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Article *in* Marine Pollution Bulletin · May 2016

DOI: 10.1016/j.marpolbul.2016.03.071

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Contents lists available at ScienceDirect

Marine Pollution Bulletin

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Osiris A. Valdez Banda [a,*], Floris Goerlandt [a], Vladimir Kuzmin [b], Pentti Kujala [a], Jakub Montewka [a,c,d]

[a] Aalto University, Department of Mechanical Engineering (Marine Technology), Research Group on Maritime Risk and Safety, Kotka Maritime Research Centre, Heikinkatu 7, FI-48100 Kotka, Finland
[b] Admiral Makarov State University of Maritime and Inland Shipping, Makarov Training Centre, P.O. Box 22, 195112 Saint Petersburg, Russia
[c] Finnish Geospatial Research Institute, Geodeetinrinne 2, 02430 Masala, Finland
[d] Gdynia Maritime University, Faculty of Navigation, Department of Transport and Logistics, 81-225 Gdynia, Poland

ARTICLE INFO

Article history:
Received 7 March 2016
Accepted 27 March 2016
Available online 18 May 2016

Keywords:
Maritime safety
Maritime risk management
Formal Safety Assessment
Winter navigation operations
Accidental oil spill
Bayesian networks

ABSTRACT

The wintertime maritime traffic operations in the Gulf of Finland are managed through the Finnish–Swedish Winter Navigation System. This establishes the requirements and limitations for the vessels navigating when ice covers this area. During winter navigation in the Gulf of Finland, the largest risk stems from accidental ship collisions which may also trigger oil spills. In this article, a model for managing the risk of winter navigation operations is presented. The model analyses the probability of oil spills derived from collisions involving oil tanker vessels and other vessel types. The model structure is based on the steps provided in the Formal Safety Assessment (FSA) by the International Maritime Organization (IMO) and adapted into a Bayesian Network model. The results indicate that ship independent navigation and convoys are the operations with higher probability of oil spills. Minor spills are most probable, while major oil spills found very unlikely but possible.

1. Introduction

The Gulf of Finland (GOF) is recognized as one of the most transited maritime areas in the world (Kuronen et al., 2009; Lappalainen et al., 2014; Lehikoinen et al., 2015). In this area, ship traffic has gradually increased due to the transport of several goods to Finland and Russia and the increment of oil and liquefied natural gas (LNG) production and export from Russia (Brunila and Storgård, 2012; Kujala et al., 2009). This trend is also found during wintertime when the GOF is partially or completely covered by ice (Finnish Transport Agency, Liikennevirasto, 2014a). The navigational operations of vessels in ice conditions differ significantly from those performed in open water (Finnish Transport Safety Agency, Trafi, 2011). This creates the need for different approaches to analyse the risk of accidents which may lead to catastrophic consequences for people and the natural environment (Afenyo et al., 2015).

The analysis of the risk associated with different maritime operations and its effect on different environmental contexts has been previously carried out (Goerlandt and Montewka, 2014, 2015a; Hänninen and Kujala, 2012; Lee and Jung, 2015; Montewka et al., 2011; Mullai and Paulsson, 2011; Oltedal and Wadsworth, 2010; Qu et al., 2011; Singh et al., 2015; Sormunen et al., 2014; Ståhlberg et al., 2013; Zhang et al., 2015). Moreover, accidental risk in the GOF and the risk of oil spills and their possible devastating consequences in this area has also been previously studied (Kujala et al., 2009; Leiger et al., 2009; Lehikoinen et al., 2015, 2013; Montewka, 2009). However, these studies have been limited to navigational operations in open water, spring–summer–autumn season.

An initial analysis of the risk associated to the navigational operations performed in sea ice conditions is presented in (Valdez Banda et al., 2015a). The study describes particular types of accidents and hazards of winter navigation. This analysis included a description of the system implemented to manage the operations of vessels during winter, and a description of the particular accidental scenarios and their occurrence frequencies. This and other previous analyses (Jalonen et al., 2005; Riska et al., 2007), represent important and necessary information describing the operative performance of ships in a context where limited research has been performed. Notably, these studies have particularly detected the operation types which would benefit most from further risk management developments. However, applicable actions and recommendations for improving winter navigation operations are still lacking.

Risk management aims to develop a coordinated set of activities and methods used to direct an operation and to control the safety system and the risks that can affect the operation performance and the ability to successfully reach its objective (International Organization for

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* Corresponding author.
E-mail address: osiris.valdez.banda@aalto.fi (O.A. Valdez Banda).

http://dx.doi.org/10.1016/j.marpolbul.2016.03.071
0025-326X/

Standardization, ISO, 2009; Leveson, 2011). Thus, risk management should be linked to the identification and strengthening of the conditions which represent the basis for the successful performance of an operation (Dekker, 2014; Hollnagel, 2014).

Hence, this study presents a model for assessing the risk of winter navigation operations performed in the GOF, extending earlier work to winter conditions. The model describes and assesses the main operations performed by the vessels navigating in this area during wintertime, analyses the risk of ship collisions in the contexts of the mentioned operations, assesses the related oil spill risks, and proposes risk control options for the execution of winter navigation operations.

2. Methodology and data

The methodology utilized for the analysis is based on the structure proposed in the Formal Safety Assessment (FSA) by the International Maritime Organization (IMO). FSA is defined as a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of IMO's options for reducing these risks (International Maritime Organization, IMO, 2005). Originally, FSA represented a tool for supporting the evaluation of new regulations and compare proposed changes with existing standards (Ruud and Mikkelsen, 2008). Today, FSA is utilized to perform a balanced analysis between various technical and operational issues including the human element, and between safety and costs.

This study adopts FSA as a process for structuring a risk management model which serves as a tool for exploring the safety performance of the most common winter navigation operations of ships navigating in the ice covered waters of the GOF. Thus, the model represents an instrument for further reflection on the performance of the stakeholders involved in the execution of these operations.

FSA consist of six steps, which are taken as a basis for defining the risk management model structure. Table 1 presents these six steps as part of the methodology for developing the model, as well as the results obtained after execution of each step.

Table 1
The six steps of the FSA used as a basis to define the model structure.

FSA step	Task
Methodology and data (Section 2)	
0	System description
1	Hazard identification
2	Risk analysis
3	Risk control options
Results (Section 3)	
4	Improve–benefit analysis
5	Recommendations

2.1. System description (Step 0)

A clear understanding of the components and context of the system and their relation to accidents is essential for defining the model scope and for identifying the main factors influencing the performance of winter navigation operations.

2.1.1. Ice conditions

In the GOF, the first sea ice cover appears in the eastern part (Russian coastal areas) and it gradually extends westwards. The type of ice experienced every winter in this area includes different forms of floating and fasted ice, starting from the formation of new ice and ending with the most extreme formations of consolidated packed ice. Ice ridges and very thick ice levels can be also experienced in this area, representing the main challenges to the execution of the ship traffic operations. The formation of different types of ice in the GOF depends on the severity of the winter experienced, mild winters (e.g. winter 2014–2015) with few spots of light ice conditions, and/or severe winters (e.g. winter 2003–2004) with a total ice covered GOF. A more elaborated description of ice types and ice formation in the GOF is presented in Riska et al. (2007).

2.1.2. Winter navigation operations

Winter navigation operations are categorized in two general types: ship independent navigation and icebreaker assistance operations. Ship independent navigation is described as the navigational operation that begins when a merchant vessel enters areas covered with sea ice and navigates in them without in site assistance of any other type of vessel. Icebreaker assistance includes four main operation types: escorting, a single ship, leading convoy of several ships, cutting loose when a vessel got stuck in ice, and towing a ship (Rosenblad, 2007).

2.1.3. The Finnish–Swedish winter navigation system (FSWNS)

The FSWNS guides and rules the navigational operations performed by ships every winter at the Baltic Sea, including operations performed in the GOF (Riska et al., 2007). The FSWNS aims at ensuring the safety of the vessels and crew navigating in ice conditions and protecting the natural environment (Finnish Transport Agency, Liikennevirasto, 2014b). The system is ruled by ice class regulations which define the technical requirements for the vessels attempting to navigate in ice conditions. This is complemented with additional requirements for cargo handling and with the meteorological and ice information received from ice services. Based on this information, traffic restrictions are settled in different zones of the Baltic Sea. The restrictions aim at supporting ship traffic flow and better coordination of icebreaker assistance. The complete description of the FSWNS is presented in Finnish Transport Safety Agency (Trafi) (2010).

2.1.4. Input from the human performance

The input from the human performance in this study is limited to the interaction among the crew performing operations on the ship's bridge during the execution of the four described operations. The analysis of the human performance assesses several common performance conditions for performing the tasks included within the execution of the operations. An extended description of the implemented method for this analysis is presented in Section 2.3.6.

2.2. Hazard identification (step 1)

In previous studies, extreme ice conditions and the expertise of the people performing winter navigation operations have been pointed as the main challenging factors for ensuring the safety of navigation in ice conditions (Valdez Banda et al., 2015a,b). These studies present detailed information given by the accidents commonly reported in the GOF, the ice condition in which these accidents occurred, and detailed description of hazardous scenarios based on accidental data and expert consultation. This section summarizes the findings of these studies and posteriorly adopts these into the structure of the proposed model.

2.2.1. Accident types

The most common accident occurring during winter navigation operations is collision, including mainly ship-to-ship collision, ship-to-icebreaker collision and few cases of icebreaker-to-ship collision. This accident accounts for almost 50% of the accidents occurred in ship independent navigation and around 95% of the accidents occurred in icebreaker assistance operations. The second most common accident is propeller damage, which is mainly reported by ship independent navigation.

2.2.2. Ice and weather conditions

Consolidated ice with an ice thickness between 15 and 40 cm are the conditions in which most of the accidents are reported. Ice ridges represent another common factor reported in the accidents. Experts in winter navigation have ranked these conditions together with poor visibility and extreme temperatures and weather conditions (winter storms, strong winds, icing on board, etc.) as the main conditions challenging the performance of ships.

2.2.3. Identification of hazardous scenarios

Based on accident data and expert opinions, hazardous scenarios can be portrayed. For example, accident data presents that the navigation of several general cargo vessels in consolidated ice with an ice thickness between 15 and 40 cm represent a higher risk of collision. Moreover, when general cargo vessels navigate independently in an ice channel, manoeuvres such as passing, crossing and encountering represent another hazardous scenario which may lead to collision.

In icebreaker operations, assisting several vessels in an ice channel with extreme ice conditions, low temperatures, ice thickness between 30 and 60 cm and consolidated ice with ridges represent one of the most complicate scenarios. For example, complex situations where the assisted vessels formed in the convoy need to keep a high speed and close distance in order to avoid getting stuck in ice, hence, increasing the risk of collisions with more severe consequences.

Moreover, expert consultation has also identified hazardous scenarios such as the manoeuvring of a ship in a limited space area (e.g. in an ice channel). This is a hazardous scenario because the ice conditions in the edges of the channel may cause an involuntary bouncing of the vessel back to the channel and provoking a collision when e.g. passing another vessel. A detailed list of hazardous scenarios can be found in Valdez Banda et al. (2014).

2.3. Risk analysis: risk management model constitution (step 2)

The understanding of the theoretical foundation and functionality of the model is essential for its proper employment. Therefore, it is fundamental to understand the risk perspective adopted in the analysis, also to clearly identify the components included within the model, and to understand their actual function. Fig. 1 presents the general description of the different components included in the risk management model of winter navigation.

