Maritime risk and safety management with focus on winter navigation

Osiris A. Valdez Banda
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Abstract

Maritime transport is commonly categorized as one of the riskiest industry sectors. In Finnish sea areas, the risks increase during winter navigation when ships have to navigate in sea ice conditions. In order to support and ensure the integrity of people, ships, and environment during winter navigation, different safety and risk management strategies are developed. Risk management aims at developing methods for detecting, analysing, mitigating, and controlling the risks threatening the safety of winter navigation. Safety management aims at establishing and promoting organizational practices for planning, implementing, reviewing, controlling, and improving the safety performance of winter navigation.

This thesis provides a review of the current safety performance of winter navigation in Finnish sea areas and proposes alternatives to control and improve it. To this end, the thesis first provides understanding and evidence of the risks threatening the safety of the winter navigation system. Ship collisions during ship independent navigation and ship collisions in convoy operations in medium and severe ice conditions are identified as the accidents with highest risk.

These identified contexts are the basis for developing a model that analyses the risk of collision during winter navigation. The model combines the analysis of the role of humans in the execution of the operations and operational aspects of the performance of ships in ice conditions. It is used as a risk management tool that proposes risk control options and assesses their potential efficiency for supporting and improving the safety performance of winter navigation. The assessment of the risk control options points out the need for improving and simplifying safety and risk management in the planning and executing of winter navigation operations. In particular, there is a lack of coherent safety management systems that would enable practical adoption and application of regulatory demands, ensure their suitability to actual operational needs, and determine coherent safety key performance indicators.

Based on this, the thesis offers a method for executing a systematic application and performance measurement of the requirements contained in maritime safety management regulations. Moreover, the thesis introduces a process for designing maritime safety management systems based on a system engineering approach and proposes a tool for reviewing safety performance. Through a case study, these proposed alternatives are combined for designing a safety management system for one of the main responsible actors controlling and ensuring the safety of ship navigation. This case study makes a representation of the advantages in the management of maritime risk and safety, with a special focus on winter navigation.

Keywords  Risk management, safety management, Finnish-Swedish Winter Navigation System


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Preface

This thesis is based on the work done at the Maritime Risk and Safety research group at the Department of Mechanical Engineering (Marine and Arctic Technology) in Aalto University. The thesis has been elaborated as part of the work carried out during the projects CAFE (co-founded by the European Union), WINOIL (co-founded by the European Union, the Russian Federation and the Republic of Finland) and STORMWINDS (co-founded by the European Union, the Academy of Finland, the Estonian Research Council, the Research Council for Environment Agricultural Sciences and Spatial Planning in Sweden). Financing for concluding this thesis has been received from Insinööritieteiden tohtorinkoulutuspaikkojen 2017 jakaminen and Merenkulun Säätiö. These financial support sources are gratefully acknowledged.

Initially, I would like to immensely thank my supervisor, prof. Pentti Kujala for his trust and support to my person and the ideas for developing the work presented in this thesis. I especially appreciate the provided freedom to combine the focus of this work on my personal research interests and the core research interests of Aalto’s Marine and Arctic Technology. Special thank goes to my thesis advisor dr. Floris Goerlandt, for all the long discussions, his outstanding criticism and feedback to my work, and his excellence guidance during all these years. This has been essential for achieving my research goals. I would also like to thank my former colleague Maria Hänninen, her guidance and introduction to the doctoral research life have been fundamental to begin this doctoral research journey. I am also thankful to my other co-authors Jakub Montewka, Jouni Lappalainen and Vladimir Kuzmin for their support and valuable contributions to the research. I also want to express my gratitude to Prof. Jin Wang and dr. Xiaobo Qu who act as the pre-examiners of this thesis, and to prof. Jens-Uwe Schröder-Hinrichs for accepting to be opponent despite his very busy agenda.

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Espoo, Friday, 5 May 2017
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List of publications

This thesis consists of an overview and of the following publications, which are referred to in the text by their Roman numerals.

