An allision risk model for passing vessels and offshore oil and gas installations on the Norwegian Continental Shelf

Martin Hassel, Ingrid Bouwer Utne and Jan Erik Vinnem, Dept. Marine Technology, NTNU

Abstract :

This article presents a new risk model for estimating the probability of allision risk (the impact between a ship under way and a stationary installation) from passing vessels on the Norwegian Continental Shelf (NCS). Offshore petroleum operators on the NCS are required by the Norwegian Petroleum Safety Authority (PSA) to perform risk assessments to estimate the probability of impacts between ships and offshore installations, both for field related and passing (merchant) vessels. This has typically been done using the aging industry standard COLLIDE risk model, but this article presents a new risk model based on a Bayesian Belief Network (BBN) that can replace the old COLLIDE model for passing vessels. The new risk model incorporates a wider range of risk influencing factors (RIFs) and enables a holistic and detailed analysis of risk factors, barrier elements and dependencies. Even though the risk of allision with passing vessels is very small, the potential consequences can be critical. The new risk model is more transparent and provides a better understanding of the mechanisms behind allision risk calculations. The results from the new model are aligned with industry expectations, indicating an overall satisfactory performance. The article discusses several key elements, such as the use of expert judgement to estimate RIFs when no empirical data is available, model sensitivity, and a comparative assessment of the new risk model to the old COLLIDE model.

Keywords: Risk Analysis; Risk Model, Allision; Passing Vessels; Collision; COLLIDE; Bayesian Belief Network

ABBREVIATIONS

AIS – Automatic identification system
BBN – Bayesian belief network
CPT – Conditional probability table
ECDIS – Electronic chart display and information system
FSA – Formal safety assessments
GPS – Global positioning system
HEP – Human error probability
HOFs – Human and organizational factors
NCS – Norwegian continental shelf
OIM – Offshore installation manager
OOW – Officer on watch
PSA – Petroleum Safety Authority Norway
RIF – Risk influencing factor
SBV – Standby vessel
TCPA – Time to closest point of approach

1 INTRODUCTION

The risk of a ship hitting an offshore oil and gas installation (an allision) is one of the accident scenarios with the biggest potential consequences from the installation's point of view. Allision risk is constituted by potential impacts from field related/visiting vessels and passing (merchant) vessels. The Petroleum Safety Authority Norway (PSA) raised a concern that risk assessments and the risk posed by passing merchant ships in transit might be conservative in existing risk assessments [1, 2], which means that more knowledge is necessary to determine the allision risk related to passing traffic. The term "allision" is distinguished from "collision" in that it refers to an impact between a ship under power and a stationary manmade surface object, such as an offshore installation. Collision is typically an impact between two moving ships and is outside the scope of this paper.

During the last 50 years of petroleum exploration on the NCS and more than a couple of thousand accumulated installation years, only two incidents or allisions involving non-field-related or passing vessels impacting with Norwegian installations have been recorded. [3] In 1988, a submerged West German submarine allided with the steel jacket platform Oseberg B located about 140 km west-northwest of Bergen. [4] In 1995, a small German vessel, the 628 GT general cargo ship MS Reint, came head-on towards the Norwegian operated Norpipe H7 steel jacket platform on the German Continental Shelf. No lives were lost, and the ship only caused minor damage; nevertheless, the incident could just as easily have caused a major accident if the ship had hit one of the two nearby exposed risers. [3]

On the UK Continental Shelf, there have been more incidents with major accident potential, for example, in 1967 (cargo vessel Gisna/rig Sea Quest), in 1983 (cargo vessel Marag Mette/platform Viking DD), in 1985 (cargo vessel La Paloma/platform Kinsale B), 1988 (cargo vessel Irving Forest/rig Glomar Labrador 1), in 2002 (fishing vessel Marbella/platform Viking

BD), and in 2007 (cargo vessel MV Jork/platform Viking E). A more recent allision occurred in the Dutch Sector of the North Sea in 2016 [5], when an oil and chemical tanker hit an unmanned and out-of-service platform, which caused damage to both the tanker and the platform, with no injuries or pollution. Both Norwegian and UK authorities define allision as a major accident hazard due to the potentially severe consequences. [6, 7]

Field-related or visiting vessels are considered a more frequent threat to installations than passing vessels, and more research efforts have so far focused on analysing risk related to the former. The PSA registered 21 collisions between facilities and field-related (visiting) vessels on the NCS from 2006-2018, and one in 2019. [2, 8] Passing vessels, however, have higher speed and may therefore cause more severe damage to the platform in an allision. Visiting vessels, if they have been approved for approach, would often have lower speed in vicinity of the platform. Therefore, it is necessary to have different analyses and risk models for the two allision scenarios with offshore installations, i.e., (i) field related/ visiting vessels, and (ii) passing vessels, which is the background for the work presented in this paper.

The main objective of this paper is to present the new risk model, which enables the quantification of allision risk of passing vessels with offshore installations (Scenario ii). The focus is on offshore oil and gas installations on the NCS. The industry focus has shifted from merely calculating a quantitative value of the risk, to a wish for a more holistic understanding of the various risk influencing factors (RIFs), their interrelationship, and the overall risk picture. Modelling the impacts between field-related vessels and offshore installations (Scenario i) is not part of the scope of work for this article. Several other researchers and industry actors have looked more closely at field-related vessels and their activity. [9, 10]

The remainder of the paper is structured as follows: Section 2 describes the state-of-the-art relevant to the work. Section 3 presents the methodology. Section 4 shows the results of the quantification process and model tests, while further analysis is found in Section 5. Section 6 discusses the model and results, while the conclusion is found in Section 7.

2 STATE – OF – THE – ART

Traditionally, probabilistic risk assessments in the marine domain have used tools, such as fault and event trees; see, for example, Fowler & Sørgård [11] and Rosqvist et al. [12]. In recent years, the use of different types of Bayesian Belief Networks (BBNs) has become increasingly popular for marine applications; the most relevant for the present work found in the research on the risk of impact between service vessels and offshore wind turbines [13], and in the work focused on bridge pylons. [14]

A Formal Safety Assessments (FSA) study of large passenger ships conducted by DNV [15] used BBNs to estimate the probability of failure and the consequences given a critical course towards shore or other obstacles. Other networks were used with only slight modifications for tankers and bulk carriers regarding groundings, in an FSA of electronic chart display and information systems (ECDIS). [16] Povel [17] used a BBN to show how an Automatic Identification System (AIS) influences how the Officer On Watch (OOW) is made aware of a potential allision situation. His work was based on Lützen & Friis-Hansen's [18] BBN for OOW reaction time. Trucco et al. [19] modelled a Maritime Transport System using a BBN, and it was used in a case study where they quantified the human and organizational factors (HOFs) in a risk analysis looking at the design of a High-Speed Craft. It primarily looked at the risk of ship collisions in open waters, but the approach allowed for the identification of probabilistic correlations between a collision accident and the BBN model of the operational and organisational conditions. Norrington et al. [20] used BBNs to model the reliability of search and rescue operations in the UK. Kujala et al. [21] have used BBNs to calculate the probability of error situations in marine traffic in the Gulf of Finland. Hänninen & Kujala [22] have also used BBNs in a similar fashion, to model the causation for collision probability for an area in the Gulf of Finland with crossing traffic.

Martins & Maturana [23] presented a BBN-based methodology to analyse human reliability and how this method applies to the operation of an oil tanker, regarding the risk of collision accidents, while [24] have developed a probabilistic model for accidental cargo oil outflow from tankers after ship collisions using a BBN. Montewka et al. [25] used a BBN to develop a risk analysis framework for maritime transportation systems. They chose a BBN as it allowed them instant propagation of knowledge through the framework. Akhtar & Utne [26] used BBN methodology to model the effects of fatigue on the risk of ships grounding. Thieme et al. [27] provided an extensive review over recent collision and grounding risk models. Even though several of the above-mentioned works are interesting and useful, and BBNs have been developed for both ship collisions and groundings, none of them focuses on the context of allision risk.

The allision risk models commonly used in industry to calculate the probability of ship-installation impacts typically have two steps; (i) to determine the potential risk without considering risk reduction, (ii) introducing different types of risk reducing factors (e.g., the effects of evasive/corrective action). The most commonly known risk models are:

- COAST (Computer Assisted Ship Traffic Model) / COLLIDE [28 - 30]
- CRASH / MARCS (Computerised Risk Assessment of Shipping Hazards / Marine Accident Risk Calculation System) [31, 32]
- COLLRISK [33, 34]
- SOCRA / SAMSON (Ship Offshore platform Collision Risk Assessment / Safety Assessment [36 - 37]
- COLWT [38, 39]

The most commonly used models on the NCS are COLLIDE, CRASH, and COLLRISK, which use information about shipping lanes gathered from the Automatic Identification System (AIS) to assess the probability of impacts between passing vessels and offshore installations. The new risk model presented in this paper provides an alternative to the aging COLLIDE model, which has been the industry standard for the last two decades. [28, 29]. In [28], challenges with COLLIDE were discussed. The current paper presents the quantification of the new risk model in terms of a Bayesian Belief Network (BBN), and includes a comparison to the old COLLIDE model. The goal of the new allision risk model is to enable a thorough understanding of which barriers influence the probability of allision the most, how these barriers are connected to other RIFs, and to better reflect the intuitive expectations of the authorities and industry actors. New barriers, technology and procedures are relevant today, and the new allision risk model enables a more dynamic and holistic view of relevant RIFs than COLLIDE.

3 METHODOLOGY

3.1. Scope of model

The new model presented in this paper is focused on allision risk for passing vessels and optimized for use on the NCS. It does not cover ship–ship collisions or specialized navigation, for example, in pack-ice or inshore areas. The model provides a sort of bird's eye view of an allision scenario, where the installation and vessel will most likely have very different views on a developing situation. From the installation's point of view, any vessel with course line inside the safety zone (radius of 500m from installation) represents a possible threat, while the passing vessels may be ignorant of or indifferent to the installation's existence and operations and regard the installation as yet another obstacle in the ocean, along its path.

3.2. Bayesian Belief Networks

BBN is a framework for reasoning under uncertainty and is widely used for representing uncertain knowledge. [19] BBN makes complex problem analysis perspicuous since interrelations and dependencies of the model parameters become visible. [40] For details on

BBN, see, e.g., Rausand. [41] Compared to other methodologies and models, BBNs are acknowledged for their ability to combine empirical data with expert knowledge, their handling of missing data, over-fitting, and their ability to present causal relationships while also providing an easily understandable graphical representation. [42, 43] On the other hand, the relatively high number of probability parameters even in small and simple models and the discrete variables have been claimed to be drawbacks of BBNs. [43-45] All of these general pros and cons apply to maritime accident prevention BBN models as well. [46]

Stakeholders prefer tangible output, such as a calculation of the impact probability or the ability to quantify and rank RIFs, to be used as valuable input to barrier management. Quantifying RIFs when little or no data exists can be a difficult task, even for subject matter experts, so the elicitation of expert judgements for a selection of nodes in the model was done using a Delphi process.

3.3. Workshops with subject matter experts

During the first months of 2016, a panel of eight experts got together for a series of workshops. The experts have experience in risk assessments, allision and collision risk assessments ranging from 5-25 years. Several of the expert panel are professors, and more than three quarters of the panel have research experience om the area. All the experts have good knowledge of the industry practice within this domain, and three experts have extensive practical experience with ship navigation. The expert panel age range is from 40-60 and consisted of one woman and seven men.

The experts were not significantly influenced by groupthink, as described by Janis [47] or Peterson et al. [47], but peers' argumentation did seemingly result in stronger personal beliefs at times, aligned with observations by Makkonen et al. [49] Academic training and knowledge about predictions, bias and other relevant mechanics for the estimation process seemed to make the experts more confident than those with a more experience-based background. [50]

The initial process was based on the COLLIDE model, and other known RIFs typically included in collision risk assessments. Øien [51] defines a RIF as *"an aspect (event/condition) of a system or an activity that affects the risk level of this system/activity"*. Throughout the development process of the new allision risk model, reasons for nodes and their position/links were justified through discussion. The aim was to develop a graphical representation of all the key factors that affect the probability of an allision between a passing vessel and an offshore (petroleum) installation. Quantifying RIFs when little or no data exists can be a difficult task, even for subject matter experts, so the elicitation of expert judgements for a selection of nodes in the model was done using a Delphi process.

The Delphi method was developed in the 1950s by the RAND Corporation and provides feedback on the "group response" after a group of experts individually and anonymously reply to a set of questions. The process repeats itself for several iterations, in order to achieve some form of convergence of opinion. [52] Today, the Delphi method is used to structure a communication process in a group, so that a group of individuals, as a whole, can deal effectively with complex problems. [53] The method is an iterative process where the experts typically answer questionnaires individually first, then meet the rest of the group to discuss their estimates, explain their thinking and answers, before re-evaluating and answering again.

Critics claim that the Delphi method is prone to peer-pressure and is much too time-consuming, as the preparation and data processing can take quite some time. [54] However, empirical studies by Rowe et al. [55] found that while non-experts tended to regress towards the mean, experts were less inclined to change their assessments over time, thereby reducing the overall variance over (Delphi) rounds. [56]

The method is, however, well suited when bringing together experts with different backgrounds, and through the process of reaching consensus is able to draw on the full range of experience and feedback of the expert group. In this way, initial assessments may be naturally modified when experts are made aware of previously unknown influencing factors or elements. The method is a way of synthesizing expert judgement in such a way that one is left with an aggregate that represents a composite judgement based on the expertise of all the participants. [57] Full consensus is not a requirement as the real aim is to facilitate a structured group communication process, but naturally forming consensus is an indicator of low levels of uncertainty, which is good. Adaptations to the original stringent regime of rounds of questionnaires and feedback, making a more continuous and personal group dynamic, do not degrade the empirical results. [58]

Even though the process is based on the prediction or guesswork of a group of experts, the aggregated estimations of experts can often provide useful data suitable for an intended purpose. If expert opinions are the only available source of information, the Delphi method is a particularly useful forecasting tool for events that do not happen very often. Studies have shown that it is important to select experts with widely differing backgrounds and knowledge, operating with the most distinct information possible, while still being relevant subject matter experts. This reduces the conditional pairwise correlation and improves accuracy. [59, 60]

4 THE ALLISION RISK MODEL

The quantitative risk model contains 38 nodes, of which 15 were subject to the quantification process by the expert panel, as the remaining nodes are either quantifiable through available data or determined by stakeholders, such as oil and gas companies. For example, for any specific case, the operator of the installation an allision risk analysis is being carried out for, determines variables/nodes such as the type of installation, type of traffic surveillance implemented, the presence and details of standby vessel or helicopter and other similar factors/nodes. The state of many other nodes is known through standard data sources, such as AIS data, vessel specifics and historical weather data. Figure 1 shows the allision risk model with the nodes quantified by the expert panel, in blue[1].

[1] Details about the BBN model can be provided by contacting the co-author Martin Hassel.

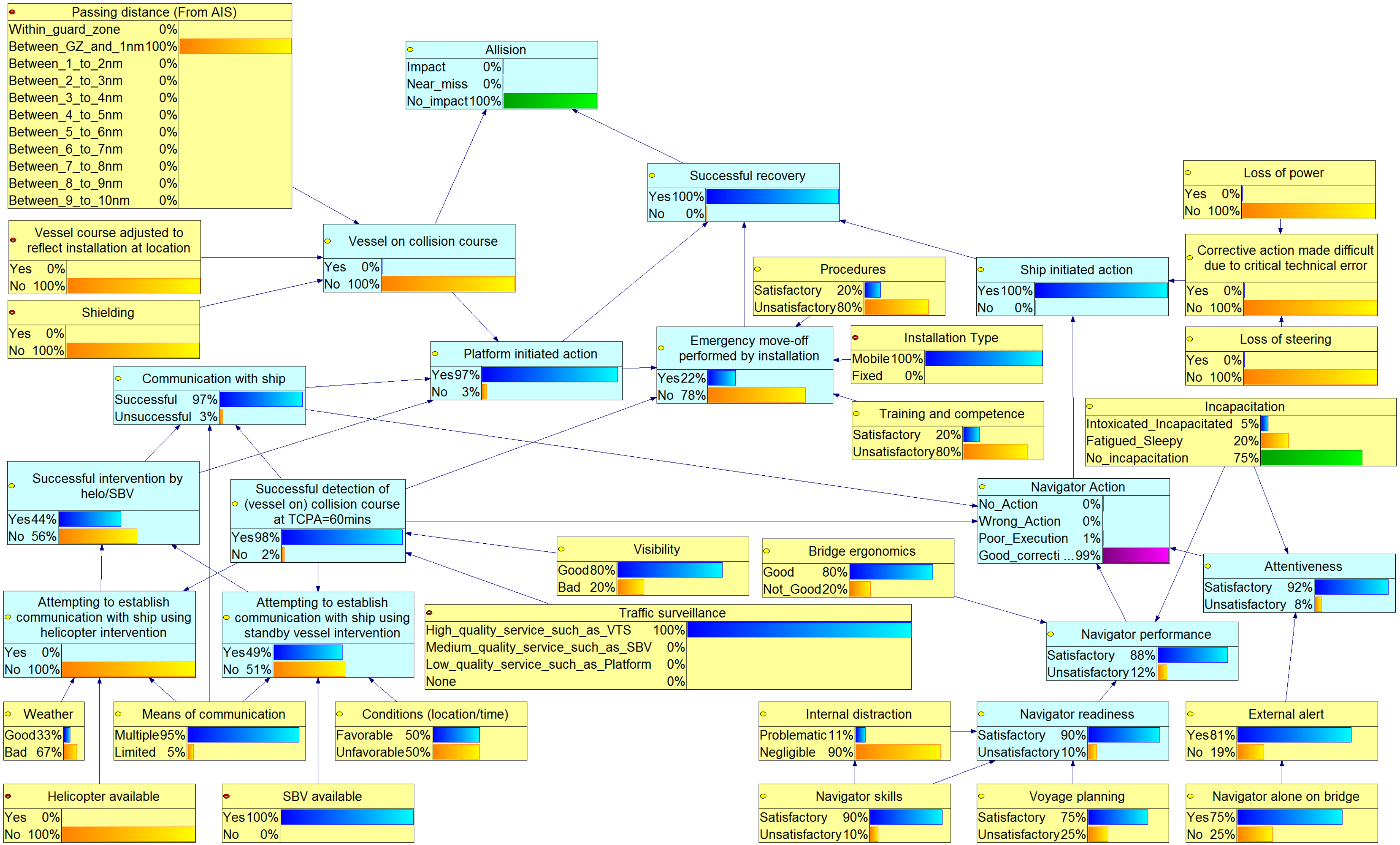

Figure 1 – The quantified allision risk model, showing nodes quantified by expert panel, in blue. (Values rounded to 0 decimals, meaning 0% may very well be 1.0E-04 and 100% may be 99.9% etc.)

The different states of the nodes quantified by the expert panel are shown in Table 1.

Table 1 – Node-states, with definition/description

States	Allision	Adapted/based on – references
Yes	Physical impact between ship and installation	[61]
Near-miss/No	No physical impact between ship and installation, but passing distance less/more than double the width of the installation	
	Successful recovery	
Yes/No	Action to avoid allision has been/has not been carried out successfully	[62, 63]
	Vessel on collision course (at distance 10 nautical miles [nm] or less)	
Yes/No	Vessel course intersects/does not intersect installation guard zone	[62]
	Ship initiated action	
Yes/No	Vessel initiates/does not initiate action to avoid impact	[62]
	Communication established with ship on collision course	
Successful/ Unsuccessful	Attempts to establish communications with ship on collision course successful/ unsuccessful at TCPA (Time to Closest Point of Approach) of 60 minutes	[62, 63]
	Platform initiated action	
Yes/No	Installation has/has not initiated action towards ship on collision course at TCPA of 60 minutes	[3]
	Emergency move-off performed	
Yes/No	Installation has/has not performed an emergency move-off	[30]
	Successful intervention by helicopter / standby-vessel (SBV)	
Yes/No	SBV or helicopter has intercepted vessel on collision course, and established contact with vessel / intervention with vessel on collision course has not been performed or has been unsuccessful	[30]
	Successful detection of vessel on collision course at TCPA=60mins	
Yes/No	Vessel on collision course detected/not detected by installation or third party responsible for traffic surveillance, at TCPA of 60 minutes or more	[30, 62-66]
	Navigator action	
No action	OOW (Officer On Watch) takes no specific action	[67, 68]

Wrong action	OOW performs an action to avoid impact, but the action is wrong for the situation at hand	
Poor execution	OOW performs an action to avoid impact, but the execution is poor, limiting the resulting effect	
Good corrective action	OOW takes appropriate action to avoid impact	
	Attempting to establish communication with ship on collision course by means of helicopter intervention	
Yes/No	Helicopter attempting to establish communication with vessel on collision course by intercepting vessel/ No interception attempt by helicopter	[30]
	Attempting to establish communication with ship on collision course by means of SBV intervention	
Yes/No	SBV attempting to establish communication with vessel on collision course by intercepting vessel / No interception attempt by SBV	[30]
	Navigator performance	
Satisfactory/ Unsatisfactory	OOW performance in accordance with standard requirements and expectations (satisfactory performance level)	[26, 62, 68, 69]
	OOW performance not in accordance with standard requirements and expectations (unsatisfactory performance level)	
	Navigator attentiveness	
Satisfactory/ Unsatisfactory	OOW attentiveness in accordance/not in accordance with standard requirements and expectations	[26, 68, 70]
	Navigator readiness	
Satisfactory/ Unsatisfactory	OOW readiness in accordance/not in accordance with standard requirements and expectations	[68, 71]

The large offshore installations in the North Sea and associated waters need a long period to prepare for and carry out evacuation. They will start to prepare for production shutdown, trying to establish radio contact with the vessel and mustering of personnel at an early stage. Some installations use 50 minutes, others use 60 minutes. The model assumes the conservative value, 60 minutes, prior to possible collision, and assumes start of lifeboat launching about 30 minutes prior to the possible collision [72].

The nodes described in Table 1 were identified from the literature and from COLLIDE. These nodes were presented to the expert panel, and through the iterative

Delphi process the results were elicited. Table 2 shows the average values elicited by the expert panel, for the most positive state and most negative state for each node that was quantified. The expert panel was relatively aligned for the most part, providing values with a satisfactory degree of consensus (determined as “high” in Table 2), where the experts were all in the same spectrum of the scale, with answers ranging from 70% to 90%, for example, or 90% to 100%. Three nodes, "Communication with ship", "Emergency move-off" and "Navigator action", split the expert panel (marked “low” in Table 2), with no consensus reached, even after multiple rounds and hearing peer arguments as to why their estimates were what they were. Values ranged from 20% to 70% in one case and in another case had the panel polarized with half the experts leaning towards one end of the scale, with the other half leaning towards the opposite end of the scale. The final quantification was done based on an evaluation of the similarity of the values, how the experts had understood the scenarios, and how well that aligned with the intention of the questionnaire. A sensitivity analysis was also performed to investigate how these would affect the final node. These results are further discussed in Section 6.

Table 2 – Quantification by expert panel

Node	Probability value of max positive state (panel average)	Probability value of max negative state (panel average)	Degree of consensus (high/low)
Allision	0.0000	0.1000	High
Successful recovery	0.9975	0.0000	High
Vessel on collision course	0.0050	0.0500	High
Ship initiated action	0.9995	0.0005	High
Communication with ship	0.9200	0.4975	Low
Platform initiated action	0.0028	0.5875	High
Emergency move-off performed by installation	0.5750	0.0165	Low
Successful intervention by helicopter/SBV	0.9350	0.0125	High
Successful detection of vessel on collision course at TCPA=60 min	0.9800	0.0050	High
Navigator action	0.9640	0.1620	Low
Attempting to establish communication with ship using helicopter intervention	0.8580	0.4800	High
Attempting to establish communication with ship using SBV intervention	0.9460	0.7625	High
Navigator performance	0.9640	0.1620	High
Attentiveness	0.9658	0.2220	High
Navigator readiness	0.9640	0.2360	High

5 ANALYSIS OF THE MODEL AND VALIDATION

5.1. Sensitivity

The BBN model is highly sensitive to the passing distance and probability of a vessel being on a collision course. All the nodes (blue in Figure 1) that have been quantified by the expert panel have been tested to see how much the final result is affected by setting the node to the maximum positive effect or maximum negative effect (1 or 0). This is important information, as a high level of uncertainty in the quantification process may not affect the result too much, if the overall result is not very sensitive to extreme values of the node. However, nodes that significantly influence the end result should be the target of focussed efforts in order to minimize uncertainty.

The node with the greatest effect on the end result is the node "vessel on collision course", which makes the probability of allision (end node) worse by a power of two, or better by making the end result zero. The second node that may influence the allision probability significantly is the node "passing distance". This node is one of the parent nodes of the node "vessel on collision course» and is thus strongly connected. It can change the end result negatively by one power, or positively by a power of six.

The two above-mentioned nodes have a significantly higher degree of influence over the end result compared to the other nodes, as shown in Figure 2. The dotted line, which represents the baseline, is taken from an actual dataset, where most risk factors are relatively favourable. This means that most nodes will have a bigger relative change from the baseline when turned to their most negative states, compared to being turned to their most positive states. Some nodes, such as the node "traffic surveillance", are already in their maximum positive state for the baseline calculation and can thus only become more negative. Figure 2 shows, for example, that the node “emergency move-off” that had the expert panel divided is amongst the least sensitive nodes, meaning that the end result will only be marginally affected by this node being set to maximum (1) or minimum (0).

A sensitivity analysis is provided in Figure 3, which shows node changes most in the sensitivity analysis. It is related to Figure 1 but shows the result more visually. The red nodes change most, white ones least. The grey nodes are irrelevant.

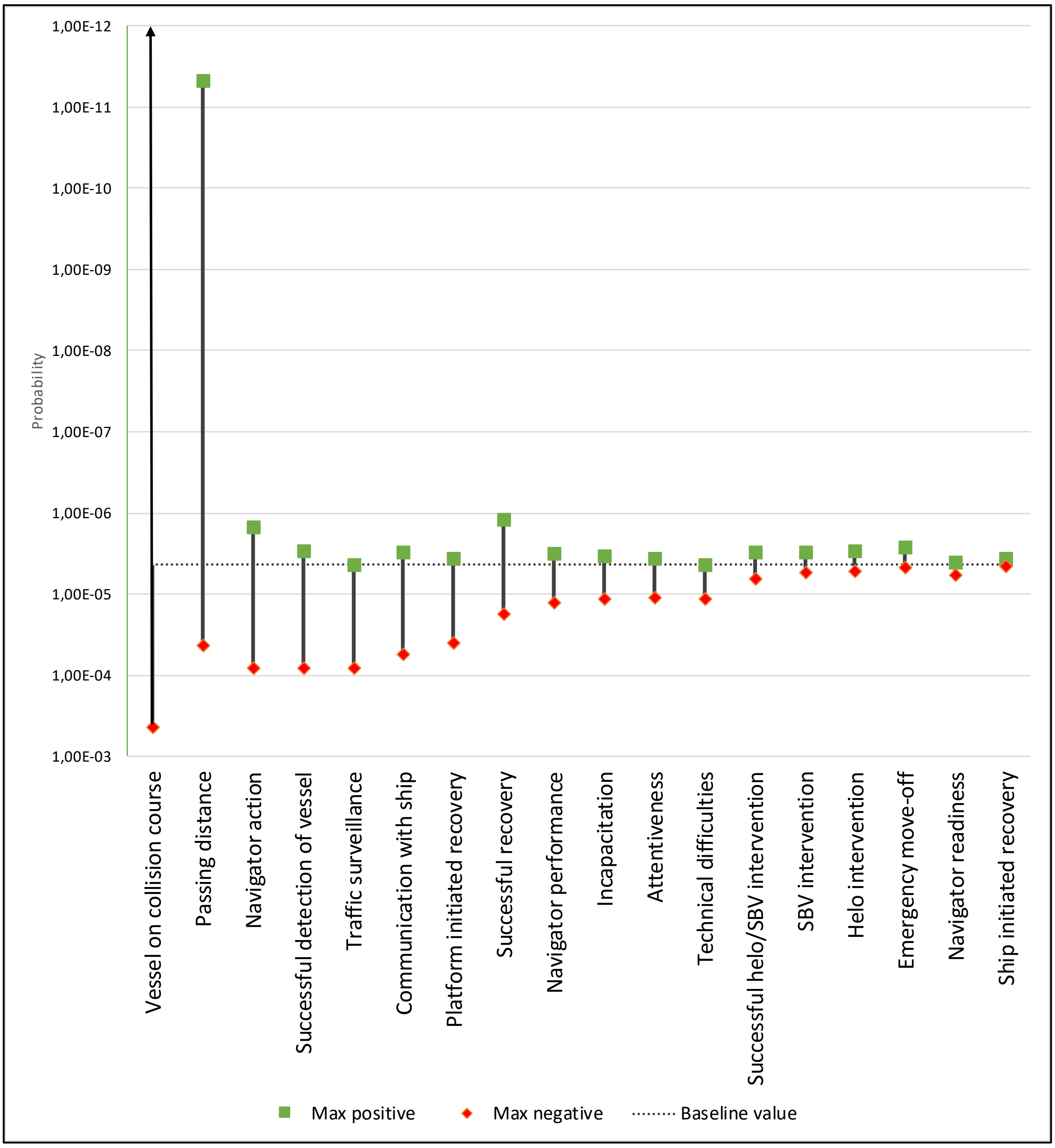

Figure 2 – Sensitivity analysis of nodes quantified by expert panel (the first element goes to zero, outside the axis)

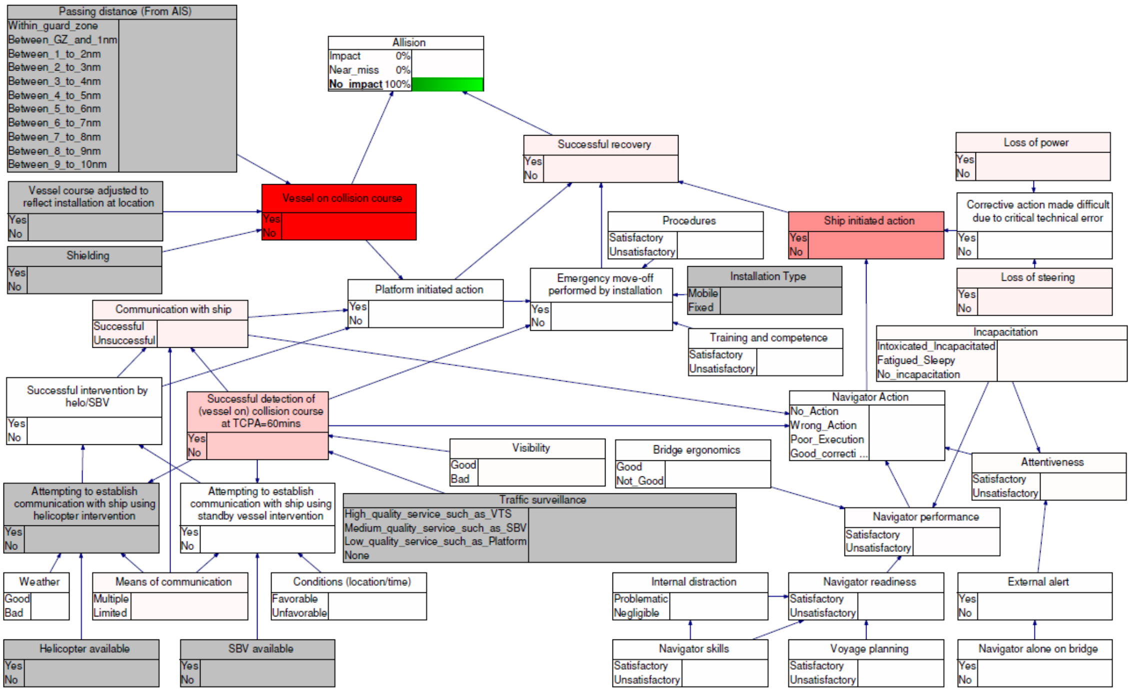

Figure 3 – Sensitivity analysis of the model by setting "Allision" as target node, in state "No Impact". Red nodes change most. Grey nodes are irrelevant.

5.2. The new allision risk model vs. COLLIDE

New technology does not necessarily reduce the risk. It may even make an already complex and busy workplace situation worse. A good grasp of the causal factors leading up to an incident is vital. Many of the causal factors in the old risk models are still valid today, but new technology may have introduced new causal factors while reducing the likelihood of the occurrence of more familiar factors.

COLLIDE was developed in the late 1980s and early 1990s. [29, 30] At the time, GPS was not widely in use as a ship navigation tool, and the common means of navigation was hyperbolic radio navigation, like DECCA or LORAN. The COLLIDE risk assessment model takes into account inaccuracies of navigation from both human error and navigation equipment, as well as weather. While hyperbolic radio navigation was relatively accurate, it had nothing like the accuracy or ease of use offered by GPS, which was introduced in the mid/late 1990s. Several elements in the COLLIDE risk model became outdated as operational aspects, such as using installations for position-fixing became a thing of the past with the introduction of GPS. The accuracy and global coverage of GPS changed the way open water navigation was performed, causing some of the underlying assumptions of COLLIDE to no longer be relevant or valid. GPS became the primary means of position fixing, and navigators are now conditioned to expect good GPS performance.

One of the basic premises of the original COLLIDE models is the notion that normal merchant ships move along routes/shipping lanes. This assumption was established before the introduction of AIS, but has since been "verified" with AIS data aggregated over time that shows an actual grouping of vessel movements to what can only be described as routes. [73] The initial assumption made sense logically, as the optimal way between two points on the open ocean is a straight line, and all experience at the time supported the assumption, and still does. The term "route" was originally used for a voyage from port to port, where parts of one route could merge with or overlap with other routes for certain sections of the route. Today, it is only relevant to look at a limited area around an installation of interest, typically a circle with a 10-nautical mile (nm) radius. This makes a route's start and endpoints less relevant, while how the route is distributed and its parameters within the area of concern have become more relevant. Openly available AIS data shows that ships moving in routes are no longer an assumption, but empirical data. It is now a matter of choice of how to best model these routes, with generic probability distributions applied to all routes, or by investigating and applying other distributions on a route by route basis.

It could be argued that not all routes are truly "proper" shipping lanes, as they may lack established separation schemes or the volume and/or regularity that one may consider necessary to label the traffic as a route. The minimum requirements and/or common framework to define what makes up a route are not universally agreed upon. The most common attributes that make a route are that ships have to travel in the same direction, at least within a small tolerance limit, and there has to be a certain level of traffic volume along the route's direction, over time. Since there is no universal methodology to define routes for risk models based on AIS data has raised the question of using each individual vessel track as input, rather than routes. By aggregating AIS data and identifying routes, it is possible to reduce the uncertainty of individual tracks. A ship may not always return to the exact same track, but the accumulated probability distribution of a route is more robust and not as sensitive to changes compared to a model that uses individual tracks as input.

The COLLIDE risk model has a core assumption that a certain percentage of the geometric traffic distribution will navigate blindly along a route's course (meaning the vessel will continue along its course as if blind to obstacles in its path), and this assumption has to a large degree been kept in the new model, as shown in Figure 1. It could be argued that this assumption may not be entirely valid, or at least overly conservative, and that the model should rather operate with some kind of "per time unit" or "per length unit" error-probability that could lead a vessel into a collision course with an installation. Although this is not completely without merit, the current modelling is still deemed by the authors to be the most appropriate and logical way to represent this issue, as a "per time/length unit" feature adds more uncertainty and sensitivity to model the probability of being on a collision course in a too detailed manner given the current data available.

To validate the results calculated by the BBN model, comparison has been made to three recent COLLISION collision risk assessments by Safetec Nordic AS. The model in this article has four nodes related to vessel position and movement (Figure 1). The passing distance says something about how many ships are expected to pass the installation and at what distance, etc. The shielding node represents any physical barriers that would prevent a direct hit from a non-responsive vessel heading towards the installation of concern. The installation and the objects that may be located around it to provide shielding have a known geometry and the data regarding this has little or no uncertainty, but there is some uncertainty surrounding the exact direction an errant vessel might be coming from. The node related to adjusting the course reflects whether unmodified AIS data is used or an estimated future course based on past AIS data and knowledge about a future installation to be installed on the field. The last of these nodes, "vessel on collision course", represents the number of vessels that are on a collision course, as opposed to the potential number of vessels on collision course that the other two represent. It is also affected by the quality and attentiveness of the navigator, while the other nodes in this area are largely empirical in that they are based on historical data. Having a separate node for vessels being on collision course means that the model no longer assumes total blind navigation but makes an estimation of how many of the potential candidates will end up on a collision course due to blind navigation.

The risk assessments used for validation of the new model were performed for offshore installations on the NCS, located on the west coast of Norway. Five ship routes picked at random from three different projects have been compared. The routes have various passing distances, standard deviation and number of passings per year, and make up a wide range of all the relevant attributes used in calculating an allision risk frequency. COLLIDE groups vessel tracks into routes, which are represented by a normal distribution with a standard deviation set by the tracks that make up the route, and a passing distance set at the centre of the route/tracks. In order to be able to compare such a model to the BBN risk model, each route had to be studied in more detail, and divided into segments of various passing distances, corresponding to the BBN node states. Table

3 shows the distribution (passing distance) of the vessels in the selected routes. A future software solution of the new BBN risk model should incorporate a continuous probability function, similar to COLLIDE, to ensure maximum accuracy and fidelity. However, for comparative purposes it should be sufficient to calculate the risk from vessels at 1 nm increment passing distances and compare the total results for each route with the equivalent COLLIDE calculations of the corresponding routes. The values from both risk models can be found in Table 4, along with basic route information, such as standard deviation (SD) and passing distance (Closest Point of Approach - CPA).

Table 3 – Vessel distribution (passing distance) of routes used in comparison, annual number of passings.

	Distance										
Route	< GZ	GZ - 1 nm	1 - 2 nm	2 - 3 nm	3 - 4 nm	4 - 5 nm	5 - 6 nm	6 - 7 nm	7 - 8 nm	8 - 9 nm	9 - 10 nm
A	29	58	26	5							
B	3	43	44	6	2						
C			22	340	1081	527	224	112	28		
D							22	266	1012	569	1077
E	138	903	716	277							
F	3	5	9	12	9	6	5				
G	4	10	18	20	12	2	1				
H		12	8	2	9	7	5				
I	1	10	6	5	5						
J	1	6	14	11	6	1					
K	5	40	37	11	1						
L	2	6	3	10	22	10	11	6			
M	3	13	37	70	15	9	4	1	1		2
N					12	40	18	8	16		
O			1	2	7	12	17	10	5	7	4

Table 4 – Comparative example of probability of impact from selected routes, per installation year

Route	CPA	SD	No. of vessels in route per year	COLLIDE	BBN Model
A	0.5 nm	0.7	118	1.85E-04	4.89E-05
B	1.2 nm	0.4	98	4.79E-06	1.08E-05
C	4.7 nm	1.5	2434	3.12E-05	9.40E-07
D	9.2 nm	1.8	4674	4.52E-09	8.31E-11
E	0.9 nm	1.1	2034	1.77E-03	3.29E-04
F	1.7 nm	1.2	49	1.12E-04	5.03E-06
G	1.7 nm	1.2	67	6.41E-05	7.25E-06
H	1.8 nm	1.3	43	6.10E-05	1.79E-06
I	1.6 nm	0.8	27	1.83E-05	2.88E-06
J	2.2 nm	1.2	39	1.50E-05	2.44E-06
K	0.1 nm	1.1	94	1.34E-04	1.31E-05
L	3.4 nm	1.6	70	1.55E-05	3.69E-06
M	2.3 nm	0.9	155	5.37E-06	6.61E-06
N	4.9 nm	0.8	94	2.30E-09	2.26E-09
O	5.7 nm	1	65	1.88E-07	1.79E-08

The COLLIDE model underwent independent validation in 1996, to ensure that it reflected historical data regarding passing vessel allision frequencies, for platforms on the UK Continental Shelf. The validation showed a good correlation between the COLLIDE model estimate and historical data/reported incidents for the same period, but the COLLIDE model by no means gives the "correct" answer, 20 years later. The new BBN model should not follow the COLLIDE results exactly as that would simply imply that the new model can be replaced by a correction factor or simple offset to the existing methodology and model. The comparison is expected to show some variance across several key attributes, but still provide a certain degree of guidance and similarity. If the two models give very different (or very similar) values and they do not share any behaviour or traits (or exhibit identical behaviour), it would be more troublesome to explain the results than for a moderate degree of correlation and similarity.

Table 4 shows that the BBN model for the most part gives similar values to the COLLIDE model, usually a little lower. The values are shown in more detail in Figure 4, where one can see how the relative difference varies for most nodes. The squares represent the values from Collide and the triangles the BBN model. In Figure 5, the risk contribution of each route has been normalised by the number of ships passing the installation (shown by the red and green lines and the right axis), together with the relative distance shown by the number of standard deviations for each route (shown by the blue columns and the left axis). The results are promising, as they are relatively similar, while still being the result of two different risk models with different RIFs and values.

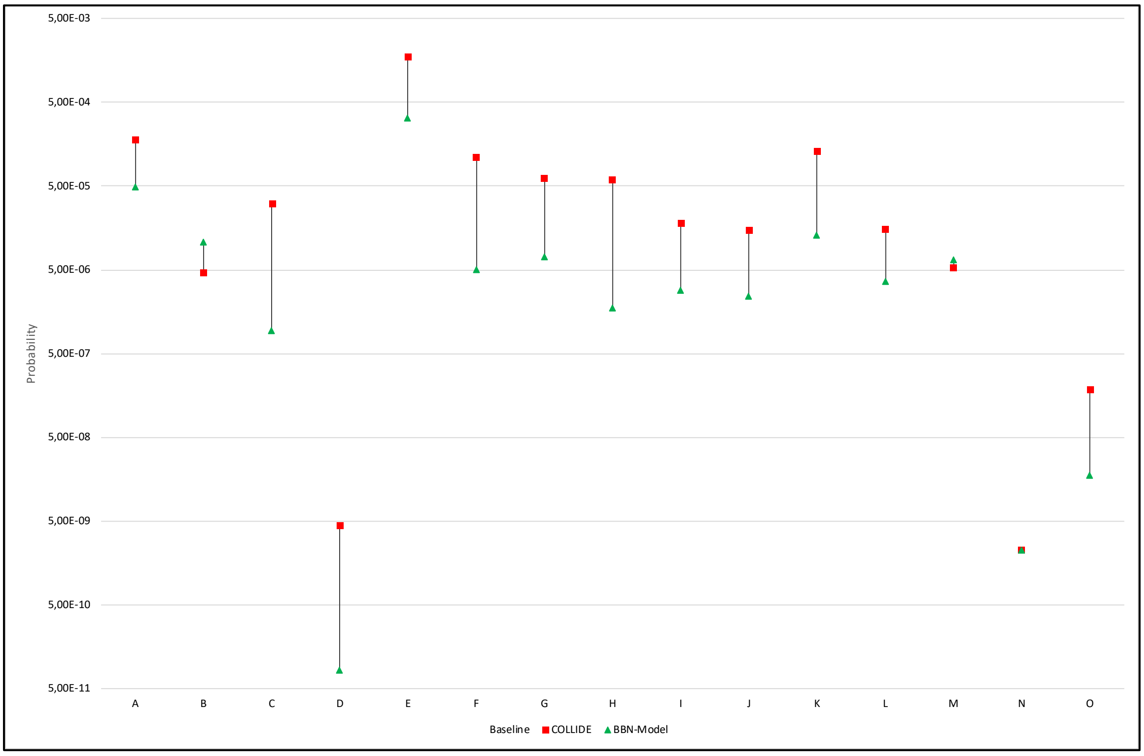

Figure 4 – Comparative example of risk contribution from selected routes (A-O).

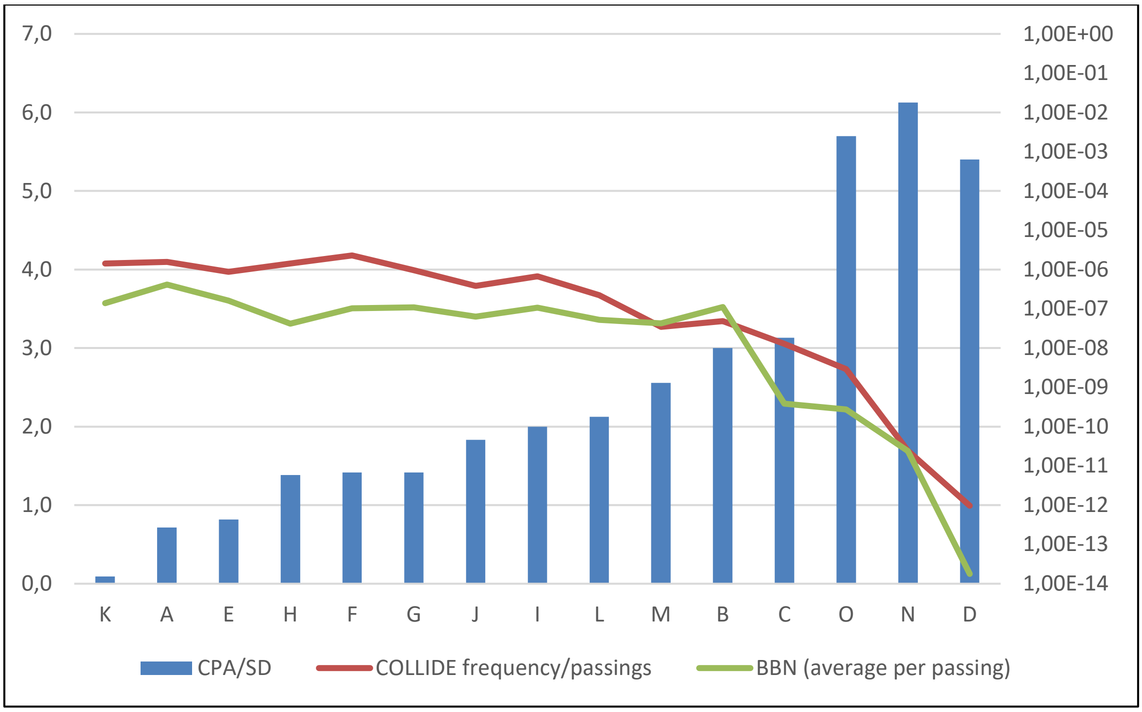

Figure 5 – Average allision risk frequency per passing (right axis) and number of standard deviations distance from route centre to installation (left axis) for routes A-O.

5.3. Uncertainty

Pitchforth and Mengersen [74] argue that the main contributors to uncertainty in a BBN model can be divided into one of four categories: structure, discretisation, parametrisation and model behaviour:

Model structure is the nodes included in the model, and the number and direction of arcs between them. Finding the right structure of a BBN is vital, as it is widely acknowledged that a large number of nodes or arcs between nodes can lead to a network that is computationally challenging. Even the (node) quantification process is very difficult and labour-intensive if the structure is too complex. The appropriate number of nodes and arcs depends on the domain and scope of the model, but it is important to ensure that there is a balance between complexity and simplicity in the model's explanation of the system. [74] The structure of the presented BBN is influenced by the original COLLIDE model, and even though it is a completely new and different model, some familiar elements can be found. New elements added to the risk model are a result of new research that has identified certain factors to be relevant in such a context, or through experience working with allision risk assessments for the industry and correspondence with offshore operators. Concerning structure, the model is deemed to have good validity, as a large part of the model is evidence-based. [62]

Discretisation is the way in which states are defined within nodes. Once the model structure is set, the nodes are assigned states. These can be intervals, categories or other ways to discretely model continuous factors. This can lead to a certain level of information loss, but is typically necessary to achieve a practical and defensible network. The choice to give most variables in the proposed network binary states may reduce the discretisation validity somewhat, but we believe this provides satisfactory validity, and is necessary to enable practical quantification and calculation.

Parametrisation is the quantification and conditional probabilities of each state and node, elicited by the expert panel. While the discretisation of continuous variables is not desirable, it simplifies expert elicitation, and acknowledges that available data is often limited. [75] The parametrisation is the result of input from the expert panel, and as such represents the values found by the expert panel to be the most relevant and valid.

The model behaviour is a result of the other three categories (structure, discretisation and parametrisation), and can be seen as the combined likelihood of the whole network, sub-networks and relationships between elements. The top result or probability of a certain node is not necessarily the only desired output of a model, as it may be very interesting to study the influencing factors and relationships across nodes under certain conditions or that cause a certain behaviour. This can make model behaviour very difficult to validate as such, and a more intuitive and subjective measure may be more appropriate to estimate the quality and validity of a model's behaviour. Initial testing of the model behaviour and output are positive through the comparison with COLLIDE.

6 DISCUSSION

6.1. Risk level

To form the basis of calculations or populate the conditional probability tables for each node, a minimum of empirical data is needed. In the absence of such data, expert judgement may be used to estimate values. In this case, expert judgement was the only realistic option, as very little specific research has been done in this domain, and no data exists for several of the nodes. For example, there has not been any documented example of an emergency move-off of a floating installation being performed as a result of an incoming ship on collision course, nor have there been any reported allisions with passing vessels on the NCS in the last 20 years.

Table 4 shows that the new model generally estimates the risk to be lower compared to the COLLIDE model. The PSA has accumulated a lot of data and experience during a relatively long period of time, and continuously seeks to improve relevant legislation so that it reflects current knowledge. Looking at trends over time and recording the number of events and near-misses in the industry, the PSA is able to request that the risk methodology is adjusted to account for new data and knowledge. This is what happened in 2011, when the PSA called for improvements in the industry due to several serious field related collision incidents. [1, 2] The new BBN model is more aligned with the PSA's comments on risk assessment predictions, and the calculations are more transparent and enable a better holistic view of the RIFs involved.

6.2. The lack of data

With better and more detailed reporting of near-misses and other incidents that may lead to allision situations, it would be easier to identify and quantify causal factors. The allision between the visiting supply vessel Bourbon Surf and the Grane installation in 2007 [76] was investigated by the police, and the captain and first officer were fined for infractions of the Law of Ship Safety[2]. It seems that there have been no investigations of near-miss events, only of allisions. According to the head of the Statoil Operations Centre, Grethe Strøm[3], it is the individual offshore installation manager (OIM) who decides if a violation of the safety zone should be reported to the police for investigation. According to Strøm, this is not done unless the violation results in some form of unwanted event/impact.

A police investigation may not uncover the causal factors that led to the situation being investigated, but it may at least provide a valuable insight and partial understanding of the indirect causal factors. It is naïve to think that only sub-standard ships or navigators could be involved in an allision, so a better understanding of the underlying and indirect causal factors could improve or validate the new risk model. Reducing the risk of allision is a reduction of the probability of occurrence, as trying to reduce the consequences sufficiently is often not a practical possibility. Better data and understanding of the scenario to be modelled is important, but complex operations have also seen new modelling theories evolve to cope with the intricate and complex relationships between influencing factors. A better understanding of the relationships and influencing factors usually creates an increased demand for data, which may be problematic, especially for

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[2] Law of Ship Safety (Translated from Norwegian: Lov om skipssikkerhet (skipssikkerhetsloven)).

[3] Personal communication (Hassel) - Procedures for breach of safety zone around offshore installations, Grethe Strøm (2015).

this type of accident scenario with very few historical incidents and proprietary data that can be hard to acquire.

6.3. The comparison with COLLIDE

The new model does not have a working software tool that enables mass calculation, so the original AIS data that was used to form the routes for COLLIDE has been investigated and divided into the states found in the node "passing distance", as can be seen in Table 3 (cf. Section 4). Calculating the risk using the new allision risk model has been done manually by adding the results from each state that comprises a route from COLLIDE. The allision probability from route B (in Table 4) is fairly small according to COLLIDE, as a low standard deviation will typically yield such results. However, looking at the original AIS data, the distribution of the vessels in route B is relatively wide, with long tails on both sides. Admittedly, these tails are small, with only 2 and 3 outlier ships. However, as previously mentioned, the passing distance and whether a ship is on a collision course are the two parameters which affect the end results the most, so even a long tail of only 3 ships can have a large impact if the passing distance is critically small, which it is in this case. It is expected that the new model will not consistently yield lower results compared to COLLIDE. The new model has a very different setup and calculates the probability of allision differently from COLLIDE, so it is expected that the probability becomes somewhat higher or lower for certain situations. There is also uncertainty in the BBN model results, as the comparison with the original COLLIDE model is a very coarse estimate found by manual calculation. The comparison of results is only intended to show sufficient similarity and a baseline benchmark.

The model is sensitive to changes in the nodes related to passing distance and collision course, which is not surprising. The act of striking an object requires close proximity and a collision course, so obviously the distance between the ship and installation is a crucial element. The passing distance is provided by historical AIS data, where the only data processing is for the removal of invalid data, irrelevant traffic and the estimation of changes to traffic within 1 nm of the location of a new installation. Experience has shown that traffic that naturally has a passing distance greater than 1 nm will repeat its tracks and pay no heed to new obstacles that appear 1 nm away from their course. However, traffic that suddenly finds a new obstacle within 1 nm of its intended track will alter course in order to achieve a passing distance close to 1 nm. [77] This means that historical data that shows traffic passing within the safety zone, or in close proximity, should be adjusted to reflect the new traffic pattern once an installation is at the location. (Allision risk assessments are typically carried out well in advance of actual drilling operations, when there is no physical object at the location of interest.) Risk assessments for new installations should not be overly conservative and use AIS data collected before the installation is on location without any form of modification. There may not be many practical alternatives to using AIS data in the immediate future, but the data should be modified to reflect known effects of introducing a physical object near existing shipping lanes.

The quantitative risk model could have been expanded with weather details like visibility, wind, waves, precipitation, daylight. Similarly, “technical condition” could have been expanded with vessel details, such as ship type, age, size, flag state and other attributes are simplified into. The effect of such simplification is a loss of fidelity, as it is no longer so apparent how the parent nodes influence the universal node. Still, these are concatenated nodes that are far away from the allision node, in areas where the desired level of detail is lower, as each node's total risk influence is limited. Nevertheless, if data were available, and computation time was not important, inclusion and quantification of such nodes might have given more precise results and more detailed information about which nodes are important for risk mitigation.

6.4. The expert panel and nodes

Three nodes divided the expert panel: the nodes "Communication with ship", "Emergency move-off" and "Navigator action". Interestingly, no correlation was found among the responses from the experts and their professional background and experience. Regarding the first of these nodes, this may be due to the time limit not being properly defined. The question to the expert panel was "What do you think is the probability that an offshore installation is able to (remotely) establish (voice) communications with a ship on a collision course?", where the parent nodes are "Ship detected at TCPA (time to closest point of approach) 60 minutes – Yes/No" and "Means of communications – Multiple/Limited". Some of the experts understood this question as the probability of establishing contact at any time before physical impact, giving it a high probability. Others interpreted the question as the probability of establishing contact "in time" to execute necessary procedures to deal with a ship on collision course, thus giving it a significantly lower probability. (The expert panel did have a high degree of consensus for the most positive state). This node is the 6th most sensitive node of the 15 quantified by the experts, and may either improve the baseline result by 41%, or worsen it by 92%.

Regarding the node "Emergency move-off", the expert panel is simply divided in their judgement. About half the panel were optimistic that an installation will successfully move off location, provided that they have good procedures and training and that they have detected an incoming ship well in advance. The other half of the panel were not very optimistic, citing that no installation has ever actually tested this procedure either in training nor as a necessity, thus giving them little confidence that such a manoeuvre would indeed be carried out. The possibility of an emergency move-off by a mobile installation in response to an incoming ship is in fact regarded by some people in the industry as a legitimate barrier element, while others view it as a "Hail Mary" when all else has failed. This node is the third least sensitive to the end result, ranked as number 13 of the 15 nodes quantified by the expert panel. It may either improve the baseline result by 62% or worsen it by only 10%.

The node "Navigator action" is based on the states of the parent nodes "Navigator awareness", "Navigator performance" and "Aware the ship is on a collision course, at TCPA 60 minutes". The most positive state had a high degree of consensus from the panel, but the negative states, particularly when the node "Aware the ship is on a collision course, at TCPA 60 minutes" was negative; the expert panel showed no consensus. Again, this may be due to the lack of a lower time limit for when a navigator should be(come) aware of being on a collision course, and then act accordingly. Human Error Probability (HEP) is a difficult thing to estimate in the best of cases, so it is not surprising that the expert panel were unable to reach a consensus in this case. There are several ways to estimate HEP values [78], but they require a more in-depth approach than has been applied to the quantification process in this case. This node is the third most sensitive to the model, and extreme values of this node can either improve the baseline result by 186% or worsen it by 95%. The quantification process did uncover a weakness in this part of the BBN, resulting in a new link between the node "Communication with ship" and the node "Navigator action", making the node "Communication with ship" a parent node of the node "Navigator action".

The size of the expert panel is deemed satisfactory, as most of the quantification is related to a highly specialized case with few experts worldwide. “Wisdom of crowds” have gained merit in recent years for being a good alternative to expert judgment by a smaller expert panel, but both approaches have strengths and weaknesses. The wisdom of crowds is great for accurately estimating the number of balls in a jar, the weight of the Eiffel tower or the total cost of raising a child and other scenarios where their answers would all be along a relatively linear scale. It has been shown that for more complex problems, the wisdom of the crowd falls short, and is better estimated by a smaller group of subject matter experts, this could be problems such as estimating the probability of a meteor strike, a nuclear meltdown or other "one-in-a-million" type scenarios. [79] The focus of this research is a type of allision scenario with very little empirical data available, and very few global experts. The expert panel involved is thus deemed satisfactory.

6.5. Final thoughts

The authors believe that the new risk model is better in several different ways. The new BBN allision risk model is much more transparent, which allows stakeholders to better understand the mechanisms behind the calculations. It also makes it possible to answer more detailed questions, such as how much a certain barrier element actually influences the final result. Stakeholders may also adjust the model in more ways, to account for special circumstances or find solutions to custom cases. New elements, such as operations in harsh climates, or new technology for surveillance or communications, can more easily be introduced to the new BBN model. The ability to turn elements on or off provides valuable insights into the efficacy and effect of individual barriers/nodes. In general, the new model architecture has resulted in a more dynamic and user-friendly model. The new model is believed to better reflect the actual allision risk levels on the NCS, based on the experience and data available. Both industry actors and the PSA have questioned the current COLLIDE model results, claiming that they could be overly conservative. The BBN model is generally less conservative, and behaves as expected for such a model. It does not imitate COLLIDE results, nor does it completely differ, indicating that the model performs satisfactorily. Hence, the new model is believed to represent a more useful and accurate tool in the estimation of allision risk levels on the NCS.

7 CONCLUSION

The allision risk model used by the industry (COLLIDE) is more than 20 years old and does not reflect the current knowledge and new technology available. The new BBN model presented in this article represents new knowledge, research, available data and the modus operandi of offshore petroleum operations today. It enables a more detailed analysis of individual RIFs and barriers, and allows stakeholders a new level of insight and functionality.

The BBN allision risk model has been quantified using available empirical data and expert judgement by a panel of subject matter experts from academia and the industry. The results are well aligned with the industry actors' expected values and comments from the PSA regarding this type of risk assessment. Calculations are done in a way that enables operators to adjust any and all RIFs to better match the actual conditions. The new model enables improved barrier management through better transparency and level of detail, and may adapt to new knowledge and incorporate new RIFs more easily than the current industry standard model (COLLIDE). The new model is believed to better estimate the allision risk level on the NCS, and will enable better risk assessments and an improved understanding of the effect of each RIF. Further work should be done to convert the risk model into a fully functioning software tool that can replace the COLLIDE model and process large amounts of data in a satisfactory manner. Additional work should also be done to increase the certainty and accuracy of critical RIFs, as new knowledge becomes available.

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REFERENCES

1. PSA. Collisions between vessels and installations: Averting unwanted contact, 2011. http://www.ptil.no/structural-integrity/risk-of-collisions-with-visiting-vessels-article7524-901.html
2. PSA. The Risk Level Project. Main report. Development trends 2018 NCS (in Norwegian: RNNP Hovedrapport utviklingstrekk 2018 norsk sokkel. Risikonivå i norsk petroleumsvirksomhet), 2018.
3. Vinnem JE. Offshore Risk Assessment. Third ed. Springer Series in Reliability Engineering. Vol. 1. London: Springer-Verlag, 2014.
4. Sveen D. Oseberg B Jacket - Damage Assessment and Repair After Submarine Collision. *Journal of Petroleum Technology* 1990; 42(11):1421-1425.
5. Schuler, M. 2016. Tanker hits oil platform in Dutch North Sea. Jan. 2nd. 2016: https://gcaptain.com/tanker-hits-oil-platform-in-dutch-north-sea/ (Accessed: 2019-12-02)
6. OGUK. Guidelines for Ship/Installation Collision Avoidance. Report, February, 2010. https://www.marinesafetyforum.org/wp-content/uploads/2018/08/OP013-Guidelines-for-Ship-Installation-Collision-Avoidance-Issue-2-Feb-2010.pdf (Accessed: 20.4.2020)
7. PSA. Defined hazard and accident conditions (DFUs), 2013. https://www.ptil.no/en/technical-competence/rnnp/rnnp-and-major-accident-risk/ (Accessed: 20.4.2020)
8. Equinor. Sammenstøt mellom Statfjord A og supplyfartøy. June, 2019. https://www.equinor.com/no/news/sammenstoet-mellom-statfjorda-og-supplyfartoey.html/?utm_source=newssubscription&utm_medium=email
9. OGP. Ship/installation collisions. International Association of Oil & Gas Producers - Risk Assessment Data Directory: International Association of Oil & Gas Producers (OGP), 2010.
10. Sandhåland H, Oltedal H and Eid J. Situation awareness in bridge operations – A study of collisions between attendant vessels and offshore facilities in the North Sea. *Safety Science* 2015; 79:277-85.
11. Fowler TG and Sørgård, E. Modeling Ship Transportation Risk. *Risk Analysis* 2000; 20(2): 225-244.
12. Rosqvist T, Nyman T, Sonninen S and Tuominen R. The implementation of the VTMIS system for the Gulf of Finland - a FSA study. In *RINA International Conference on Formal Safety Assessment*, 2002, London.
13. Dai L, Ehlers S, Rausand M and Utne IB. Risk of collision between service vessels and offshore wind turbines. *Reliability Engineering & System Safety* 2013; 109:18-31.
14. Proske D, Curbach M. Risk to historical bridges due to ship impact on German inland waterways. *Reliability Engineering & System Safety* 2005; 90:261-70.
15. DNV, Formal Safety Assessment – Large Passenger Ships, ANNEX II. 2005 http://research.dnv.com/skj/FSALPS/ANNEXII.pdf.
16. DNV. Formal Safety Assessment of Electronic Chart Display and Information System (ECDIS), 2005. http://research.dnv.com/skj/FSA-ECDIS/ECDIS.htm.
17. Povel D. Collision Risk Analysis for Offshore Structures and Offshore Wind Farms. In *ASME 25th International Conference on Offshore Mechanics and Arctic Engineering*, 2006, Hamburg.
18. Lützen M and Friis-Hansen P. Risk Reducing Effect of AIS Implementation on Collision Risk. In *Proceedings of Society of Naval Architects and Marine Engineers*, 2003, Society of Naval Architects and Marine Engineers: San Fransisco, USA.
19. Trucco P, Cagno E, Ruggeri F and Grande OA. Bayesian Belief Network modelling of organisational factors in risk analysis: A case study in maritime transportation. *Reliability Engineering & System Safety* 2008; 93(6):845-856.
20. Norrington L, Quigley J, Russel A, Van der Meer R. Modelling the reliability of search and

rescue operations with Bayesian Belief Networks. *Reliability Engineering & System Safety* 2008; 93(7): p. 940-949.
21. Kujala P, Hänninen M, Arola T and Ylitalo J. Analysis of the marine traffic safety in the Gulf of Finland. *Reliability Engineering & System Safety* 2009; 94(8): 1349-1357.
22. Hänninen M. and Kujala P. The Effects of Causation Probability on the Ship Collision Statistics in the Gulf of Finland. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation* 2010; 4(1): p. 79-84.
23. Martins MR and Maturana MC. Application of Bayesian Belief networks to the human reliability analysis of an oil tanker operation focusing on collision accidents. *Reliability Engineering & System Safety* 2013; 110: 89-109.
24. Goerlandt F and Montewka J. A probabilistic model for accidental cargo oil outflow from product tankers in a ship–ship collision. *Marine Pollution Bulletin* 2014; 79(1–2): 130-144.
25. Montewka J, Ehlers S, Goerlandt F, Hinz T, Tabri K and Kujala P. A framework for risk assessment for maritime transportation systems—A case study for open sea collisions involving RoPax vessels. *Reliability Engineering & System Safety* 2014; 124:142-57.
26. Akhtar MJ and Utne IB. Human fatigue's effect on the risk of maritime groundings – A Bayesian Network modeling approach. *Safety Science* 2014; 62:427-40.
27. Thieme C, Utne IB and Haugen S. Assessing ship risk model applicability to Marine Autonomous Surface Ships. *Ocean Engineering* 2018; 165, 140–154.
28. Hassel M, Utne IB and Vinnem JE. Analysis of the main challenges with the current risk model for collisions between ships and offshore installations on the Norwegian Continental Shelf. In *12th International Probabilistic Safety Assessment and Management Conference (PSAM)*, 2014.
29. Haugen S. *Probabilistic evaluation of frequency of collision between ships and offshore platforms.* PhD Thesis, NTNU, Trondheim, Norway, 1991.
30. Haugen, S., LH. Katteland, and F. Vollen, COLLIDE – Collision design criteria, Phase II, Reference manual. 1994: Trondheim.
31. DNV. SAFECO - Safety of Shipping in Coastal Waters, 1999. Retrieved from http://www.transport-research.info/Upload/Documents/200310/safeco.pdf
32. DNV. MARCS – A Computer System For Assessment and Management of Ship Accident Risks, 2012.
33. LR. Guidance Notes for Collision Analysis. Lloyd's Register, 2014.
34. Scandpower. (2007). CollRisk User Manual.
35. IALA. Samson, 2014. Retrieved from https://www.iala-aism.org/wiki/iwrap/index.php/SAMSON
36. MARIN. Computer Program SAMSON, 2014.
37. van der Tak, C., & Glansdorp, C. C. (n.d.). Ship Offshore platform Collision Risk Assessment (SOCRA).
38. Otto, S, Nusser, S, & Braasch, W. Collision risk of ships with offshore wind farms and the danger of pollution of coastal regions [In German] (GL-O 01-234). Retrieved from Germanischer Lloyd Offshore and Industrial Services GmbH, 2002. http://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/2686.pdf
39. Povel, D. Collision Risk Analysis for Offshore Structures and Offshore Wind Farms. Paper presented at the *25th International Conference on Offshore Mechanics and Arctic Engineering*, Hamburg, 2006.
40. Hänninen M. Analysis of human and organizational factors in marine traffic risk modeling. Helsinki University of Technology, Espo, 2008.
41. Rausand M. *Risk asssessment. Theory, methods, and applications*. Hobroken: Wiley, 2011.
42. Heckerman D, Geiger D and Chickering D. Learning Bayesian networks: The combination of knowledge and statistical data. *Mach. Learn*. 1995; 20:197-243.

43. Uusitalo L. Advantages and challenges of Bayesian networks in environmental modelling. *Ecological Modelling* 2007; 203:312-8.
44. Jensen FV and Nielsen TD. *Bayesian Networks and Decision Graph*s. 2nd ed. New York: Springer, 2007.
45. Chen SH and Pollino CA. Good practice in Bayesian network modelling. *Environmental Modelling & Software* 2012; 37:134-45.
46. Hänninen M. Bayesian networks for maritime traffic accident prevention: Benefits and challenges. *Accident Analysis & Prevention* 2014; 73:305-12.
47. Janis IL. *Victims of Groupthink*. 2nd ed. Boston: Houghton-Mifflin, 1982.
48. Peterson RS, Owens PD, Tetlock PE, Fan ET and Martorana P. Group Dynamics in Top Management Teams: Groupthink, Vigilance, and Alternative Models of Organizational Failure and Success. *Organizational Behavior and Human Decision Processes* 1998; 73:272-305.
49. Makkonen M, Hujala T and Uusivuori J. Policy experts' propensity to change their opinion along Delphi rounds. *Technological Forecasting and Social Change 2016*; 109:61-68.
50. Camerer CF and Johnson EJ. *The process-performance paradox in expert judgment - How can experts know so much and predict so badly? Toward a General Theory of Expertise: Prospects and Limits.* Cambridge: Cambridge University Press, 1991, 195-217.
51. Øien K, Risk indicators as a tool for risk control. *Reliability Engineering & System Safety* 2001; 74(2): 129-145.
52. Helmer-Hirschberg O. Analysis of the Future: The Delphi Method. Santa Monica, CA: RAND Corporation, 1967.
53. Linstone HA and Turoff M, The Delphi method: Techniques and applications. Addison-Wesley Reading, MA, 1975.
54. Woudenberg F. An evaluation of Delphi. *Technological Forecasting and Social Change 1991*; 40:131-50.
55. Rowe G, Wright G and McColl A. Judgment change during Delphi-like procedures: The role of majority influence, expertise, and confidence. *Technological Forecasting and Social Change* 2005; 72:377-99.
56. Hussler C, Muller P and Rondé P. Is diversity in Delphi panelist groups useful? Evidence from a French forecasting exercise on the future of nuclear energy. *Technological Forecasting and Social Change* 2011; 78:1642-53.
57. Gordon TJ. The Delphi Method. *Future Research Methodology* 1994;2.
58. Gary JE and von der Gracht HA. The future of foresight professionals: Results from a global Delphi study. *Futures* 2015; 71:132-45.
59. Ariely D, Tung Au W, Bender RH, Budescu DV, Dietz CB, Gu H, Wallsten, TS and Zauberman, G. The effects of averaging subjective probability estimates between and within judges. *Journal of Experimental Psychology: Applied* 2000; 6(2):130-47.
60. Wallsten TS and Diederich A. Understanding pooled subjective probability estimates. *Mathematical Social Sciences* 2001; 41:1-18.
61. Merriam-Webster, *Allision*, in *The Merriam-Webster Online Dictionary*. (n.d.), The Merriam-Webster Online Dictionary.
62. Mazaheri A, Montewka J and Kujala P. Towards an evidence-based probabilistic risk model for ship-grounding accidents. *Safety Science* 2016; 86:195-210.
63. Hänninen M, Kujala P. Influences of variables on ship collision probability in a Bayesian belief network model. *Reliability Engineering & System Safety* 2012; 102:27-40.
64. Mongstad, E. Reducing the risk of allision between ship and platforms (NO: Reduserer risikoen for kollisjon mellom skip og plattform). 2012. Available from: http://kystmagasinet.no/nyheter/reduserer-risikoen-for-kollisjon-mellom-skip-og-plattform/.

65. HSE. Vessel owners and master fined £58,000 after collision. Health and Safety Executive, 2003. http://www.hse.gov.uk/press/2003/e03163.htm. (Accessed 3. Sept. 2015).
66. MAIB. Report on the investigation of the collision between the UK registered fishing vessel Marbella and the Bravo Delta offshore platform in the Rough Gas Field about 25 miles south-east of Flamborough Head 8 May 2002. Marine Accident Investigation Branch, 2003. https://www.gov.uk/maib-reports/contact-made-by-stern-freezer-trawler-marbella-with-bravo-delta-offshore-platform-off-flamborough-head-england.
67. Hockey, G.R.J., et al., Cognitive demands of collision avoidance in simulated ship control. *Human Factors* 2003; 45(2): p. 252-265.
68. Hetherington, C., R. Flin, & K. Mearns, Safety in shipping: The human element. *Journal of Safety Research* 2006; 37(4): p. 401-411.
69. Wagenaar, W.A. & J. Groeneweg, Accidents at sea: Multiple causes and impossible consequences. International Journal of Man-Machine Studies, 1987. 27(5): p. 587-598.
70. Geijerstam, K. & H. Svensson, Ship Collision Risk - An identification and evaluation of important factors in collisions with offshore installations. 2008, Lund University: Department of Fire Safety Engineering and Systems Safety.
71. Rothblum AM. Principles of Risk-Based Decision Making. Government Institutes, 2002.
72. Vinnem, JE and Røed, W. 2019. Offshore Risk Assessment, 4th Edition, Springer.
73. Aarsæther KG. Modeling and analysis of ship traffic by observation and numerical simulation. PhD thesis, Department of Marine Technology. NTNU: Trondheim, 2011.
74. Pitchforth J and Mengersen K. A proposed validation framework for expert elicited Bayesian Networks. *Expert Systems with Applications* 2013; 40:162-7.
75. Pollino CA, Woodberry O, Nicholson A, Korb K and Hart BT. Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment. *Environmental Modelling & Software* 2007; 22:1140-52.
76. NRK. Fined after near-disaster (Translated from Norwegian: "Bøtelagt etter nesten-katastrofe") https://www.nrk.no/mr/botelagt-etter-nesten-katastrofe-1.6548960 (2009)
77. Hassel M, Utne IB and Vinnem JE. An Empirical Study of Vessel Traffic Patterns Around Offshore Petroleum Installations on the Norwegian Continental Shelf. *WMU Maritime Affairs* 2016; 16, 2, 175–195
78. Kirwan B. Human error identification techniques for risk assessment of high-risk systems—Part 1: review and evaluation of techniques. *Applied Ergonomics* 1998; 29:157-77.
79. Tetlock P and Gardner D. *Superforecasting: The Art and Science of Prediction,* 1st ed. London, Random House, 2015.