2.3.1. Risk perspective and model use

The understanding of risk and the corresponding risk perspective is essential for the elaboration of a risk analysis. In this study, risk assessment is defined as the systematic consideration of the uncertainties (U) regarding the occurrence of events (A) and their consequences (C), in light of available background knowledge (BK) (Aven, 2010a). This represents adopting a constructivist basis for risk analysis, based on the integration of available data from accident reports, ice and traffic conditions registered every winter in the GOF, and the interpretation of expert views and risk assessors about common operational characteristics and the influence of the human element on the performance of operations, by using different available evidence (Goerlandt and Montewka, 2015b). In line with this perspective, the systematic approach to measure and describe risk in this study is:

$$R \sim (A, C, U|BK). \tag{1}$$

The framework aiming at risk analysis, which is presented in this article, is developed by means of Bayesian Networks (BNs). BNs represent a modelling technique that can depict relatively complex dependencies and cope with uncertainty while also having a graphical dimension (Pearl, 2014). Thus, BNs enable reflection of the available knowledge

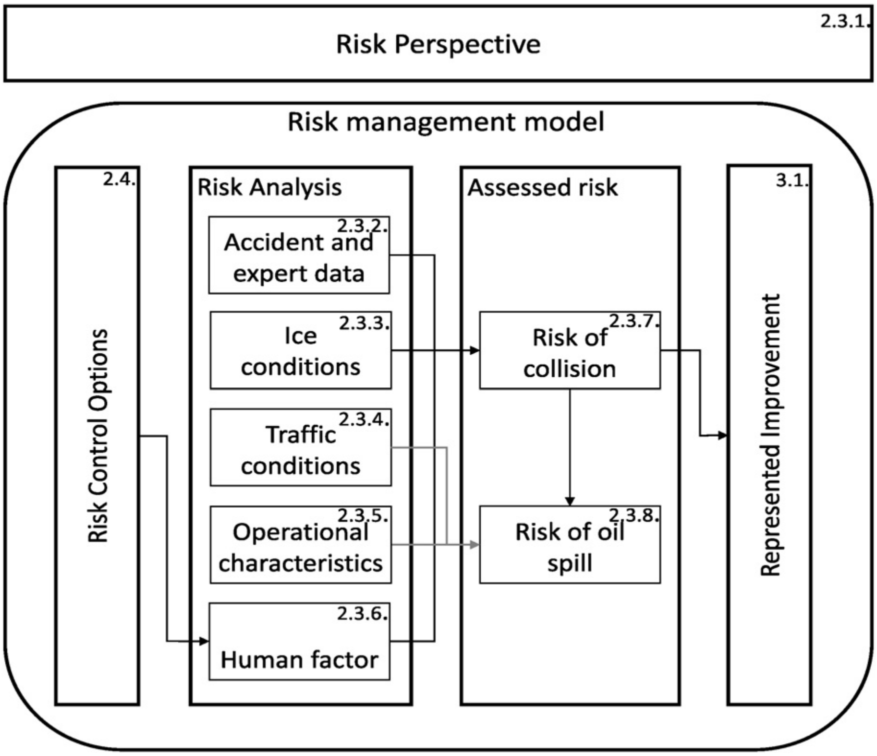


Fig. 1. A flowchart presenting the description of the components under analysis within the risk management model of winter navigation. At each variable the reference to a section which describes a given component is provided.

on the process being analysed and its understanding in a comprehensive way (Montewka et al., 2014).

A fundamental issue is to clearly define how the risk analysis is meant to be applied in decision making. Commonly, risk analysis frameworks developed by using BNs are aimed to be a tool for calculating probabilities, which are assessed with risk acceptability criteria or used in optimization procedures for making the decision in an almost automatic way (Aven, 2010b). Literature presenting these types of approach for analysing the risk of oil spills in open sea context can be found in e.g. (Lehikoinen et al., 2013; Klanac and Varsta, 2011).

The framework proposed in this article does not focus on the probabilities to determine if the risk is acceptable or unacceptable. The objective is rather to support the transmission of the evidence to the available information integrated into the model and to identify the risks of collision and accidental oils spills. Thus, the model conveys an argumentation based on available evidence, provides a basis for communication among the stakeholders of the operations and it serves as an aid to thinking. These functionality characteristics are common in non-predictive models (Hodges, 1991). The purpose of these models is to alleviate the argument rendered by the risk quantification utilizing the model, and provide transparency about the analysed risk and its evidence, which represent essential aspects of risk-informed decision making (Aven, 2011; Watson, 1994).

The main challenge for frameworks of this type is the limited time for decision makers to implement and review the total function of a framework constructed under these characteristics. Thus, the intended users of the model proposed here are panel expert-reviewers, such as the FSA Expert Group in IMO decision making (Psaraftis, 2012). Moreover, the model can also be utilized by the actual decision makers in the execution of the operations (safety managers in shipping companies, icebreaker operators, and maritime safety controllers and authorities), who are the ones with commonly restricted time-schedule and also are inexperienced in the utilization of this type of tools.

2.3.2. Accidental and expert data

The analysis of accidental data reported in Finnish maritime areas in four winter periods is utilized as one of the main references to determine the probability of collision in each operation. This data is strengthened with an assessment made by experts about the potential severity of collision in different operations. The initial determined probability is obtained by comparing the number of collisions reported and the total number of port arrival and departures in ports of Finland during the four analysed winter periods, this for the analysis of ship independent navigation. For collisions in icebreaker assistance operations, the comparison between the number of collisions reported and the number of assistance operations performed by icebreakers during three winter periods is performed. The complete description of this information is presented in Valdez Banda et al. (2015a). Table 2 summarize the probability of collision obtained for each type of operation and the severity level registered in accident reports and the severity level assessed by experts.

Table 2
The probability and severity level of collisions in winter navigation operations (adapted from Valdez Banda et al., 2015a).

Winter navigation operation	Probability of collision	Severity level[a]	
		Reported	Assessed
Ship independent navigation	1.5E − 04	LS; S	LS; S; VS
Icebreaker assistance operations			
Convoy	1.4E − 04	LS; S	LS; S; VS
Towing	3.7E − 04	LS	LS
Cutting loose	4.6E − 05	LS	LS; S

[a] Severity levels: less serious (LS), serious (S), very serious (VS).

The values presented in Table 2 are considered in order to posteriorly create the calculation of the probability of collision in the model proposed in this study (see Section 2.3.7.).

2.3.3. Analysis of ice conditions for determining the exposure to collision

The classification of the ice conditions and determination of exposure to collision in this section is determined by combining the ice conditions existing every winter in the GOF and an assessment made by experts to determine the risk of performing operations under these conditions. The utilized group of experts to create the exposure to collision based on ice conditions included:

- Two icebreaker captains from Finland; each of them with more than 15 years of practical experience in the performance of ship navigation in ice condition;
- Two Vessel Traffic Service (VTS) operators from Finland; one with about 10 years of practical experience and the other with 7 years of practical experience in the monitoring of winter navigation operations;
- One pilot also from Finland; he has more than 15 years of experience in the provision of pilotage services during wintertime.

For this classification, the experts received three different groups of ice conditions describing the main elements included in traditional ice charts (see Finnish Meteorological Institute, FMI, 2014). Thus, the first group called ice conditions A include the main type of ice covers registered in the Gulf of Finland, the second group called ice conditions B include extra conditions which can be additional to the ice conditions A, and finally a third group called ice thickness categorizing 3 scales of ice thickness. This categorization has previously been utilized in the analysis of ship accidents during wintertime (see Valdez Banda et al., 2015a). Finally, the experts are asked to group the conditions and ice thickness into three levels (High–Average–Low) which describe the exposure to collision in the context of the development of the four analysed operations. Table 3 presents exposure to collision resulted from the most common combinations assessed by the experts.

2.3.4. Traffic conditions during wintertime in the GOF

Ship traffic conditions during wintertime are limited by the traffic restrictions established in every port located in the Northern Baltic. The GOF has different ice conditions depending on the winter severity, this restricts the navigation of the vessels belonging to certain ice class. In general, the most common type of vessel navigating the GOF during winter time is general cargo, this is followed by oil, chemical and LNG tankers.

In order to accurately estimate the probabilities of the type of vessels navigating in the GOF during wintertime, the analysis of Automatic Identification System (AIS) data has been elaborated. The selected data for this analysis includes the registered vessels navigating in the GOF in two particular months, March 2011 (in a winter considered as a severe one) and January 2012 (a winter considered as an average one). Based on this data, general cargo vessels account for about 56% of the total vessels reported, tankers represent about 26%, Roll On–Roll Off passenger (Ro-Pax) vessels are about 6%, and other types represent the remaining 12%. This evidence also demonstrates that traffic trends remain similar either in severe winters or average winters. Appendix A presents detailed statistical information including the type and deadweight tonnage of vessels navigating in the GOF during the two analysed winter months (HELCOM, 2012).

2.3.5. Operational characteristics and damage estimation

The description of the operational characteristics of ships navigating independently and the three described operations of icebreakers are mainly defined by the analysis of registered AIS information (e.g. reported ship speeds) and the analysis of videos created from reported AIS

Table 3
Exposure to collision based on ice conditions. Classification performed by winter navigation experts.

Ice conditions A	Ice conditions B	Ice thickness	Exposure to collision	Classification
Consolidate, level, compact or very close pack ice	Rafted ice	> 40	High	1
	Ridge and hummocked ice	21 – 40		2
Fast Ice	None	21 – 40 & > 40		3
Close pack ice	Rafted ice	21 – 40	Average	4
New ice	Ridge and hummocked ice	01 – 20		5
	None	01 – 20		6
Open pack ice	None	01 – 20	Low	7
Very open pack ice	None	01 – 20		8

data which represent an actual description of ship navigation during wintertime (Ploskonka, 2013). The experts mentioned in point 2.3.3 have also contributed to backing up the main findings from the video analysis and for a clearer representation of the context where damages can occur. Appendix B presents more details about the variables estimated for the operational characteristics of the winter navigation operations and the actual contexts defining these variables.

The estimation of the possible area of collision has been developed by including a general analysis of the dimensions and locations of the cargo vessels and tankers navigating during wintertime within the GOF. For this purpose, Smailys and Česnauskis (2006) and McAllister et al. (2003) are the two particular studies considered for this task. The study by Smailys and Česnauskis (2006) is initially considered for obtaining a detailed description of the general characteristics of different types of tankers navigating in the Baltic. The study by McAllister et al. (2003) presents details about the locations and dimensions of bunkers located in tankers and other different types of cargo ships (containership, ro–ro vessel, cruise ship, bulk carries, etc.). Thus, these two sources of information are used to create descriptions of the layout of tankers and bunkers of the vessels navigating in the GOF.

For the actual calculation of the possible damage extent derived from collisions between ships, the simplified collision model (SIMCOL) by Brown (2002) is utilized. This study provides a set of probabilities, probability functions and equations to represent a specific collision scenario in a Monte Carlo simulation. The scenarios are defined probabilistically using a set of determined variables: collision angle, struck location, deadweight tonnage of the striking vessel, deadweight tonnage and structural characteristics of the struck vessel, and the speed of collision. This study has been implemented for the assessment of 10,000 collision scenarios including ships of different characteristics. The results present the estimation of the damage extent in struck vessels of different structure characteristics, including tankers with one single hull and also double hull. Appendix C describes the method for damage estimation and the results from the influence of collision on vessels with different structural characteristics and their incorporation on this study for calculating the probabilities in the proposed risk management model of winter navigation operations.

The SIMCOL proposed by Brown (2002) represents the damage estimation of collisions occurred in open sea waters. However, ice conditions represent a different context where the strength of the collision is higher due to the counterforce existing in severe ice conditions (e.g. ice channel borders and unbroken ice). Thus, in open sea waters the struck vessel is able to release certain degree of the total collision strength due to the freedom of movement in the water. However, this is not the case of collisions in ice conditions. Therefore, the inclusion of the possible increased effect of collisions in the ice channel and unbroken ice has been incorporated by including the results obtained by Nelis et al. (2015). This study proposes a methodology for the prediction of the collision damage in ice conditions. The methodology is based on simulations where two tankers collide at a 90 degrees angle in ice. Appendix C also presents details of this methodology and its incorporation on the calculation obtained in Brown (2002) and on the calculations for the probabilities in the constructed model in this study.

2.3.6. Human factor estimation

The analysis of the human interaction in the development of the four assessed winter navigation operations is performed by executing an expert elicitation with the support of the Cognitive Reliability Error Analysis Method (CREAM) proposed by Hollnagel (1998). This approach considers the influence of the performance conditions as more important than the postulated human error probability (Hollnagel, 2012). Thus, the combination of the input information from experts in winter navigation and the CREAM enable the assessment of the main Common Performance Conditions (CPCs) for the execution of the main relevant tasks assigned to vessels and icebreakers crew working on the ship's bridge at the moment the described winter navigation operations are performed. The CREAM has previously been used to assess the human error performance in oil tanker operations in (Akyuz, 2015; Martins and Maturana, 2013). Thus, the evaluated CPCs in the risk management model of winter navigation are:

1. Adequacy of the organization
2. Available procedures and plans to execute the operations
3. Man–machine interface and operational support
4. Available time to plan and perform the operations
5. Training and preparation
6. The quality of the collaboration on the bridge.