PI. Valdez Banda, Osiris A.; Goerlandt, Floris; Montewka, Jakub; and Kujala, Pentti. 2015. A risk analysis of winter navigation in Finnish sea areas. Accident Analysis and Prevention, 79, 100-116. DOI 10.1016/j.aap.2015.03.024


Author’s contribution

Publication I: “A risk analysis of winter navigation in Finnish sea areas”

The author developed the idea, carried out the analyses, and was the main contributor to the manuscript. Goerlandt suggested the structure of the manuscript and contributed to the manuscript. Montewka initiated the expert elicitation and provided valuable comments and suggestions. Kujala provided valuable comments and suggestions.

Publication II: “Risk management model of winter navigation operations”

The author developed the idea, prepared the expert elicitations, implemented the model, carried out the analyses, and was the main contributor to the manuscript. Goerlandt suggested the method for the analysis of the human performance and provided valuable comments and suggestions. Kuzmin carried out the expert elicitation with Russian experts and provided valuable comments. Kujala and Montewka provided valuable comments and suggestions.

Publication III: “A method for extracting key performance indicators from maritime safety management norms”

The author developed the idea, carried out the analyses, and was the main contributor to the manuscript. Hänninen contributed to the manuscript. Lappalainen organized, executed, and participated in the expert elicitations. Kujala and Goerlandt provided valuable comments and suggestions.

Publication IV: “A STAMP-based approach for designing maritime safety management systems”

The author developed the idea, carried out the analyses, and was the main contributor to the manuscript. Goerlandt provided valuable comments and suggestions.
Original features

This thesis contributes to the development of new alternatives for analysing, planning, implementing, and reviewing maritime risk and safety management, with ship winter navigation as the main context of research. The focus is on elaborating risk analysis and risk management models for identifying gaps in the management and control of the maritime safety of winter navigation operations, and proposing methods to design safety management systems and define indicators of safety performance. The following features of this thesis are believed to be original:

1. Conducting a detailed analysis to identify and review the current hazards of winter navigation and the common contexts of accidents in Finnish sea areas. Defining a risk representation of winter navigation in Finnish sea areas capable of integrating accident data and expert judgement. [PI]

2. Constructing a Bayesian network model for representing the risk of collisions in the most common ship traffic operations in sea ice conditions in the Gulf of Finland. Modelling the risk of oil spill from collisions between merchant ships, oil tankers, and icebreakers operating in sea ice conditions. [PII]

3. Using the model to create knowledge about the contexts of winter navigation operations in which captains and bridge personnel require new strategies and support. Analysing suggested risk control options aiming at supporting and improving the planning and executing of winter navigation operations. [PII]

4. Developing a framework that supports the integration of the requirements of safety management regulations into the actual operational practices of maritime organizations. [PIII]

5. Elaborating a systematic review of current safety management norms and guidelines for defining coherent safety key performance indicators and identifying the main elements of maritime safety management in Finland. [PIII]

6. Utilizing a safety engineering approach to define a guided process to design maritime safety management systems. [PIV]

7. Applying the process to design a safety management system for VTS Finland, with special consideration to the monitoring and controlling of winter navigation. [PIV]

8. Constructing a Bayesian network model for creating a tool for the systematic planning, monitoring, and reviewing of safety key performance indicators. [PIV].
Abbreviations

BN  Bayesian Network
CMO  Context-Mechanisms-Outcome
CPC  Common Performance Condition
CREAM Cognitive Reliability Error Analysis
EA  Environmental Assumption
EMSA  European Maritime Safety Agency
FMI  Finnish Meteorological Institute
FSA  Formal Safety Assessment
FTA  Finnish Transport Agency (Liikennevirasto)
FTSA  Finnish Transport Safety Agency (Trafi)
FSWNS  Finnish-Swedish Winter Navigation System
IALA  International Association of Marine Aids to Navigation and Lighthouse Authorities
IMO  International Maritime Organization
ISM  International Safety Management
KPI  Key Performance Indicator
PDCA  Pan-Do-Check-Act
RCO  Risk Control Option
Req.  Requirement
SC  Safety Constraint
SMS  Safety Management System
STAMP System-Theoretic Accident Model Process
STPA  System-Theoretic Process Analysis
VTS  Vessel Traffic Services
Special terms

**Maritime Industry:** the industry comprising organizations with activities connected to ships transporting goods and living beings.

**Maritime Transportation:** an activity in which ships transport goods and living beings from one location to another over sea or waterway areas.

**Risk analysis:** the scientific risk discipline concerned with developing concepts, principles, frameworks, and models for analysing risk.

**Risk management:** the development of methods for detecting, analysing, mitigating, and controlling the risks threatening the safety system.

**Safety key performance indicator:** a qualitative or quantitative measurement of the operational and organizational safety performance of a system.

**Safety management:** establishing and promoting organizational practices for planning, implementing, reviewing, controlling, and improving safety performance.

**Safety management system:** the set of procedures utilized to manage and ensure the safety of an organization.

**Safety performance:** a system property that reflects in which ways and to what extent the system is safe.
1. Introduction

1.1 Background and motivation

Shipping is a complex and dangerous transport mode globally (Turner and Pidgeon, 1997; Bloor et al., 2000; Perrow, 2011). However, it is the main mode for exporting and importing goods internationally with about 90% of the world’s trade (IMO, 2016; UNCTAD, 2014). In Finland, about 80% of imports and exports are transported by sea (Finnish Customs, 2016). These trends are commonly maintained during winter navigation when ships navigate in Finnish ice-covered sea waters.

Ships navigate in ice conditions for about three to five months depending on the Finnish sea area in question and the type of winter climate experienced. Northern Finnish sea and port areas may experience up to five months of frozen sea waters every year. In sea and port areas of the Gulf of Finland, sea ice may be present for up to three months (Leppäranta, 1998; Rosenblad, 2007). The characteristics of sea ice vary depending on the severity of the winter, from a thin and small ice cover called “new ice” to a thick and large cover called “level ice” or “consolidated ice” (Jalonen et al., 2005).

Every winter, the first appearance of sea ice activates the Finnish-Swedish Winter Navigation System (FSWNS). The system aims at controlling and increasing the safety performance of ship navigation in sea ice conditions within Finnish and Swedish sea areas (see Publication PI). It represents an essential tool for planning and managing risk and safety in winter navigation. For this purpose, the system implements the Finnish-Swedish ice class rules that specify the demands for ship structures and performance, including demands for ship loading, ship component allocation, and power consumption (FTSA, 2010). Moreover, it utilizes information about ice and weather conditions for determining ship traffic restrictions. The system also covers the provision of guidance information and on-site assistance by icebreakers, which represent a crucial element of the system for controlling and increasing the safety of winter navigation (Brigham, 2000).

With the current FSWNS in place, the severity of ship accidents occurring during winter navigation in Finnish sea areas is commonly minor. However, a major accident can have drastic consequences affecting people, the environment, and property. One example of such an accident is the drifting and spreading of the Runner 4 oil spill (Wang et al., 2008). Risk and safety management frameworks and controls, such as the FSWNS, are implemented to prevent accidents during winter navigation. To define these frameworks and controls, a combined approach is employed in risk and safety management to establish methods and processes for mitigating risks and preventing accidents. Risk management aims at developing methods for detecting, analysing, mitigating, and controlling the risks threatening the safety of the system (ISO, 2009). Safety management aims at establishing and promoting organizational practices for planning, implementing, reviewing, controlling, and improving safety performance (Reason, 1998).

Thus, in the context of winter navigation in Finnish sea areas, managing risks and safety entails understanding that risks are hazards to the safety of winter navigation, and safety is actually a property represented in the functioning of the system (e.g. the functioning of the FSWNS). Therefore, risk and safety must be managed at the system level (Leveson, 2011). Thus, the development of tools and strategies for managing risk and safety must adopt a systematic approach capable of understanding the current safety performance of a system, which represents how different stakeholders are contributing to a similar purpose. For the FSWNS this is: keeping ships and people safe during navigation in ice conditions and protecting the natural environment of Finnish and Swedish sea areas.
1.2 State of the art

1.2.1 Risk and safety management in Finnish sea areas

Finnish sea areas such as the Gulf of Finland and Archipelago Sea are considered to be particularly sensitive due to the characteristics of their natural environment and the ship traffic trends represented in them (Hänninen and Rytknönen, 2004; Hänninen and Kujala, 2009; Lehikoinen et al., 2015). Therefore, official resolutions have been passed to protect the environment and ensure the safety of navigation in such areas (IMO, 2006, HELCOM, 2013).

Based on this, several studies have been conducted with a view to understanding, analysing, and enhancing the management of risk and safety of ship navigation in these areas. Studies analysing the current safety performance of marine traffic and the occurrence of accidents in these areas include those of Rytkönen et al. (2002), Jalonen and Salmi (2009), Kujala et al. (2009), Hänninen and Kujala (2012; 2014), and Goerlandt et al. (2017). These studies analyse traffic trends, accident statistics, and accident data in order to represent and compare the risk of accidents, their severity, and potential consequences in different navigational contexts and locations, thereby shedding light on the safety performance of ship navigation and identifying groundings and ship to ship collisions as the most common ship accidents in Finnish sea areas.

Moreover, other studies have focused on the analysis of the risks of navigation in Finnish sea areas; see, for example, Montewka (2009), COWI (2011) Montewka et al. (2014), Sormunen et al. (2014), Goerlandt and Montewka (2014; 2015), Lehikoinen et al. (2015), Mazaheri et al. (2015), and Nisula (2015). These studies have provided models and frameworks for representing, analysing, and managing the risks contained in the execution of ship operations, covering the analysis of the risks of navigation faced by different types of vessels, such as oil tankers and chemical tankers, and the risks of navigation in different contextual scenarios.

Furthermore, analyses of organizational safety and risk management practices in the maritime cluster in Finland have been elaborated for example by Rosqvist et al. (2002), Sonninen et al. (2006), Hänninen (2014), Hänninen et al. (2014), Hänninen and Kujala (2014), Lappalainen et al. (2011; 2014), and Lappalainen (2016). These studies have supported the identification of practices, values, and joint objectives in the management of maritime safety in Finland. These studies enable the representation of the actual concept of maritime safety culture and the elements integrated into this concept, identifying the management commitment, incidents reporting, and employee involvement in safety management as crucial elements for achieving efficient management of maritime safety.

1.2.2 Risk and safety management during winter navigation

Although the majority of risk and safety studies have mainly considered ship navigation in open water as the context of reference for their analysis, studies analysing the risk and safety of ship navigation in ice conditions have been elaborated for example by Kujala et al. (2007), Kujala and Riska (2010), Montewka et al. (2015), Boström and Österman (2016), and Kuuliala et al. (2017). These mainly cover analyses of different elements of winter ship navigation, including the description and assessment of environmental and operative scenarios, technical characteristics of ship performance in ice, and the dynamics of the interactions between sea ice and ship structures. These studies have provided understanding of the practical execution of ship navigation in ice conditions, including crucial elements in the designing of ships operating in this environment and elements to be considered in the actual execution of winter navigation operations.
Risk and safety analyses focusing on the context of winter navigation in Finnish sea areas have also been developed for example by Jalonen et al. (2005). This study has presented an analysis of the risks linked to sea ice conditions and the traffic characteristics in these areas, identifying hazards in different operative scenarios. This has provided initial evidence on how accidents occur during ship navigation in ice conditions and the common factors involved in those accidents. The study thus provides an initial integrated review of a system that concentrates on different elements involved in the management of risk and safety of winter navigation.

1.2.3 The management of risk and safety of winter navigation with the Finnish-Swedish Winter Navigation System

The FSWNS represents the main reference in the management of the risk and safety of winter navigation (Juva and Riska, 2003). The system limits and specifies on a yearly basis which merchant vessels are entitled to assistance in Finnish and Swedish maritime areas during the sea ice season, including icebreaker assistance. In its current form, the system is composed of five main elements:

I. Ice class regulations: These specify the technical requirements for the design and performance of ice going vessels. The regulations include four different types of ice classes (IA Super, IA, IB, and IC) for vessels operating in specific ice conditions. See FTSA (2010).

II. Additional requirements: These are complementary to the ice class regulations, and concern issues such as loading and transport methods as well as the positioning and functioning of on-board equipment.

III. Ice services: Ice and weather forecast, ice charts, and satellite images for the different sea areas covered in the system.

IV. Traffic restrictions: These are designated for the routes to all destinations (ports) included in the system, and specify which ice classes are allowed to navigate in certain areas, supporting traffic arrangements and coordination of icebreaker assistance.

V. Icebreaker assistance: Provision of routing advice, with for example the following of waypoints, and onsite assistance, including escorting, towing, cutting loose, and vessels in convoy.

This systematic approach has been utilized since 1971 when the Finnish-Swedish ice class rules were officially introduced (Pohjanpalo, 1978). The rules have been constantly reviewed and the last update to the rules was issued in 2010 (FTSA, 2010). Carrying out different types of research to analyse the interaction between ships and ice has been essential for updating the rules and maintaining their functionality. Information produced from the ice services has also played an essential role in the functioning of the system; technological advances have supported the constant improvement of the quality of this information, from capturing images of sea ice condition with helicopters in the 1980s and 1990s to extracting more advanced and complete information with satellite images since 2003 (Sawyer et al., 2015). This has improved the process for defining traffic restrictions more accurately, enabling smoother operation of ship traffic and supporting the coordination of icebreakers. Icebreakers are core coordinators in the functioning of the system; they are responsible for defining the location of the waypoints that are the main guide for vessels navigating in sea ice conditions. The aim is for vessels to reach their destination in the most efficient way. Moreover, the waypoints support the efficient coordination of the entire icebreaker fleet to provide potential on-site assistance when demanded.

Although the system particularly integrates the five mentioned elements, its application covers other legislative frameworks and draws on input from other organizations that also contribute to the management of risk and safety of winter navigation in Finnish sea areas. Figure 1
describes the elements and functioning of the FSWNS system, including interaction with international and national maritime legislative and supportive organizations. It also presents the system output, depicting the roles of other stakeholders supporting and participating in the management of risk and safety of winter navigation.

Figure 1. Functioning and extended scope of the Finnish-Swedish winter navigation system
1.3 Objectives and structure of the thesis

This thesis provides a review of the current safety performance of winter navigation in Finnish sea areas and proposes alternatives to control and improve it. More specifically, it aims at representing in detail the current outcomes of winter navigation in terms of accident occurrence, including a representation that sheds light on the details of the functionality of the system. This representation serves as a basis for a systematic analysis to detect areas of opportunity in a maritime context with a positive expected outcome in terms of accident occurrence. It also aims to provide new risk and safety management alternatives for planning, implementing, reviewing, controlling, and improving maritime safety, with a focus on winter navigation.

This thesis has five objectives. The first three objectives focus on winter navigation risk management. Thus, the three objectives provide methods for detecting, analysing, mitigating, and controlling the risks threatening the safety of the FSWNS. The last two objectives focus on winter navigation safety management. Thus, the two objectives present new approaches for planning, implementing, reviewing, controlling, and improving the safety performance of the FSWNS. The specific objectives of this thesis are as follows:

**Objective 1**: Provide understanding and evidence of the risks threatening the safety of the FSWNS, thereby answering the following research questions in publication PI:

- What are the common hazards and risks of winter navigation in Finnish sea areas?
- What types of accidents occur? How do these accidents occur and in which conditions?
- How can the risk of winter navigation be represented graphically? How can this representation combine accident data and expert judgement?

**Objective 2**: Describe and assess the main operations of vessels during winter navigation and analyse the risk of ship collision in these operations, thereby answering the following research questions in publication PII:

- What is the current risk level of ship collision during wintertime? What types of consequences (focusing on oil spills) may be produced after a collision? How does the risk differ for operations?

**Objective 3**: Review different risk control options for supporting the performance of bridge personnel, focusing on the management of the risk involved in winter navigation operations, thereby answering the following questions in publication PII:

- What risk control options can be implemented to control and improve the performance of bridge personnel involved in the execution of winter navigation? What risk reduction potential are these risk control options expected to have?

**Objective 4**: Provide guidance for executing a systematic combination of maritime safety management regulations and the actual practices of safety management in Finnish maritime industry organizations, thereby answering the following questions in publication PIII:

- How can organizations properly interpret safety regulations to adopt the requirements set therein?
- How can measurements of safety performance (KPIs) be defined? How can these KPIs make a systematic representation of the requirements demanded in regulations and the actual practices of maritime safety management for defining the common elements of safety management in Finland?
**Objective 5:** Propose a framework for designing safety management systems (SMS) that can represent the dynamic management of safety in critical organizations, applying this framework to one of the main responsible organizations for monitoring and controlling the execution of winter navigation operations, thereby answering the following questions in publication PIV:

- How should one design a maritime SMS that can represent and constantly improve the management of safety at all different organizational levels? How should the demanded requirements and controls of such a system be defined?
- What tool can be developed to monitor, review, and guide the performance of the system in meeting the requirements and the functioning of the SMS in general?

The connections between these objectives, the publications (PI to PIV), and the structure of the thesis summary (section numbers) are shown in Figure 2.

In the summary, Section 2 outlines the main research results related to the analysis of the risks of winter navigation in Finnish sea areas, presenting accidents that occurred in winter navigation operations, a detailed analysis of ship to ship collisions, and the assessment of proposed risk control options. Section 3 summarizes the main research results related to the elaborated proposals for controlling the risks and supporting the management of safety in the FSWNS. Section 4 discusses the contribution of this thesis, the methodology and data limitations, and future work. Section 5 presents the conclusions.

### 1.4 Limitations

Maritime risk and safety are very broad research topics. This thesis focuses only on the analysis of the risk and safety of the FSWNS. As the elements of the systems are currently considered effective for the planning, coordinating, and supporting of ships navigating in sea ice conditions, the thesis focuses particularly on assessing and understanding the system output and supporting the roles of the people involved in planning, executing, monitoring, and controlling this output.

To this end, the thesis initially focuses on reviewing the current performance of winter navigation in Finnish sea areas in terms of accident occurrence. Based on this, the focus shifts to the analysis of the risk of ship collisions as these are the main risks in the four most common
winter navigation operations: ship independent navigation in ice conditions, icebreakers and ships leading convoys, icebreakers cutting loose vessels stuck in ice, and icebreakers towing vessels. For determining alternatives to support the development of these operations, the focus is narrowed to the analysis of the input from the human factor, particularly on the analysis of the support provided to the bridge crew of ships and icebreakers for managing risk and safety during the execution of operations. Thus, the focus is on the analysis of the safety management tasks implemented to plan, execute, control, and improve the execution of the operations in a systematic way, and in particular on the development of proposals for establishing safety management systems that effectively combine regulatory requirements and the actual practices of risk and safety management in organizations linked to the FSWNS.

While this study presents a coherent review of the safety performance of the FSWNS, it does not review aspects such as the basis for defining the ice class rules, the ice services provided, and the setting of traffic restrictions. These have been researched in studies such as Juva and Riska, 2003, Kujala, 1996, Kujala et al., 2007, Leppäranta, 1981, Leviäkangas and Hautala, 2009, Su et al., 2011, and Suominen et al., 2013. These elements of the system are essential and must be periodically updated as technology develops and climate change continually occurs. This enables upgrading the designs of ice going vessels, improving traffic flow by setting traffic restrictions and modernizing ice information services.

Moreover, while the results presented in this thesis may also be more widely applicable to other problems and/or industries, this is not explicitly claimed or further addressed. Furthermore, no claims are made about the presented safety and risk management frameworks being the only possible ones. The aim is to provide alternatives for managing risk and safety with clear underlying principles, enabling comprehension and integration on their applicability. Finally, limitations regarding the utilized methodologies, the executed analyses, and the produced outputs of this thesis are discussed in Section 4.
2. Winter navigation in Finnish sea areas: the exploratory context of analysis

2.1 Current execution of winter navigation in Finnish sea areas

This section presents the analysis of the risks of winter navigation in Finnish sea areas, focusing on the types of accidents and the context in which these occur.

2.1.1 Accidents occurring during winter navigation operations

In order to analyse accidents occurring during winter navigation in Finnish sea areas, this section presents a summary of the analysis of statistics and information about prior accidents in this context. The analysis is strengthened with the incorporation of judgements made by experts assessing the risks of winter navigation based on their experiences from the actual execution of ship operations. Detailed descriptions about the type of data and methods implemented to extract and process said information are presented Section 4 of publication PI.

The information is presented in two categories: accidents occurring when ships navigate independently in sea ice conditions and accidents occurring in icebreaker assistance operations. The results indicate that ship collisions are the main type of accident occurring during winter navigation. In the case of ship independent navigation, ship to ship collision and propeller damage due to ice contact are the two main types of accidents that occur. In icebreaker assistance operations, ship to icebreaker collision is the most typical accident. Figure 3 shows a graphical representation of the accident types that occur in winter navigation, presenting the information in the described accident categories.

The types of vessels involved in the registered accidents are mainly general cargo vessels, followed by accidents involving RoPax, bulk carriers and oil/chemical tankers. The sizes of the vessels involved in accidents are mainly below 5000 deadweight tonnage. Accidents during ship independent navigation are more common in the Gulf of Finland and accidents in icebreaker assistance operations are more frequent in the Bay of Bothnia. Ships with ice class IA represent the main ice class involved in accidents. The analysis of the sea ice context of these accidents shows that accidents during ship independent navigation and icebreaker assistance operations mainly occur in consolidated level ice with ice thickness between 15 and 40 cm (see publication PI).

Figure 3. Types of accidents occurring during winter navigation, categorized by operation.
The consulted experts, who include icebreaker and ship captains, pilots, and VTS operators, have identified different hazardous scenarios in the execution of ship independent navigation and icebreaker assistance operations (see Tables 2 and 3 in publication PI). These scenarios indicate that ship collision is the main accidental risk during winter navigation. The experts mention that this type of accident can lead to the most severe consequences for people, property, and natural environment.

Based on the analysed accident data, the average number of accidents per winter period in ship independent navigation is 10.75. In icebreaker assistance operations, five accidents occur on average. In the case of ship independent navigation, the combination of the number of accidents that occurred and the total number of arrivals and departures registered in the winter periods when these accidents occurred, provides a probability of an accident of 6.1 E-04 per arrival and departure, meaning that there are approximately 16,445 port arrivals and departures for one accident. In the case of icebreaker assistance operations, the combination of the number of accidents and the total number of assisted vessels when the accidents occurred also provides a probability of an accident of 6.1 E-04 per assisted vessel, with approximately 1527 on-site assistance operations executed for one accident.

Figure 4 presents a matrix for visualizing the risks of accidents in winter navigation, including all types of operations. The figure presents the probability of each type of accident in the analysed periods and the severity of the accidents. Severity is represented in two ways: with the position of a circle indicating the level of severity (less serious, serious, and very serious) of the reported accident, and with a line linked to the circle representing an expert’s estimate of the possible severity of the consequences. The size of the circle and the type of line represent the evaluation of the strength of the evidence (data and expert judgement). Thus, Figure 4 presents ship collision as the accident with the highest probability; the positioning of the circle between the severity categories less serious and serious means that collisions of both levels of severity have been reported, while the extension of the line indicates that experts have stated that this accident could have up to very serious consequences. The strength of the evidence in both cases has been evaluated as medium. Similar matrices representing the risk of accidents in ship independent navigation and icebreaker assistance operations are presented in publication PI.

![Figure 4. Visualization of the risk of accidents in winter navigation (all types of operations)](image-url)
2.2 Winter navigation risk management

The analysis of the risks of winter navigation in Finnish sea areas has identified ship to ship collision as the risk with the highest probability of occurrence and with potentially the most severe consequences. Thus, this section presents an analysis of the common winter navigation operations executed by ships and icebreakers, focusing on reviewing potential options to manage the risk of collisions during this navigational season. To this end, a model for managing the risk of collisions during winter navigation operations is elaborated. The structure of the model is based on the Formal Safety Assessment (FSA). The FSA is a frequently utilized and discussed framework provided by IMO (Wang, 2006 and 2001). Section 2 in publication PII provides details of the structuring of the model with the FSA.

2.2.1 Scope of the risk assessment of winter navigation operations.

The risk assessment concept adopted for establishing the basis of the model is defined as the systematic consideration of the uncertainties (U) regarding the occurrence of an event (A) and its consequences (C) in light of background knowledge (Aven, 2010). In this case, the model focuses on the consideration of uncertainties regarding the occurrence of a ship collision in the execution of winter navigation operations and the potential oil spills that it may cause, in light of available background knowledge.

The framework aiming at risk analysis for representing the structure of the model is developed by means of Bayesian Networks (BNs). This is a modelling technique that can depict relatively complex dependencies and cope with uncertainty while also having a graphical dimension (Hänninen, 2014; Pearl, 2014). The aim is to create a model that enables one to reflect on the available evidence about the aspects under analysis and understand their interdependencies in a comprehensive way. The model estimates the risk of ship collision and oil spills and provides reasoned risk quantification for supporting risk-informed decision making.

The model covers the analysis of four winter navigation operations involving ships and icebreakers. The first concerns ship independent navigation, that is, the navigation of a merchant vessel in ice covered waters without on-site assistance by icebreakers or any other vessel. The second is icebreaker convoy, in which an icebreaker leads a convoy of several ships and opens a path in the ice for them. The third is icebreaker towing, in which an icebreaker tows a ship that has difficulties with navigating in sea ice conditions. The fourth is icebreaker cutting loose, in which an icebreaker releases a vessel stuck in ice (Rosenblad, 2007). Each operation is represented as a sub-model of the general model presented in Figure 2 of publication PII. Figure 5 presents the sub-model for the assessment of ship independent navigation. The figure presents the elements of analysis contained in the sub-models elaborated for each operation. Each sub-model includes the analysis of:

a) Human factor: this is limited to the analysis of the interaction among the crew executing tasks on the bridge of ships and icebreakers during the execution of the operation. The analysed information is extracted from expert consultations.

b) Operational characteristics: this covers the analysis of the potential encounter situations, potential collision angle, vessel speeds during the operations, the manoeuvring space, and potential impacted area. The information is extracted from the analysis of videos of the operations produced with Automatic Identification System (AIS) data; the extent of the damage caused by a collision is then estimated based on a collision damage model.

c) Traffic conditions: this represents the analysis of the type and size of the vessels commonly navigating in Finnish sea areas during wintertime, including the traffic
direction and the loading conditions of the vessels. This information is extracted from traffic data.

d) Ice conditions: this analyses the sea ice context in which the operations are executed. This information is extracted from ice services reports.

Figure 5. Sub-model "ship independent navigation" of the risk management model of winter navigation operations. