoon}$	0.01	0.2

Sinking Time

Ship damage	No/Minor	Major	Catastrophic
Rapid	$0^{\rightmoon}$	$0^{\rightmoon}$	$0.3^{\heartsuit}$
Medium	$0^{\rightmoon}$	$0^{\rightmoon}$	$0.4^{\heartsuit}$
Slow	$0^{\rightmoon}$	$0^{\rightmoon}$	$0.3^{\heartsuit}$
No sinking	$1^{\rightmoon}$	$1^{\rightmoon}$	$0^{\heartsuit}$

Nearby Ships

Escort ship	Yes	No
Multiple	0.5006	0.1514
Single	0.4994	0.3492
None	0	0.4994

Helicopter Evacuation Possible

Sinking time	Rapid	Medium	Slow	No sinking
2+ within 2 hours	$0^{☽}$	0.85	0.85	0.85
2 within 2 hours	$0^{☽}$	0.15	0.15	0.15
Not possible	$1^{☽}$	0	0	0

Values used for the analysis of the measure "Improved helicopter readiness":

Sinking time	Rapid	Medium	Slow	No sinking
2+ within 2 hours	0	1	1	1
2 within 2 hours	0	0	0	0
Not possible	1	0	0	0

Immersion Suits Available

Yes	0
No	1

Values used for the analysis of the measure "Immersion suits available for all passengers":

Yes	1
No	0

Passenger State of Health

Good	0.63
Poor	0.37

Values used for the analysis of the measure "Minimum health requirements for passengers":

Good	0.9
Poor	0.1

Escort Ship

Yes	0
No	1

Values used for the analysis of the measure "Escort ship":

Yes	1
No	0

E f-N Curves

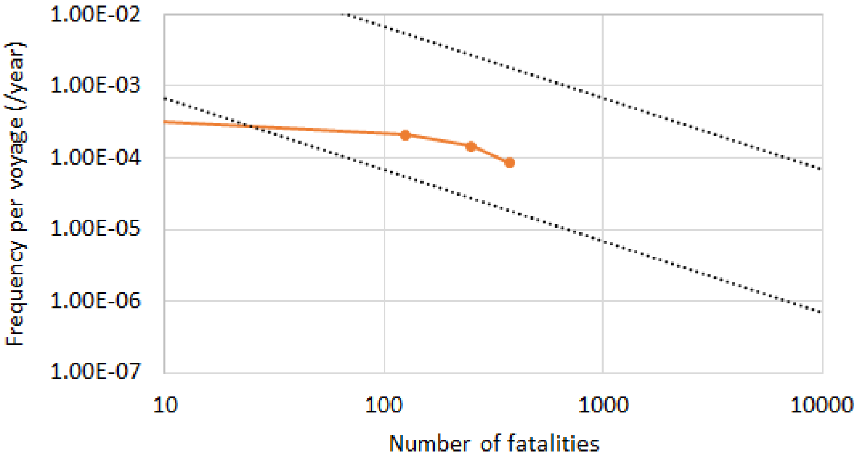


Figure E.1: f-N curve from the model without implementation of measures for a cruise ship with 500 passengers

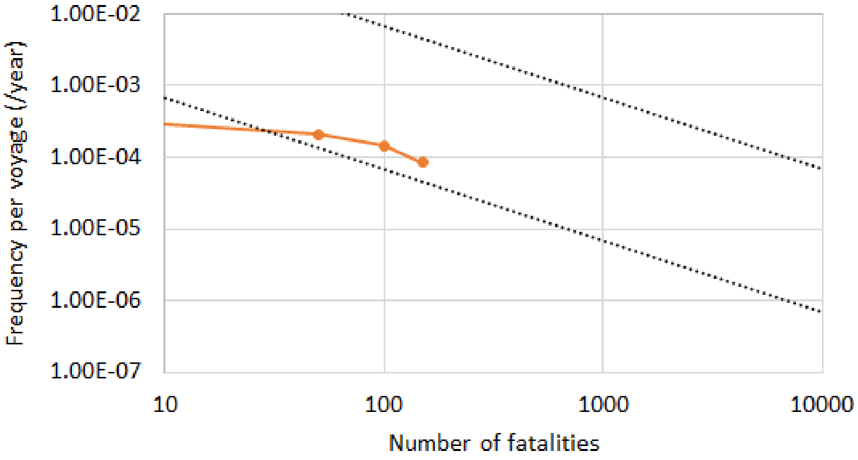


Figure E.2: f-N curve from the model without implementation of measures for a cruise ship with 200 passengers

F Criticality Tables

Grounding

Table F.1: Criticality of the nodes when setting the probability of no grounding to 1 ($P_{(\text{Grounding = No grounding})} = 1$). The strength of knowledge and their change in state from the original value determine each node's (and, for some, state's) criticality.

			Strength of knowledge			
Node	**State**	**Change**	**Node**	**Parental**	**CPT**	**Criticality**
Successful recovery	Either	1.93E-02	S	M	M	H
Grounding	Either	2.59E-02	S	S	M	H
Navigational error	Either	2.17E-02	S	M	S	H
Technical failure	Either	3.42E-03	W	M	M	H
Situational awareness	Either	1.25E-02	S	M	S	H
Being off course	Either	2.49E-02	S	S	S	H
Signal quality	Either	1.74E-03	M	W	M	H
Ship damage	No_Minor	3.88E-03	S	M	M	H
Waterway complexity	Either	1.94E-03	M	M	M	H
Ship damage	Major	3.42E-03	S	M	M	H
Loss of control	No	3.42E-03	M	S	M	H
Detection of grounding course	Either	1.15E-02	S	S	S	H
Maintenance routine	Either	1.69E-03	W	S	M	H
Loss of control	Total	1.86E-03	M	S	M	M
Loss of control	Partial	1.57E-03	M	S	M	M
Safety culture	Either	1.54E-03	M	-	M	M
Communication, cooperation & monitoring	Either	2.92E-03	S	-	M	M
Evacuation rate	Satisfactory	9.51E-04	S	M	W	M
Emergency training	Either	6.15E-04	W	S	W	M
Lifeboat availability	Full	1.29E-03	S	M	M	M
Lifeboat availability	None	1.24E-03	S	M	M	M
Weather conditions	Either	2.14E-03	M	S	S	M
Evacuation rate	None	7.04E-04	S	M	W	M
Distance to shore	Long	1.99E-03	M	-	S	M
Visibility	Either	1.87E-03	M	S	S	M
Technical redundancy	Either	6.17E-04	W	S	M	M
Unexpected change of situation	Either	1.31E-03	M	-	S	M
Distance to shore	Medium	1.02E-03	M	-	S	M
Distance to shore	Short	9.64E-04	M	-	S	M
Ship damage	Catastrophic	4.56E-04	S	M	M	M
Voyage preparation	Either	2.11E-04	M	M	M	M
Evacuation rate	Limited	2.46E-04	S	M	W	M
Heel angle	Either	1.25E-04	W	S	W	M
Sinking time	No sinking	4.56E-04	S	S	M	L
Number of fatalities	None	4.56E-04	S	S	M	L
Helicopter evacuation possible	None	1.37E-04	W	M	S	L

Table F.1 continued from previous page

			Strength of knowledge			
Node	**State**	**Change**	**Node**	**Parental**	**CPT**	**Criticality**
Helicopter evacuation possible	2+ within 2 hours	1.16E-04	W	M	S	L
Number of fatalities	0-24%	2.46E-04	S	S	M	L
Sinking time	Medium	1.82E-04	S	S	M	L
Sinking time	Rapid	1.37E-04	S	S	M	L
Sinking time	Slow	1.37E-04	S	S	M	L
Lifeboat availability	Partial	5.31E-05	S	M	M	L
Number of fatalities	75-100%	8.56E-05	S	S	M	L
Number of fatalities	25-49%	6.61E-05	S	S	M	L
Helicopter evacuation possible	2 within 2 hours	2.05E-05	W	M	S	L
Number of fatalities	50-74%	5.89E-05	S	S	M	L
Immersion survivability	Either	4.00E-06	M	M	W	L
Season	Either	0.00E+00	S	-	S	L
Escort ship	Either	0.00E+00	M	-	S	L
Nearby ships	Multiple	0.00E+00	W	S	M	L
Nearby ships	Single	0.00E+00	W	S	M	L
Nearby ships	None	0.00E+00	W	S	M	L
Immersion suits available	Either	0.00E+00	W	-	S	L
Passenger state of health	Either	0.00E+00	W	-	S	L

Number of Fatalities

Table F.2: Criticality of the nodes when setting the probability of 0 number of fatalities to 1 ($P_{(\text{Number of fatalities = None})} = 1$). The strength of knowledge and their change in state from the original value determine each node's (and, for some, state's) criticality.

			Strength of knowledge			
Node	**State**	**Change**	**Node**	**Parental**	**CPT**	**Criticality**
Ship damage	Catastrophic	4.56E-04	S	M	M	H
Ship damage	No_Minor	4.55E-04	S	M	M	H
Successful recovery	Either	3.31E-04	S	M	M	H
Sinking time	No sinking	4.56E-04	S	S	M	M
Number of fatalities	None	4.56E-04	S	S	M	M
Grounding	Either	4.45E-04	S	S	M	M
Helicopter evacuation possible	None	1.37E-04	W	M	S	M
Heel angle	Either	9.12E-05	W	S	W	M
Navigational error	Either	3.77E-04	S	M	S	M
Signal quality	Either	5.89E-05	M	W	M	M
Helicopter evacuation possible	2+ within 2 hours	1.16E-04	W	M	S	M
Technical failure	Either	5.35E-05	W	M	M	M
Evacuation rate	Satisfactory	9.85E-05	S	M	W	M
Lifeboat availability	None	1.45E-04	S	M	M	M
Lifeboat availability	Full	1.41E-04	S	M	M	M
Waterway complexity	Either	6.55E-05	M	M	M	M
Evacuation rate	None	8.47E-05	S	M	W	M
Number of fatalities	0-24%	2.46E-04	S	S	M	M
Being off course	Either	4.26E-04	S	S	S	M
Situational awareness	Either	2.12E-04	S	M	S	M
Sinking time	Medium	1.82E-04	S	S	M	M
Weather conditions	Either	1.64E-04	M	S	S	M
Sinking time	Rapid	1.37E-04	S	S	M	M
Sinking time	Slow	1.37E-04	S	S	M	M
Loss of control	No	5.36E-05	M	S	M	M
Detection of grounding course	Either	2.11E-04	S	S	S	M
Visibility	Either	1.04E-04	M	S	S	M
Immersion survivability	Either	1.56E-05	M	M	W	M
Number of fatalities	75-100%	8.56E-05	S	S	M	M
Maintenance routine	Either	2.68E-05	W	S	M	M
Number of fatalities	25-49%	6.61E-05	S	S	M	M
Helicopter evacuation possible	2 within 2 hours	2.05E-05	W	M	S	M
Number of fatalities	50-74%	5.89E-05	S	S	M	M
Loss of control	Total	2.89E-05	M	S	M	M
Safety culture	Either	2.56E-05	M	-	M	M
Loss of control	Partial	2.47E-05	M	S	M	L
Communication, cooperation & monitoring	Either	4.92E-05	S	-	M	L

Table F.2 continued from previous page

Node	State	Change	Strength of knowledge Node	Parental	CPT	Criticality
Emergency training	Either	1.02E-05	W	S	W	L
Evacuation rate	Limited	1.38E-05	S	M	W	L
Distance to shore	Long	3.20E-05	M	-	S	L
Technical redundancy	Either	9.88E-06	W	S	M	L
Unexpected change of situation	Either	2.21E-05	M	-	S	L
Distance to shore	Medium	1.65E-05	M	-	S	L
Distance to shore	Short	1.55E-05	M	-	S	L
Voyage preparation	Either	3.56E-06	M	M	M	L
Lifeboat availability	Partial	3.41E-06	S	M	M	L
Ship damage	Major	1.56E-06	S	M	M	L
Season	Either	0.00E+00	S	-	S	L
Escort ship	Either	0.00E+00	M	-	S	L
Nearby ships	Multiple	0.00E+00	W	S	M	L
Nearby ships	Single	0.00E+00	W	S	M	L
Nearby ships	None	0.00E+00	W	S	M	L
Immersion suits available	Either	0.00E+00	W	-	S	L
Passenger state of health	Either	0.00E+00	W	-	S	L

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