For the quantification of the failure probability in each CPC, a detailed expert elicitation process was executed. The relations of the scores from adopted CPCs and the control modes are considered as proposed in the extended method for the calculation of the performance influence index and Cognitive Failure Probability (CFP) in He et al. (2008). These CFPs pivot on three components in the assessment of the failure: detecting, assessing and acting. These six CPCs and the three mentioned components are incorporated and assessed in a BN to determine the probabilities of human error in each winter navigation operation. The description of the expert elicitation process and the utilized methodology is presented in detail in Valdez Banda et al. (2015b).

Table 4
Probability of collision depending on the level of the accidental exposure (due to ice conditions) and the existence of human error.

Exposure	Independent navigation	Convoy	Towing	Cutting loose
High 1	0.40	0.40	0.20	0.15
High 2	0.35	0.35	0.15	0.13
High 3	0.30	0.30	0.12	0.11
Average 4	0.20	0.20	0.10	0.09
Average 5	0.15	0.15	0.08	0.07
Average 6	0.10	0.10	0.05	0.05
Low 7	0.05	0.05	0.03	0.03
Low 8	0.03	0.03	0.02	0.02

2.3.7. The risk of collision

In order to calculate the probability of collision, a combinatorial analysis between accident and expert data (see 2.3.2), exposure to accidents due to ice conditions (see 2.3.3), and the human error probability (see 2.3.6) has been executed. The consideration of these three information sources enables the designation of collision probability scales for each type of winter navigation operation. Table 4 presents the designated collision probability scales for each operation.

The designated probability of collision for each operation type resulted from the integration of historical data of the accidents reported during wintertime and assessments made by experts regarding the complexity of different ice conditions and the influence of the human performance. These established probabilities attempt to represent an informative scale to assess the risk of collision in the development of the analysed operations. Thus, the probabilities are degrees of belief by experts based on the available information as the one described above (Aven, 2010a).

2.3.8. The risk of oil spills

The potential oil spill derived after a collision is calculated based on two general assumptions: the struck vessel is a tanker with the common characteristics of those navigating in Baltic Sea area (see Smailys and Česnauskis, 2006) and the area of collision is on cargo tank(s), or the struck vessel is also a tanker or another type of vessel but the area of collision is on the bunker tanks.

For calculating the oil outflow from cargo tanks in a tanker, the study by Smailys and Česnauskis (2006) is utilized. This study proposes a modified methodology which is suitable for expeditious application based on existing complex general purpose methods designated for estimation of the expected outflow. The methodology is suitable for application when there is also limited data about design of the cargo tanks and particulars of the accident. The input data needed for applying this method are the volumes of the cargo tanks and probabilities of possible damage.

Table 5
The assessed RCOs designated to each CPC for supporting and improving the human performance during winter navigation.

CPC name	RCOs
Adequacy of the organization	Improve organizational safety culture Improve the safety management Improve personnel's satisfaction
Available procedures and plans	Improve emergency drills Improve operational procedures
Man–machine interface and operational support	Improve the process for designation of responsibilities Improve e-navigation support Improve ship bridge design
Available time	Improve time management
Training and preparation	Improve navigational training Improve planning skills Improve safety and risk management training
Collaboration quality	Improve communication (in the bridge)

In the case of accidental oil spills from bunker tanks, the study performed by McAllister et al. (2003) is utilized to calculate the oil outflow. This study provides a detailed risk assessment of oil spills from bunker tanks of cargo vessels in the event of collision. The study proposes a probabilistic oil outflow methodology based on IMO guidelines and draught regulations. The study based its methodology on the data collected and analysed from bunker oil spills in accidents occurred to different types of ships during a period of 14 years.

In the risk management model of winter navigation proposed in this paper, the calculation of the oil outflow in both cases depends on the input data from the estimation of the damage extent (see 2.3.5) and the characteristics of the vessels involved in the accidents (size, type, traffic direction, and loading conditions). Thereby, these considered aspects are linked to calculation methods of the potential oil outflow proposed in the two mentioned studies. Appendix D describes more details about the methodology for the calculation of the oil outflow from accidental oil spill from cargo and bunker tanks and its integration to the constructed model.

2.4. Risk control options: risk management model constitution (step 3)

In order to analyse and implement possible actions to reduce the risk of collisions and accidental oil spills, 13 Risk Control Options (RCOs) are integrated in the model structure (see Section 3.1). These RCOs are focused in the analysis and detection of potential areas of opportunity in the performance of the ship's and icebreaker's crew who are located in the bridge executing different tasks at the moment the four analysed winter navigation operations are implemented. The analysis of the tasks involved in the execution of ship operations has previously been implemented in the assessment of ship collisions (see Hänninen and Kujala, 2012). In the structure of the risk management model of winter navigation, to each CPC included for the analysis of human performance (see point 2.3.6), one or more RCOs are designated. The aim of this section of the model is to assess the potential influence of these RCOs in the performance of the crew when executing the operations. Table 5 presents the 13 RCOs designated to improve the human performance during winter navigation operations.

In order to include the values for calculating the potential influence of the proposed RCOs on the winter navigation operations, an expert elicitation is performed. Experts from Finland and Russia participated in the elicitation. The consulted experts included ship and icebreaker captains and officers with significant time of experience in the practical development of navigational operations during wintertime. More details about the description of the RCOs, information about the consulted

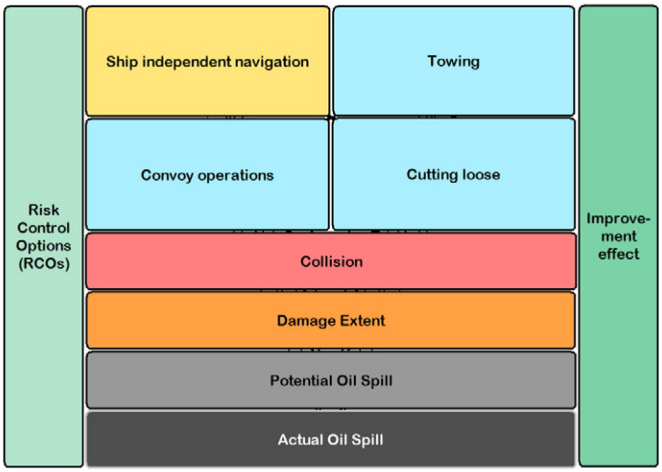


Fig. 2. The main structure of the proposed "risk management model of winter navigation".

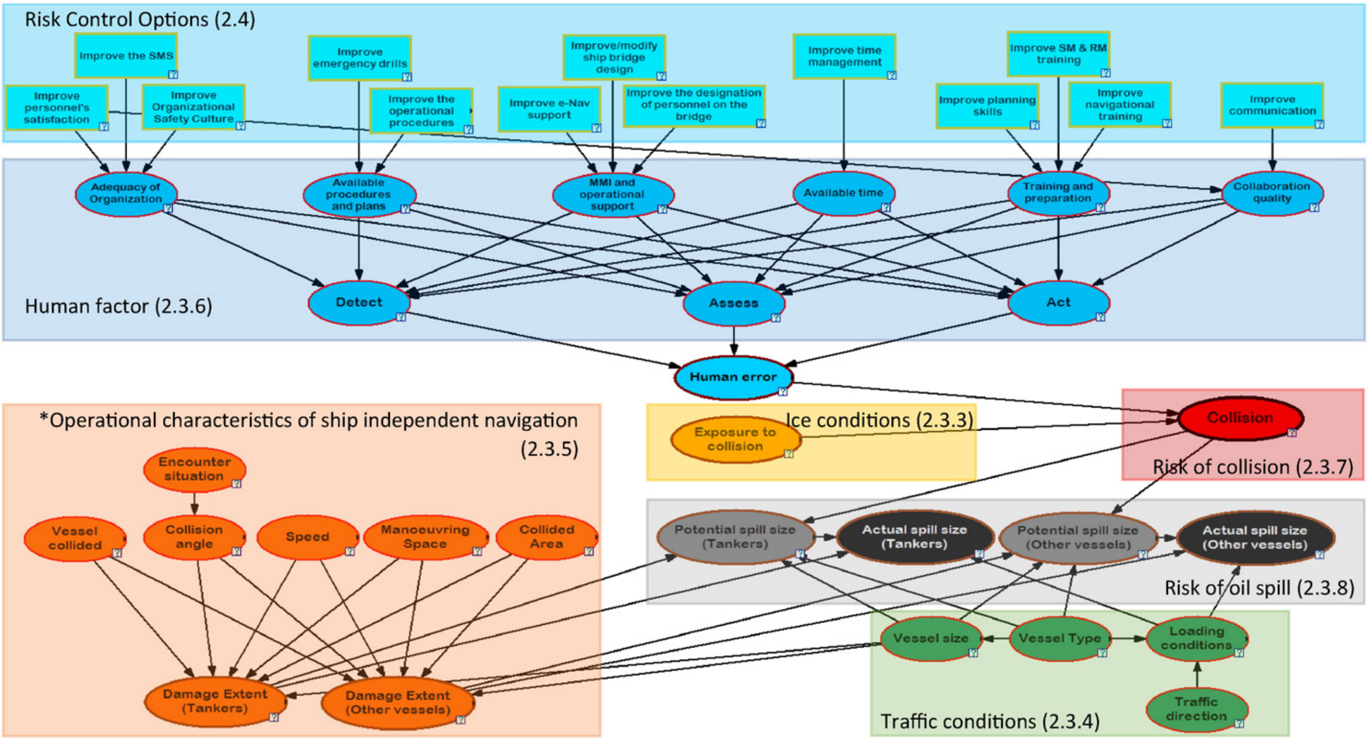


Fig. 3. The constructed Bayesian network model for the analysis of the four winter navigation operations. This figure presents the model for the analysis of ship independent navigation (*the included components of the operational characteristics used to estimate the damage extent differ in each winter navigation operation, see Appendix B).

experts and the expert elicitation process is available in Valdez Banda et al. (2015b).

3. Results

3.1. The model structure

The structure of the final model initially includes a network presenting different sub-models which contain several components included in the four models constructed to evaluate the probabilities of collision and potential oil spills in the four analysed winter navigation operations. Moreover, as a way to easily find the resulted probabilities of the main outcome variables of the network, other sub-models are also incorporated. These sub-models have a direct access to the main output variables of the four models created for the analysis of winter navigation operations. Fig. 2 presents the general structure of the risk management model of winter navigation.

Table 6
The estimated percentage of improvement in human performance with the application of the proposed RCOs.

RCOs	Percentage of improvement							
	Independent navigation		Convoy		Towwing		Cutting loose	
	FIN	RUS	FIN	RUS	FIN	RUS	FIN	RUS
Improve navigational training	17%	13%	13%	19%	13%	13%	13%	12%
Improve safety and risk management training	17%	13%	13%	8%	13%	13%	13%	12%
Improve e-navigation support	15%	9%	13%	8%	13%	7%	9%	9%
Improve time management	10%	5%	12%	5%	12%	5%	13%	5%
Improve planning skills with training	0%	13%	0%	8%	0%	13%	0%	12%
Improve ship bridge design	12%	0%	10%	0%	10%	0%	13%	0%
Improve organizational safety culture	6%	5%	7%	4%	6%	3%	6%	6%
Improve the safety management	6%	3%	7%	2%	8%	1%	8%	3%
Improve personnel's satisfaction	4%	5%	4%	6%	5%	5%	4%	6%
Improve emergency drills	0%	8%	0%	8%	0%	8%	0%	6%
Improve operational procedures	0%	8%	0%	8%	0%	8%	0%	6%
Improve the process for designation of responsibilities	0%	7%	0%	8%	0%	8%	0%	8%
Improve communication (in the bridge)	6%	0%	3%	0%	3%	0%	3%	0%

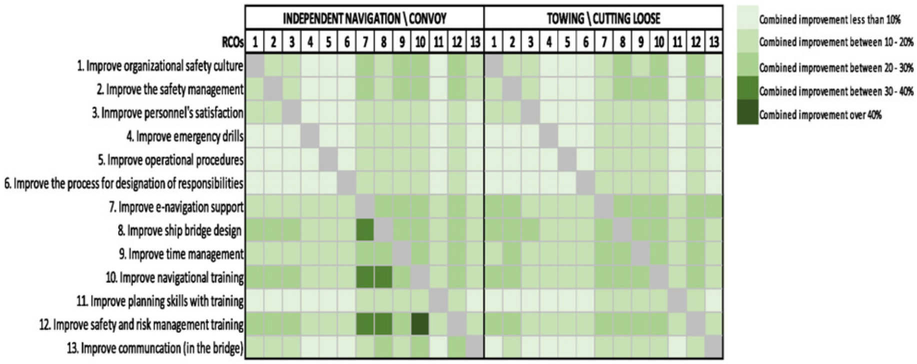


Fig. 4. Percentage of expected improvement in ship/icebreaker crew's performance (located in the bridge) with the combination of the proposed RCOs for each winter navigation operation (Finnish experts).

This main structure (Fig. 2) includes four sub-models representing the analysis of the analysed winter navigation operations. The other nodes presented in the figure are used for having an easy and fast access to the probabilities of collision, damage extent, potential oil spills in m^3, the actual oil spill in tons, and the effect of the risk control options. Fig. 3 presents the resulted Bayesian network(s) included in each sub-model for the analysis of risks in the four winter navigation operations.

3.2. Improve-benefit analysis: risk management model analysis (step 4)

The analysis of the influence of the RCOs after the execution of the elicitation with winter navigation experts from Finland and Russia has identified which are the potential actions with a more significant positive effect to ensure and improve the performance of the crew located on ships and icebreakers. Table 6 presents the estimated percentage of improvement of each RCO proposed, classified by operation and country of the consulted experts.

Furthermore, the model is able to identify which are the most effective combinations between the proposed RCOs in each operation. Figs. 4 and 5 present four matrices describing the combination of the RCOs and the generated percentage of expected improvement of the human performance for the four analysed operations. The estimations made by winter navigation experts in Finland and Russia are depicted in Figs. 4 and 5 respectively.

3.3. Recommendations: the outcome of the risk management model (step 5)

3.3.1. Model general outcome

Based on the analysis of accident statistics, ship independent navigation and convoy are the winter navigation operations whit the higher probability of collision. In the functioning of the model, the combination between accident statistics, the established probabilities for the exposure to collision, and the probability representing the human performance, presents also higher risk of collision in the two mentioned operations.

The analysis of the operational characteristics in each winter navigation operation enables the extraction of the probabilities of oil spill. Table 7 presents the probability of oil spill from cargo tanks and bunkers which are obtained with the application of the risk management model of winter navigation.

3.3.2. Extended results from the analysed RCOs

Improving navigational training, improving risk management training and improving e-navigation support are the RCOs with a higher probability to improve the performance of the crew located in the bridge when executing the four analysed operations (see point 3.2). In this section, an extended description of the results obtained by the analysed RCOs with the experts is presented. The aim is to describe in more details the results of the analysis of human factor and its connection with the detected areas of opportunity for improvements in the winter navigation operations. This information represents the extended description of particular aspects needed in connection with the implementation of the proposed RCOs. The explanatory description of these aspects were obtained during the expert consultations. Tables 8 and 9 presents detailed information extracted from the consultation performed with to winter navigation the mentioned experts in Finland and Russia.

4. Discussion

4.1. The model structure

Basing the foundations of the produced risk management model of winter navigation on the structure of the FSA proposed by IMO, enables the establishment of a tool for supporting a risk analysis and management of the most practiced navigational operations during wintertime at the GOF. The tool is able to combine the most relevant elements for

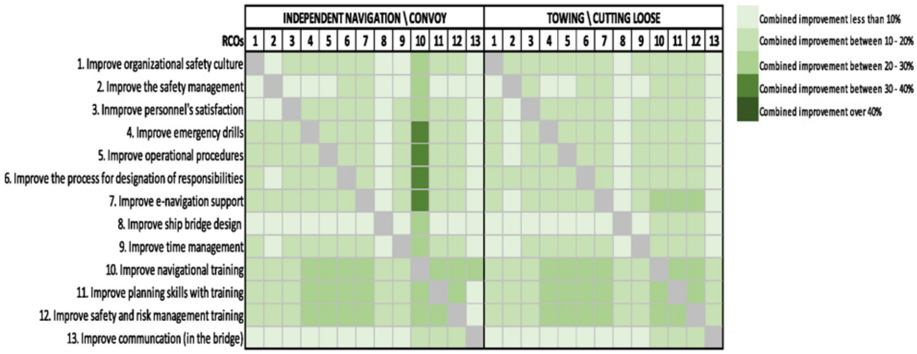


Fig. 5. Percentage of expected improvement in ship/icebreaker crew's performance (located in the bridge) with the combination of the proposed RCOs for each winter navigation operation (Russian experts).

Table 7
The probability of oil spill by operation.

Oil spill in tons	Probability by operation*			
	Independent navigation	Convoy	Towing	Cutting loose
Cargo oil				
1–1000	0.002	0.001	1.0E−05	1.2E−05
1000–5000	0.005	0.002	0	1.02E−05
5000–15,000	0.004	0.002	0	6.6E−05
>15,000	0.003	0.003	0	0
Bunker oil				
1–1000	0.002	0.002	9.4E−05	5.7E−04
1000–5000	0.005	0.005	8.4E−05	9.0E−05
>5000	0.001	0.001	8.4E−05	7.2E−06

Higher spill sizes overestimates due to limitations of underlying engineering models.

analysis of the characteristics of these operations, the ship traffic conditions in the GOF during wintertime, the context (ice conditions) where the operations are preformed, and the analysis of the human performance. Together, these elements are used to calculate the risk of collision and potential oil spills derived from it.

For the analysis of these mentioned elements, several methodologies are implemented. A method for the calculation of the damage extent in ship-to-ship collisions in ice conditions (Brown, 2002; Nelis et al., 2015), methods for estimating the potential oil spills after the collision (McAllister et al., 2003; Smailys and Česnauskis, 2006), and a method for human error quantification (Hollnagel, 1998; He et al., 2008). Moreover, several information sources are needed to provide input data for executing the mentioned methods. Thus, using Bayesian networks as the mean to create the model structure enables the integration of the listed methods and several information sources such as historical information registered in data bases (e.g. accidents reported and traffic statistics) and qualitative information extracted and adapted from expert consultations (e.g. determining the influence of the human factor).

In general, the constructed structure of the model provides options to use it as a tool to display and easily represent the risk of collision and accidental oil spill, and/or as tool to analyse the influences between the different variables involved during the execution of the winter navigation operations.

4.2. The results obtained from the model application

4.2.1. Risk of collision and accidental oil spill and the elements for its calculation

The model presents ship independent navigation and convoy as the two operations with the higher risk of collision which can lead to oil spills. The model indicates that the probability of these accidental events is higher in the case of ship independent navigation and convoy represents the second operation with a higher risk. The accidental risk of these two operations is also represented in the accidental reports analysed in (Valdez Banda et al., 2015a) and confirmed by the results obtained from the expert consultation performed in this study and the general results obtained from the model application.

The model indicates that oil spills of 1000 to 5000 tons are the most probable (with a maximum of 1.4% probability) to occur in the two mentioned operations, these combining oil spills from cargo tanks and bunkers. Major oil spills, meaning spills over 15,000 tons, are less probable (with a maximum of 0.8% probability) and these are mainly rising from collisions with oil tanker vessels during the execution of the mentioned operations. In the case of towing and cutting loose operations, the probability of collisions ending in oil spills is almost non-existent. Thus, the model and its informative outcome can be utilized for supporting the planning of the required capacities for oil spill response vessels in sea ice conditions within the GOF, which is a relevant issue in oil spill risk management (International Maritime Organizations, IMO, 2010). Thereby, providing elements to support the analysis and management of the risk of accidental oil spills in a navigational context where little research has been performed (Lehikoinen et al., 2015, 2013; Montewka et al., 2014; Nelis et al., 2015).

The application of this model aims at providing representative trends for identifying the risks and areas of opportunity within the development of the analysed winter navigation operations. Thus, probabilities are using for that particular purpose and these should not be interpreted as mean to predict the oncoming state of the winter navigation operations. The subjective nature of the risk analysis, where uncertainties are assessed in a comprehensive manner, is acknowledged e.g. by Flage et al. (2014) and the results should be understood as such. Moreover, this model is constructed under the characteristic of Bayesian networks which is limited to provide certain understanding of safety

Table 8
Detailed issues pointed during the analysis of the influence of the human factor on the development of winter navigation operations (Finnish experts).

CPC assessed as less efficient	Available procedures and plans for managing and supporting the winter navigation operations Issues detected: - Extensive paper work demanded during the performance of the operations Need detected: - Better integration of regulatory demands, administrative procedures and the resulted safety management demands Other facts: - The quality of instructions contained in the operational procedures and plans is good and it fulfils the essential needs for the development of the operations.
Operation	Issues and needs detected
Ship independent navigation	Issues detected: - The operation is evaluated as the lowest in terms of efficiency. - The lack of experience and skills demanded for the performance of this operation is a constant issue. Need detected: - Improvement of navigational training is the action proposed to enhance the efficiency of the operation.
Convoy	Issues detected: - Lack of real time information and methods for creating an appropriate situational awareness and guide the execution of the operation Need detected: - Adequate navigational training and training for creating better methods for assessing the risks of the operation - New technological tools and methodologies for enhancing situational awareness for supporting an efficient control of this and also other operations
Cutting loose	Issues detected: - The execution of the operations relies almost completely in the knowledge and skills of the master. Need detected: - Adequate navigational training and training for creating better methods for assessing the risks of the operation - Improving the ship bridge design can bring significant advantages for supporting an operation in which ship manoeuvring is crucial.

Table 9
Detailed issues pointed during the analysis of the influence of the human factor on the development of winter navigation operations (Russian experts).

CPC assessed as less efficient	Man–machine interface and operational support for the execution of the operations Issues detected: - Without appropriate expertise and training, technology can be inefficiently implemented and used. Need detected: - Expertise, adequate navigational training, and appropriate methods for managing the risk and safety of the operations Other facts: - Technology is a crucial component to support winter navigation operations nowadays.
Operation	Issues and needs detected
Ship independent navigation	Issues detected: - Ship independent navigation and convoy operations ranked as the lowest in terms of efficiency Need detected: - Improve navigational training and risk and safety management training - Creating more efficient plans for ship voyage - Better communication with other relevant partners in the execution of the operation and better integration of those in the planning phase - New ways for ship routing in complex ice scenarios
Convoy	Issues detected: - Ship independent navigation and convoy operations ranked as the lowest in terms of efficiency Need detected: - Improve navigational training and risk and safety management training - Creating more efficient plans for executing the operation - Better communication with other relevant partners in the execution of the operation and better integration of those included in the planning phase

and accident occurrence based on the context and purposes defined in the analysis (Hänninen, 2014; Montewka et al., 2014).

4.2.2. The analysis of human factor and the proposed RCOs

The description and assessment of the human performance influence on the development of the winter navigation operations attempt to numerically represent the impact from the main executors of the operations (ship/icebreaker master and his/her crew) on the accidental risk of collisions. This analysis is strengthened by incorporating the current outcome of the operations based on accident statistics and the analytical contribution from other relevant partners supporting the execution of the operations.

The results of the analysis of the human performance are presented in the contexts of two nations heavily involved in the navigational operations in the GOF. First, the analysis performed with winter navigation experts from Finland detected that the available procedures and plans for managing and supporting the winter navigation operations is the CPC with the higher need for improvement. This group of experts particular pointed out the need for having safety management systems and methodologies with a more efficient integration between safety regulatory and administrative demands and the correct understanding of the practical context of the operations. Second, the analysis performed with experts from Russia appraised man–machine interface and operational support for the execution of the operations as the CPC with the higher need for improvement. These experts identified the need for providing adequate formation to the persons responsible for executing the operations in order to have an efficient utilization of the different used technologies for controlling the operations while keeping an appropriate situational awareness at any time during their execution.

The two groups of experts have assessed navigational training and safety and risk management training as the most efficient RCOs to improve the performance of winter navigation operations. These are linked to the lack of expertise and adequate formation to perform ship navigational operations particularly in extreme ice conditions which is also an issue mentioned by the experts. The experts from Finland particularly pointed out the need for developing actions of improvement which are focused on creating methods which can properly understand and analyse the risk of winter navigation. Furthermore, these methods must adequately integrate the developments of new technologies for supporting the situational and operational awareness. The improvement of the design in the human operational environment is also pointed as a potential action for supporting the execution of the operations, particularly in cutting loose operations. Thus, opening the need for developing analysis of work environment, collaboration modes and ergonomics applied in the context of the operation. In this context, practical training on-board and the use of ship simulators is essential for providing appropriate formation for the personnel working on the bridge and also for testing the function of the utilized technologies.

Russian experts stated the need for improving planning skills aiming at enhancing the quality and efficiency of the ship voyage plans. They have also mentioned the need for having better communication with other winter navigation members assisting in the development and control of the operations. Thus, finding new ways for supporting the planning and monitoring of the operations with icebreakers and VTS centres, and improving the practicalities of the operations with pilots.

Thus, the two groups of experts seem to share ideas that for controlling the risks of the winter navigation operations, the improvement of the skills and knowledge of the personnel executing the operations is the action to implement. However, it is important to remark that experts specified that improving skills and knowledge requires of training which has been structured based on reasoned elements extracted from the analysis of the operations. Thus, avoiding the common reaction of just increasing the amount of training when the need for training is detected (Er, 2005; Gholamreza and Wolff, 2008). The role of technological tools and appropriate working environments for supporting winter navigation is also pointed as essential element to improve the performance of the operations. Nevertheless, the experts particularly mentioned that technology is efficient as long the knowledge and expertise of the people are also adequate to exploit its maximum capacity.

The influence of the RCOs on the improvement of the human performance has straightforward representation in the risk management model of winter navigation. The use of probabilities to portray the influence of each RCO on the values of the human performance and the stated risk of collision represents a simple form for describing the results of applying an elaborated method for analysis of human performance. Another significant advantage of the model is the possibility of detecting which RCOs are probably more efficient when are jointly applied (see Figs. 4 and 5). Thus, for ship independent navigation, improvement of safety and risk management training and navigational training is the most effective combination of RCOs based on Finnish experts. The same combination is pointed by the experts from Russia, but the effect is not as strongly represented as in the case of Finland. Convoy operations have the improvement of e-navigation support and risk management training as the most effective combination of RCOs based on Finnish experts. Russian experts marked the improvement of e-navigation support and improvement of operational procedures as the most effective combination of RCOs in the same operation.

The application of this model is not evaluating the cost of the RCOs, as would be required by the original process of the FSA. For the reason of brevity this has been changed for a representation of an improved-benefit analysis in the application of these RCOs. This is a detected limitation of the model which aims at pointing an area of opportunity for future research in the topic.

4.3. Evaluation of the model and data

The process for evaluation of the model and data is based on the validity criteria for the analysis of risk proposed in Aven and Heide (2009) and adapted in Goerlandt and Kujala (2014). This focused on defining the reliability of the model and data in terms of accuracy of the risk metric and reliability in terms of ranking across different part of the system. The process includes 4 stages:

- One, defining the degree to which the produce risk numbers are accurate compared to the underlying true risk. The model is structured based on the risk perspective specified in Eq. (1); it does not make claims about the true probability of collision and potential oil spill. Rather, the model applies a quantitative ranking based on a combination of probabilities extracted from historical data and estimations made by experts about the risk level of different ice contexts. As the main aim of the model is to convey an argumentation based on available evidence, accounting for uncertainties of outcome and in the underlying evidence, there is no reference to an underlying "true" risk. This follows from the adopted risk perspective as described in Section 2.3.1.
- Two, defining the degree to which epistemic uncertainty assessments are complete. Appendix E presents a classification of the variables and their sources of information where the strength of the background knowledge is defined. The process to assess the strength of the knowledge is adapted from the basic ideas proposed in Goerlandt and Montewka (2015a); Kloprogge et al. (2011) and Flage and Aven (2009) which are combined for presenting a single classification process presented in Valdez Banda et al. (2015a).
- Three, defining the degree to which the analysis addresses the right quantities (model parameters and observable events). The presented model is focused on observable events (ship collisions) rather than a "probability" which cannot be interpreted. The aim of the model is to estimate probabilities about (possibly) real events based on the risk perspective described in Section 2.3.1. The quantity of interest is actually the observable characteristics and events of the system (the variables in the model).
- Four, defining how well the constructed model represents the winter navigation operations, construct validity as expressed in Trochim and Donnelly (2008). This type of validity focused on the evaluation of face and content validity. Face validity reviews operationalisation and the degree to how the obtained results represent a good translation of the construct. Content validity reviews operationalisation against the relevant content domain for the construct. Thus, these forms of validation are represented in this model by incorporating analysis of accidents reported in the context of interest (ice conditions), this is also strengthened by incorporating a risk analysis of these conditions based on expert knowledge. Moreover, the model provides appropriate methods for estimating the possible outcome of a collision in ice conditions and to assess the influence of the human performance on the development of the operations. However, neither accident reports nor the consulted experts contain information and/or have experience about the oil spills in ice conditions within the GOF.

5. Conclusions

This article has introduced a risk management model for winter navigation operations which is structured in a Bayesian network based on the stated methodology of the FSA by IMO. The model incorporates and process data from reported accidents, ship traffic and ice conditions statistics. Furthermore, the model also includes qualitative information extracted from the analysis of human performance in the execution of the operations. The model also comprehends different methodologies for the analysis of the human error, the calculation of the damage extent derived from collision in ice conditions, and the potential amount of oil spills during wintertime navigation operations in the GOF. The constructed model can be utilized in probabilistic reasoning about the dependency patterns between several variables involved in the execution of the most common winter navigation operations executed by ships and icebreakers.

Ship independent navigation and convoy are the navigational operations with the higher risk of collisions deriving in potential oil spills during winter time in the GOF. The model presents minor oil spills (<5000 tons) as the most probable to occur, and these seem to be only possible during the execution of the two mentioned operations. In these operations, major oil spills (>15,000 tons) are less probable but not impossible based on the model results. On the other hand, collisions which may cause potential oil spills during towing and cutting loose operations seem to be very unlikely.

The proposed model enables the implementation of a more in deep analysis of different context involved in the execution of the operations. In the analysis of the performance of the people involved in the practical execution of the operations, ship independent navigation and convoy are the operations detected as the ones with the higher need for human performance improvement. The existing procedures and plans for managing and supporting the winter navigation operations and the man–machine interface and operational support for the execution of the operations are the performance conditions of the winter navigation operations which are in a higher need of improvement. The improvement of navigational training and safety and risk management training seem to be the most recommendable options to control the risk of failures in human performance which may lead to accidental collisions and oil spills. The creation of more efficient electronic navigational tools and a better planning of the operations are the RCOs in the second level of priority based on the results presented in the model. It can be concluded that the proposed model can serve as decision support tool which is capable to analyse and manage the risks of the winter navigation operations performed in the GOF.

In regard to expanding the model usability, in future the model could incorporate new options focused in controlling the risks of the existing traffic and ice conditions, and new options for the technical specifications of ships structures and implementation of the operations. Moreover, the cost–benefit analysis of the proposed RCOs is another option that should be taken into consideration. Thus, these aspects could certainly provide new means to the consideration of which elements of safety and risk management should be also tackled in order to strength the presented study and the general safety of winter navigation in GOF.

Acknowledgement

The work presented in this article is part of the research project "Winter Navigation Risks and Oil Contingency Plan" (WINOIL) in association with the Kotka Maritime Research Centre (Merikotka), and further developed within the project “Strategic and Operational Risk Management for Wintertime Maritime Transportation System” (BONUS STORMWINDS). This project has received funding from BONUS, the joint Baltic Sea research and development programme (Art 185), funded jointly from the European Union's Seventh Programme for research, technological development and demonstration and from the Academy of Finland. The authors want to express their gratitude to the Finnish Transport Agency and the Finnish Transport Safety Agency for the analysed data, and special thanks to the winter navigation experts who participated in the assessment exercises.

Appendix A. Vessel traffic statistics in the Gulf of Finland March 2011 and January 2012 (HELCOM, 2012)

Table A.1
Type of vessels navigating in ice conditions at the GOF.

Vessel type	March 2011	January 2012
General Cargo	206	188
Containership	102	79
Bulk Carrier	67	41
Ro-ro Cargo	43	33
Reefer	27	19
Vehicles Carrier	26	15
Oil Crude Tanker	79	68
Oil/Chemical Tanker	135	100
LNG Tanker	7	5
Ro-Pax	39	42
Passenger	7	8
Other	102	79

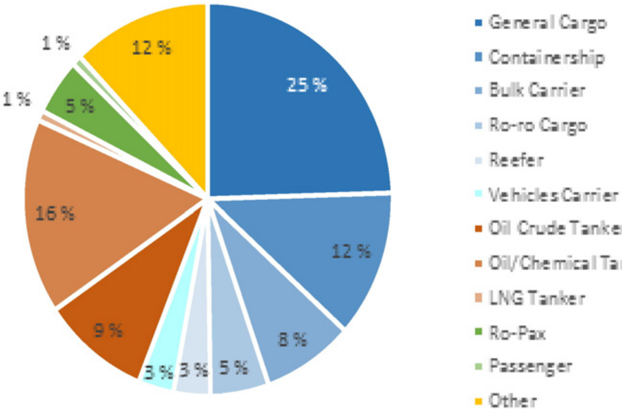


Fig. A.1. Types of vessels navigating the GOF in March 2011.

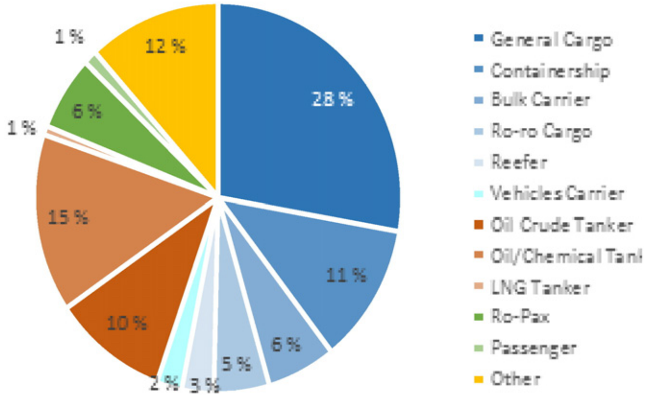


Fig. A.2. Types of vessels navigating the GOF in January 2012.

Table A.2
Deadweight tonnage of the vessels navigating the GOF during wintertime (in ice conditions).

DWT (in thousands)	March 2011	January 2012
1 - 5	254	206
5 - 10	278	232
10 - 20	128	108
20 - 40	71	55
40 - 60	20	15
60 - 80	16	15
80 - 100	8	2
100 - 120	60	42
140 - 160	5	3

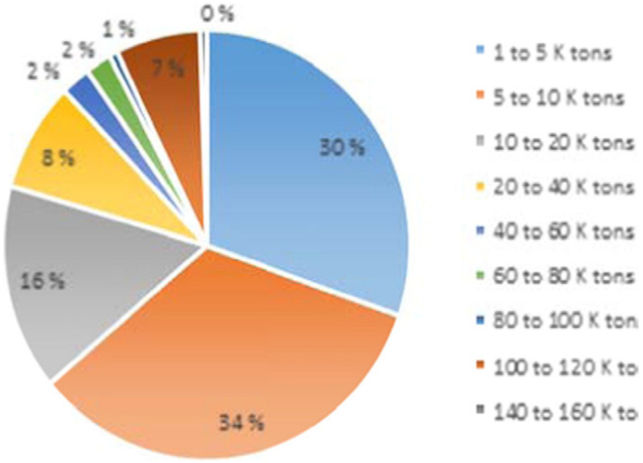


Fig. A.3. Deadweight tonnage (in thousands) of the vessels (all type) navigating during March 2011 and January 2012.

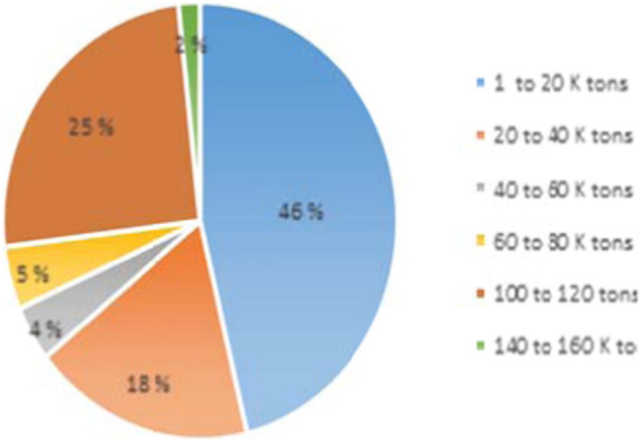


Fig. A.4. Deadweight tonnage (in thousands) of tankers navigating during March 2011 and January 2012.

Appendix B. Variables considered for the analysis of the operational characteristics and the calculation of the damage extent

Table B.1
The variables utilized for the analysis of the operational context of winter navigation. These variables and their respective states are utilized for the estimation of the possible damage extent in each particular winter navigation operation after an occurred collision.

Variable	State	Winter navigation operation				Probability estimated from:
		Independent navigation	Convoy	Towing	Cutting loose	
1. Encounter situation	1. Meeting in ice channel	✓	✗	✗	✗	Video analysis (AIS data analysed in Ploskonka (2013)) and expert knowledge
	2. Meeting in unbroken ice or ice cover water	✓	✗	✗	✗	
	3. Crossing in ice channel	✓	✗	✗	✗	
	4. Crossing in unbroken ice or ice cover water	✓	✗	✗	✗	
	5. Passing in ice channel	✓	✗	✗	✗	
	6. Passing in unbroken ice or ice cover water	✓	✗	✗	✗	
2. Struck vessel	1. Tankers	✓	✓	✗	✓	Traffic statistics (AIS data)
	2. Others	✓	✓	✗	✓	
3. Collision angle	1–19. Nineteen angles in a scale of 10, from 0° to 180°	✓	✓	✗	✓	Video analysis (AIS data)
4. Speed of collision	1. 1 to 5 kn	✓	✓	✓	✓	AIS data
	2. 5 to 10 kn	✓	✓	✓	✓	
	3. 10 to 15 kn	✓	✓	✓	✓	
	4. 15 to 20 kn	✓	✓	✓	✓	
	5. >20 kn	✓	✓	✗	✗	
5. Manoeuvring space	1. Ice channel	✓	✓	✓	✓	Video analysis (AIS data) and expert knowledge
	2. Unbroken ice	✓	✓	✓	✓	
	3. Ice cover water	✓	✗	✗	✗	
6. Struck area	1. Cargo area (tank)	✓	✓	✗	✓	Tankers and bunkers layout
	2. Bunker	✓	✓	✗	✓	
	3. Other area	✓	✓	✗	✓	

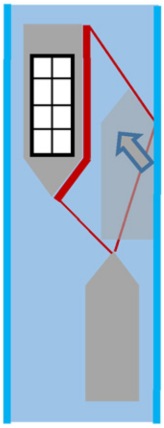


Fig. B.1. Meeting in ice channel.

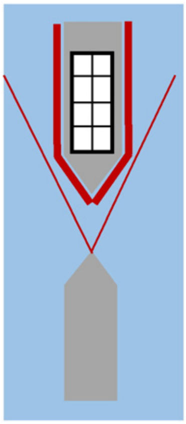


Fig. B.2. Meeting in unbroken ice or ice covered water.

1. Encounter situation
   This variable is utilized for the analysis of ship independent navigation. It describes the winter navigational context where collisions make occur. The Figs. B.1 to B.6 represent the states (context) included in the encounter situation.
2. Struck vessel
   This variable contains two general states: the probability that the struck vessel is a tanker and the probability that the struck vessel is other than a tanker. These probabilities are estimated based on the registered traffic conditions in the GOF (Appendix A).
3. Collision angle
   This variable has 19 states (possible angles of collision), starting from 0° angle and ending with 180° angle. The assessment of

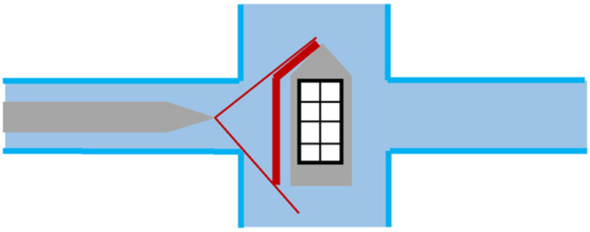


Fig. B.3. Crossing in ice channel.

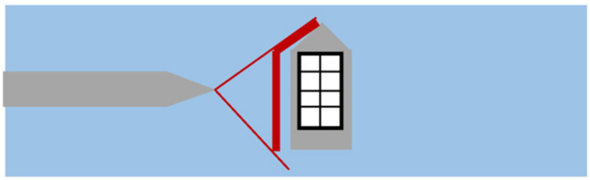


Fig. B.4. Crossing in unbroken ice or ice covered water.

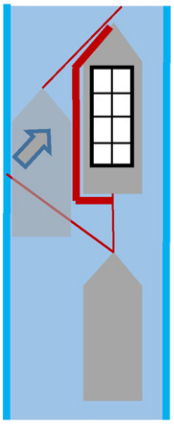


Fig. B.5. Passing in ice channel.

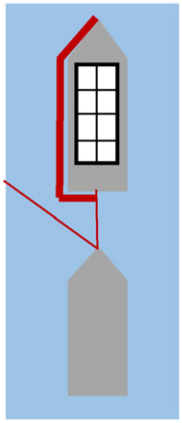


Fig. B.6. Passing in unbroken ice or ice covered water.

this variable is fundamental for the posterior estimation of the damage extent in each operation. The probabilities of these angles are based on the analysis of the videos describing the practical performance of winter navigation operations. The videos are produced by using the registered AIS data during 01.01.–31.03.2011. Figs. B.7 to B.10 present the potential angles of collision by operation.

4. Speed of collision

   This variable includes five states describing a certain range of speed registered during the performance of each winter navigation operation. These speeds are also obtained from the analysis of the AIS data registered during 01.01.–31.03.2011. Fig. B.11 reported speeds during the performance of all winter navigation operations.

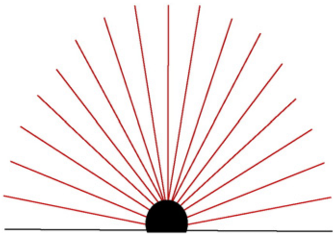


Fig. B.7. Potential collision angles in ship independent navigation.

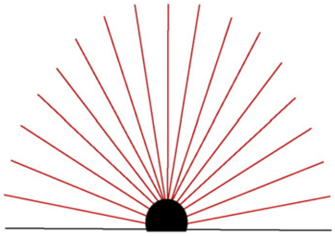


Fig. B.8. Potential collision angles in convoy operations.

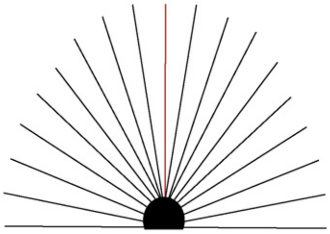


Fig. B.9. Potential collision angles in towing operations.

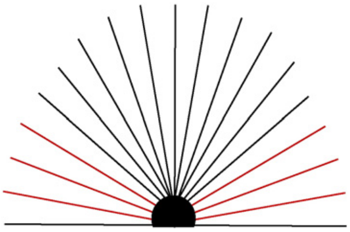


Fig. B.10. Potential collision angles in cutting loose operations

5. Manoeuvring space

   This variable describes the three main general sea ice context in which operations are performed: ice channel, unbroken ice and ice covered water (light ice conditions). The probabilities for each state (context) are estimated from the ice conditions registered in the AIS data during 01.01.–31.03.2011. Icebreaker operations are only executed in ice channel and unbroken ice.

6. Struck area

   The probabilities for the three states of this variable are estimated after analysing the layout of tankers and bunkers in different types of vessels described in McAllister et al. (2003) and Smailys and Česnauskis (2006). For this estimation, general layouts describing the location of tankers and bunkers are created. Moreover, estimation of the percentages that tankers and bunkers cover within the complete structure of vessels have also been elaborated. Figs. B.12 and B.13 present the elaborated general layout describing the location of tankers and bunkers.

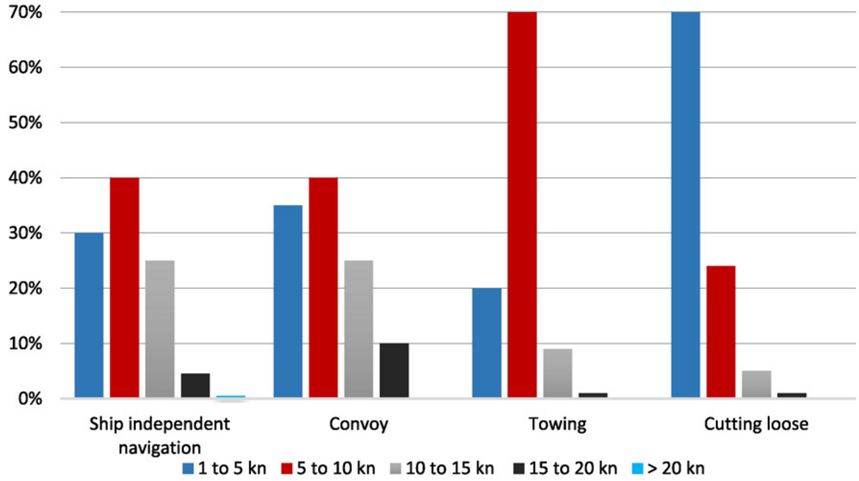


Fig. B.11. Registered speeds during winter navigation operations (01-31.03.2011).

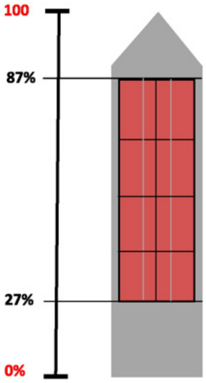


Fig. B.12. General layout of tanks in ship tankers.

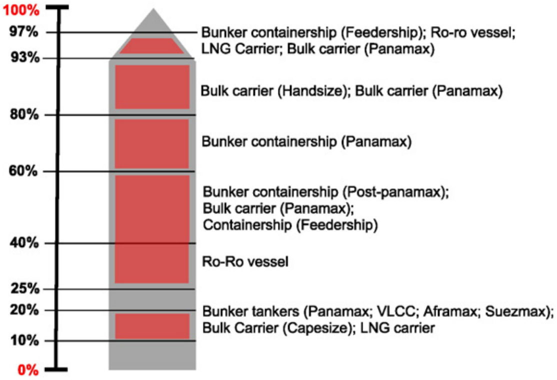


Fig. B.13. General layout of bunker locations in different type of ships.

Appendix C. Calculation of the damage extent in ship to ship collision

The evaluation of the damage extent initially requires the input from the factors described in Appendix B and also the traffic statistics described in Appendix A. These two documents include the speed of collision and the characteristics of the struck and striking vessel which are fundamental to determine the damage extent and impact penetration presented by Brown (2002).

The bow entrance angle is another relevant factor for elaborating the calculations, this parameter is obtained for the considered vessels types in this mentioned study. Table C.1 presents the values of the regression coefficients for encountering vessel mass and angles. The mass of encountering vessel M_{ev} is conditional to the vessel type, size and also loading conditions. The mass of fully laden general cargo, bulk carrier, container, and passenger vessels is obtained from data-based regression models presented by Brown (2002). Table C.1 also presents the regression coefficients when having a statistical fit with R^2 values around 0.98. In the risk management model proposed in this study, this information is also influenced by the description of ship direction within the GOF (see Section 2.3.8). Thus, the functional form is described as follows, with L the ship length:

$$M_{ev} = \frac{a\sqrt{L}}{c}. \tag{C.1}$$

Table C.1
Regression coefficients for encountering vessel mass and bow entrance angle η, based on Brown (2002).

Ship type	c	a	η
Bulk carrier	6.6	0.332	40
General cargo	6.93	0.325	40
Container ship	5.49	0.353	34
Passenger ship	8.22	0.299	34
Tanker	N/A	N/A	76

Thus, considering the calculations and results obtained in the total number of cases studied in the mentioned analysis, estimations for the probabilities of hull penetration and damage length in metres are possible to extract. These estimations refer to ship to ship collision on a 90 degrees' angle. Table C.2 presents the cases collected from Sandia Report and limited USCG Tanker collision data as presented in Brown (2002), the probability calculation for damage extent and hull penetration and the estimated number of tanks affected.

Table C.2
Probabilities for hull penetration, damage length and tanks affected in ship to ship collision on 90° angle (values adopted from Brown, 2002).

Metres	Number of cases		Probability		Tanks affected[a]	
	Hull penetration	Damage length	Hull penetration	Damage length	Hull penetration	Damage length
<1	2533	2546	0.261	0.254	0	1
1	2533	6000	0.261	0.598	0	1
2	1200	1200	0.124	0.120	0	1
3	700	200	0.072	0.019	1	1
4	550	50	0.057	0.005	1	1
5	450	25	0.046	0.002	1	1
6	370	5	0.038	0.000	1	1
7	300	0	0.030	0	1	1
8	325	0	0.033	0	2 (b)	1
9	220	0	0.022	0	2 (b)	1
10	120	0	0.012	0	2 (b)	2 (b)
11	100	0	0.010	0	2 (b)	2 (b)
12	90	0	0.009	0	2 (b)	2 (b)
13	80	0	0.008	0	2 (b)	2 (b)
14	70	0	0.007	0	2 (b)	2 (b)
15	30	0	0.003	0	2 (b)	2 (b)
16	15	0	0.001	0	2 (c)	2 (b)
17	5	0	0.001	0	2 (d)	2 (b)

[a] Considering the layout of (6 × 2) and the values (in metres) of the tanker distance in beam and length (see Brown, 2002).

[b] Accounts for two tanks affected only for tankers of 5000 deadweight tonnage.

[c] Accounts for two tanks affected only for tankers from 5000 to 40,000 deadweight tonnage.

[d] Accounts for two tanks affected only for tankers from 5000 to 60,000 deadweight tonnage.

Thus, considering the values obtained in Table C.2 and the defined layout of the tankers navigating in the GOF (described in Appendix B). Table C.3 presents the probabilities of affectations in tanks and bunkers.

Table C.3
Probabilities of affectation of tanks and bunkers in tankers navigating in the GOF.

Area affected	Probability
0 tanks	0.792
1 tank	0.087
2 tanks	0.005
Bunker	0.117

The study by Brown (2002) considers single hull tankers of 45,000 and 15,000 dead weight tonnage (DWT) (SH 150 and S45) and double hull tankers also of 45,000 and 150 DWT (DH45 and DH150). Thus, a mean collision scenario is defined as the point of reference for the values of the main variables required for the calculation of the damage extent. Table C.4 presents the damages values of this mean scenario.

Table C.4
Mean scenario and damage values.

Mean value	DH150	SH150	DH45	SH45
Mean struck ship velocity (kn)	2.49			
Mean striking ship velocity (kn)	4.27			
Mean strike location	0.47			
Mean collision angle	90			
Mean striking ship displacement (tons)	13,660			
Mean damage penetration	1385	2.28	1281	1571
Mean damage length	2523	3.87	2291	2809

Thus, the mean values for double hull tankers (DH150) are utilized for generating penetration values depending on the collision angle, speed and deadweight tonnage of the striking ship. The selection this type of tanker enables the covering of the potential scenario with most serious consequence in the GOF. The values of DH150 presented in Brown (2002) are adopted for the calculations in to this study. Initially, the potential penetration depending on different speeds is calculated. Then, the penetration depending on the angle of collision is also calculated. Finally, the penetration depending of the deadweight tonnage of the striking vessel is also calculated. For the last two calculations, a speed of 6 knots is utilized as reference. Table C.5 present the obtained reference values.

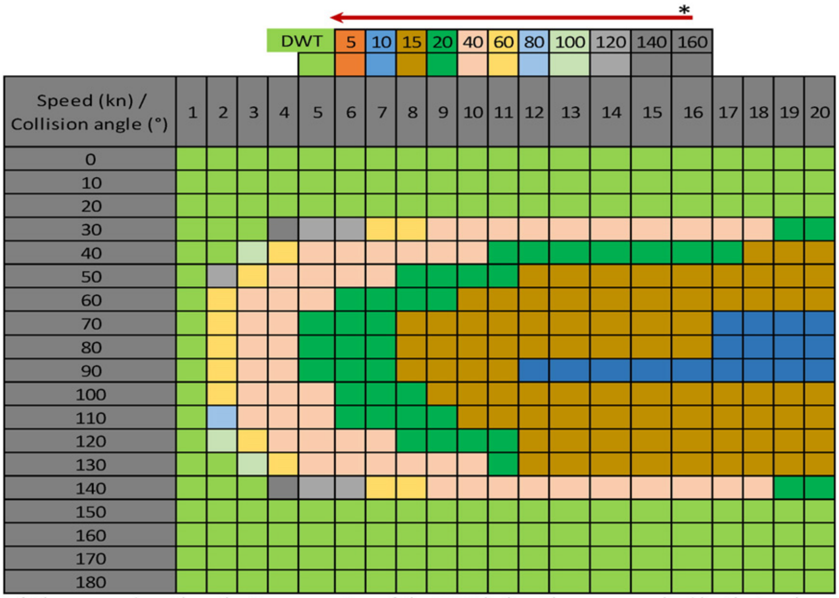
Table C.5
Reference values for damage penetration in double hull tanker DH150 based on speed, deadweight tonnage and angle of collision of the striking ship.

Collision speed (kn)–penetration (m)	Collision angle (°)–penetration (m) (in 6 kn speed)	Striking vessel DW (tons)–penetration (m)
1–0.4	0–0	0–0
2–0.64625	10–0	5000–0.38
3–0.8925	20–0	10,000–0.92
4–1.13875	30–0.42	13,660–1.385
4.27–1.11385	40–0.76	15,000–1.4
5–1.670833	50–1.1	20,000–1.8
6–1.956667	60–1.44	40,000–2.6
7–2.2425	70–1.78	60,000–3.05
8–2.528333	80–1.79	80,000–3.3
9–2.814167	90–1.8	100,000–3.5
10–3.1	100–1.4855	120,000–3.7
11–3.5	110–1.3333	140,000–3.9
12–3.9	120–1.1	160,000–4
13–4.3	130–0765	
14–4.7	140–0.43	
15–5.1	150–0	
16–5.68	160–0	
16–6.26	170–0	
18–6.84	180–0	
19–7.42		
20–8		

In March 2011, about 60% of the vessels navigating in the GOF were ice class IA. Ice class IB accounts for about 13% of the total vessels registered and ice classes IC, II and IA super share similar percentages (Valdez Banda et al., 2015a). The hull structured design demanded for ice classes IA, IB, IC (see Finnish Transport Safety Agency, Trafi, 2010) have been particular considered when selecting the structural characteristics for calculating the damage extent on vessels which are not tankers. Therefore, a similar process (as the one described above) was executed for calculating the damage extent on a single hull tanker of 45,000 deadweight tonnage (SH45). The selection of the SH45 provides a point of reference which better represents the type of vessels navigating in the GOF.

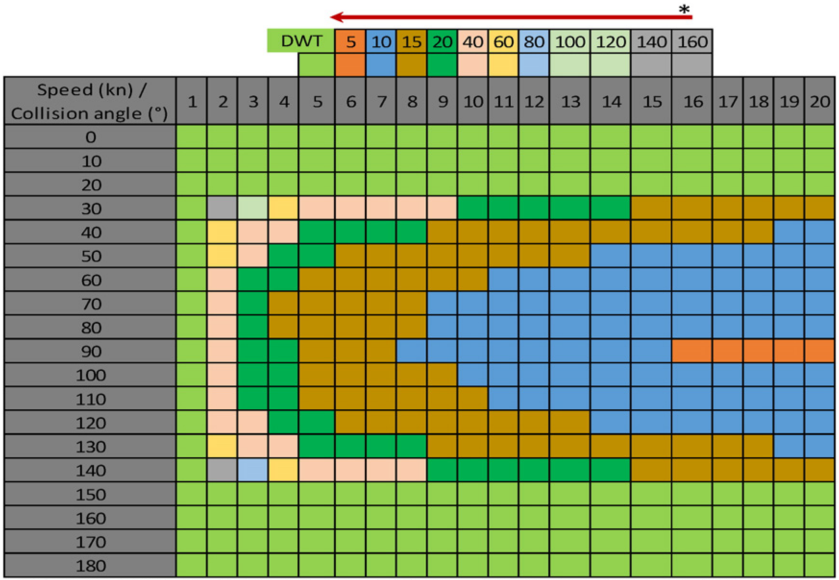
Finally, the update of the values for calculating the damage extent in the context of a collision in ice conditions (e.g. in the ice channel and/or in unbroken ice) are elaborated by utilizing the study performed by (Nelis et al., 2015). This study implements an approach which considers the failure of ice sheet by bending and then ridding down the sloping surface. The reference ice thickness considered in the study is 1.5 m. Thus, utilizing the results obtained by Nelis et al. (2015) and the values of the tankers DH 150 and SH45 presented in Brown (2002) is possible to see an increment of about 12% in the penetration damage in collisions under ice conditions. Surprisingly, the results of the collision calculations in ice have not significantly increase the deformation energy and penetration depth of struck ship compared with open water collision (Nelis et al., 2015).

Fig. C.1 presents a matrix describing collision scenarios which may lead to potential penetration of a tanker in a DH150. The description of these scenarios depends on the collision angle and speed. Moreover, these values are updated depending on the DWT of the striking vessel. Fig. C.2 presents the potential penetration of a tanker DH150 in the context of a collision in ice conditions. Figs. C.3 and C.4 present similar matrices for the values of the tanker SH45 which is utilized for calculating the damage of bunkers in other vessels.



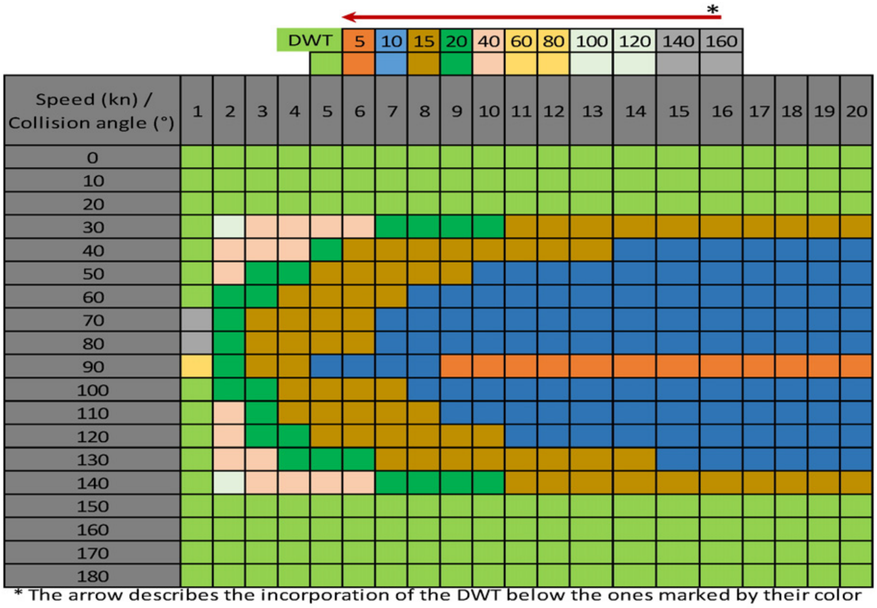
* The arrow describes the incorporation of the DWT below the ones marked by their color (e.g. color blue 10k DWT includes 5k DWT, and 15k DWT includes 10k and 5k, etc.)

Fig. C.1. Matrix describing the angle of collision and speed of striking vessels (classified by DWT) which may cause the penetration of a cargo tank in a tanker DH150.



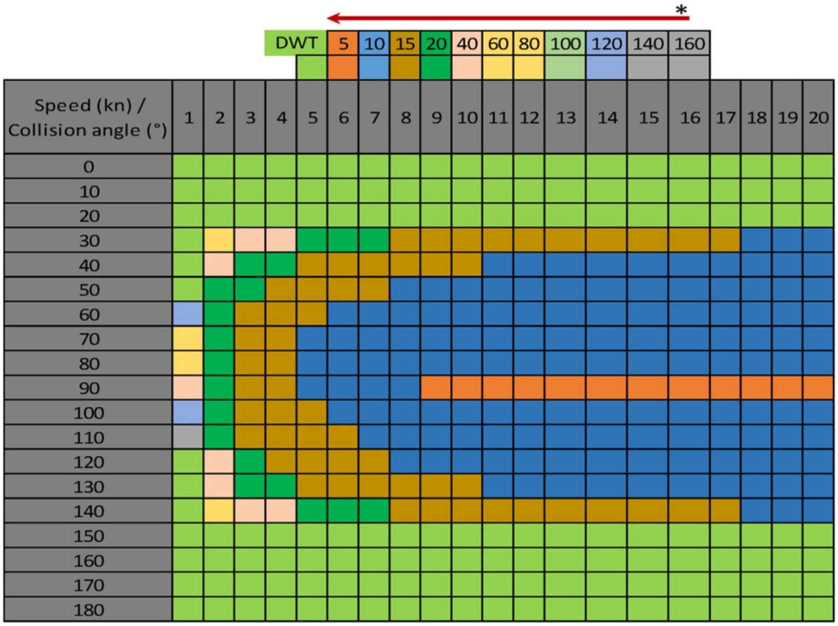
* The arrow describes the incorporation of the DWT below the ones marked by their color (e.g. color blue 10k DWT includes 5k DWT, and 15k DWT includes 10k and 5k, etc.)

Fig. C.2. Matrix describing the angle of collision and speed of striking vessels (classified by DWT) which may cause the penetration of a cargo tank in a tanker DH150 (in ice channel and unbroken ice).



* The arrow describes the incorporation of the DWT below the ones marked by their color (e.g. color blue 10k DWT includes 5k DWT, and 15k DWT includes 10k and 5k, etc.)

Fig. C.3. Matrix describing the angle of collision and speed of striking vessels (classified by DWT) which may cause the penetration of a cargo tank in a tanker SH45.



* The arrow describes the incorporation of the DWT below the ones marked by their color (e.g. color blue 10k DWT includes 5k DWT, and 15k DWT includes 10k and 5k, etc.)

Fig. C.4. Matrix describing the angle of collision and speed of striking vessels (classified by DWT) which may cause the penetration of a cargo tank in a tanker SH45 (in ice channel and unbroken ice).

Appendix D. Calculation of the oil outflow from accidental spills in the event of collision

The calculation of the potential oil outflow from accidental oil spills initially requires the input from the factors described in Appendixes A, B and C. These appendixes provide information regarding the characteristics of ship traffic in the GOF, the input information regarding the layouts of cargo and bunker tanks, and the estimation of potential damage in the event of collision. Moreover, information regarding traffic direction and loading conditions is also relevant to estimate the oil outflow, this information is obtained based on analysed AIS data and the reported points of departure and arrival marked in the planned buoyance of the vessels included in this data.

The calculation of the oil outflow from cargo tanks is based on a simplified method proposed by Smailys and Česnauskis (2006). The application of this simplified method is based on two main assumptions: the number of constructive design of tankers is limited to certain region (in this case Baltic Sea) and their hull and cargo tank geometrical characteristics are similar. As a fact, the length of all arranged cargo tanks for the majority of tankers is the same (Goerlandt and Montewka, 2015a). The method considers the typical arrange of cargo tanks in tanker navigating in this area and its dependency on the size (DWT) of these vessels. These characteristics have already been incorporated in the layout specifications presented in Appendix B.

For the calculation of the cargo volume, the initial volume of a cargo tank is calculated as product of its length, width, height and corresponding volumetric coefficient. The volumetric coefficients are calculated based on the analysis of 15 different design and deadweight. Table D.1 presents the oil outflow parameters estimated by the modified methodology proposed in (Smailys and Česnauskis, 2006).

Table D.1
Oil outflow parameters (from cargo tanks) estimated for some tankers navigating in Baltic Sea area (adapted from Smailys and Česnauskis, 2006).

DWT	Cargo tank arrangement scheme	DH[1], m	Z1[2], m	L[3], m	Bs[4], m	ds[5], m	Ds[6], m	0.98 V$\sum$[7], m3	MOS[8], m3
5000	6 × 2	1.0	1.1	95	16.5	6.2	8.3	5848	109.5
5000	6 × 2	1.5	1.5	95	16.5	6.2	8.3	5848	65.3
40,000	6 × 2	2.0	2.0	170.2	30.9	11.7	17	46,784	936
60,000	6 × 2	2.0	2.0	203.5	36	12.2	18	70,175	1523
95,000	6 × 2	2.0	2.0	235.2	41.8	13.8	19.8	111,111	2874
150,000	6 × 2	2.0	2.0	264	48	16.8	24	175,439	5338

[1] Distance between inner and outer hulls.
[2] The vertical distance from the moulded baseline to the lowest point on the cargo tank being considered.
[3] Length of cargo tanks arranged in one longitudinal line along the waterline.
[4] Moulded breadth, [5] depth, [6] moulded depth.
[7] Initial volumes of cargo tank.
[8] Mean oil outflow from side damage.

The calculation of the oil outflow from bunker tanks is based on the method produced in study presented in McAllister et al. (2003). This study includes an analysis of data extracted from bunker oil spill in US, Canadian and international waters in 15 years. Thus, collecting around 10,500 spill incidents suffered by 21 types of cargo vessels with different characteristics and with different bunker layouts and locations. The methodology for performing the bunker outflow calculations is mainly based on algorithms provided in the IMO MARPOL Annex I Regulation 22 "Accidental Oil Outflow Performance".

The simplified approach created for the applicability of the proposed methodology in this study is restricted to the vessels with bunker thanks that exceed 100 m^3 of fuel capacity. Other four general assumptions are also required to apply this methodology: the ships shall be assumed loaded to the partial load line draught, oil fuel tanks shall be assumed loaded to 98% of their capacity, the nominal density of the fuel is 1000 kg/m^3, and permeability of each oil fuel tank shall be taken as 0.99. Table D.2 presents the oil outflow parameters estimated for the different types of vessels using the simplified methodology proposed in (McAllister et al., 2003).

Table D.2
Oil outflow parameters estimated (from bunker tanks) for some cargo navigating in Baltic Sea area (adapted from McAllister et al., 2003).

DWT	Vessel type	MOS[8], m^3
Tankers		
37,000	Panamax	122
40,000	Panamax	122
46,000	Panamax	20
82,000	Aframax	71
85,000	Aframax	111
121,000	Suezmax	136
136,000	Suezmax	230
151,000	Suezmax	203
Containership		
11,000	Feedership	8
15,000	Feedership	67
25,000	Feedership	176
29,000	Panamax	118
36,000	Panamax	286
55,000	Post-Panamax	319
Passenger		
9000	Cruise	12
28,000	Ro–ro	706
Bulk carrier		
25,000	Handysize	7
28,000	Handysize	7
31,000	Handysize	6
45,000	Panamax	151
161,000	Capesize	188
LNG carrier		
161,000	LNG	518

[8] Mean oil outflow from side damage.

Considering the oil outflow parameters estimated in both studies, a series of defined scales have been elaborated and incorporated into the risk management model. Thus, defining the volume of potential oil spills derived from damages to one and two cargo tanks and/or bunker tanks in the event collision. Table D.3 presents the produced scales (based on oil tankers and merchant vessels navigating in the GOF) for estimating the volume of oil accidental spills in the model.

Table D.3
Scales for the calculation of the volume of oil accidental spills in the event of collision during winter navigation

Volume in m^3	Volume in tons				
	One tank damage	Two tanks damage	Bunker min	Bunker max	Tonnage scale for the model
5–12.5	n.a. (non applicable)	n.a.	37.31	93,29	37,31–98,28
20.8	n.a.	n.a.	155.23	n.a.	155.23
65.3–71.7	487.33	974.66	487.33	535.09	487.33–535.09
109.5–122.4	487.33	974.66	817.19	913.47	817.19–913.47
136	n.a.	n.a.	1014.96	n.a.	1014.97
151.6–176.7	n.a.	n.a.	1131.39	1318.71	1131.39–1318.71
203.9–286.3	n.a.	n.a.	1514.99	2134.47	1514.99–2134.42
319.4	n.a.	n.a.	2383.68	n.a.	2383.68
706.3	n.a.	n.a.	n.a.	n.a.	3824.56
936	4678.4	9356.80	n.a.	n.a.	4678.40
1523	5847.92	11,695.83	n.a.	n.a.	5847.92
2874	9259	18,518	n.a.	n.a.	9259
5338	14,619.92	29,239.83	n.a.	n.a.	14,619.90

Appendix E. The strength of the background knowledge

This section presents the assessment of the strength of the background knowledge (evidence) utilized to construct the risk management model of winter navigation. The background knowledge is differentiated by evidence based on data (operational and accident reports and traffic statistics) and expert judgements (human factor analysis and risk exposures). Table E.1 presents the categorization of the strength in these two types of evidence which is based on the ideas presented in Kloprogge et al. (2011); Flage and Aven (2009) and Goerlandt and Montewka (2015a). Table E.2 presents the assessed strength of the evidence in each variable of the constructed model.

Table E.1
Guidelines for categorizing the strength of the background knowledge (evidence)

Evidence base	The following conditions are met
Data (DA)	
High	Low number of errors in the available data High accuracy of the methods for recording High reliability of the data source Much relevant data available Low number of missing data sets Low level of underreporting

Table E.1 (*continued*)

Evidence base	The following conditions are met
Medium	Conditions between those characterising high and low strength of the evidence
Low	High number of errors in the available data Low accuracy of the methods for recording Low reliability of the data source Little available data High number of missing data sets High level of underreporting
Expert judgement (EJ)	
High	A lot of reliable data is available The assertion is seen as very reasonable There is a broad agreement among the experts The phenomena involved are well understood
Medium	Conditions between those characterising high and low strength of the evidence
Low	Data is unreliable The assertion is seem as unreasonable There is a lack of consensus among the experts The phenomena involved are not well understood

Table E.2
The strength of the evidence in the variables of the proposed risk management model of winter navigation

Variable	Information source	Strength of the evidence
Operational characteristics		
Encounter situation	Videos based on AIS data (DA) and expert judgement (EJ)	Medium (DA); medium (EJ)
Struck vessel	Traffic statistics (DA)	High (DA)
Collision angle	Videos based on AIS (DA)	Medium (DA)
Speed of collision	Statistics from AIS data (DA)	Medium (DA)
Manoeuvring space	Videos based on AIS data (DA) and expert judgement (EJ)	Medium (DA); medium (EJ)
Struck area	Definition of cargo and bunker tanks based on ship layouts (DA)	Low (DA)
Traffic conditions		
Vessel size	Traffic statistics (DA)	High (DA)
Vessel type	Traffic statistics (DA)	High (DA)
Loading conditions	Traffic statistics (DA)	Medium (DA)
Traffic direction	Traffic statistics (DA)	High (DA)
Human factor		
Adequacy of the organization	Expert judgement (EJ)	Medium (EJ)
Available procedures and plans	Expert judgement (EJ)	Medium (EJ)
MMI and operational support	Expert judgement (EJ)	Medium (EJ)
Available time	Expert judgement (EJ)	Medium (EJ)
Training and preparation	Expert judgement (EJ)	Medium (EJ)
Collaboration quality	Expert judgement (EJ)	Medium (EJ)
Exposure to collision		
Combines:	Ice reports (DA)	High (DA)
Ice conditions;	Accident reports (DA)	Low (DA)
Accident data	Expert judgement (EJ)	Medium (EJ)
Expert analysis		
Risk Control Options (RCOs)		
Analysis of the influence from the 13 proposed RCOs (see Section 2.4)	Expert judgement (EJ)	Medium (EJ)

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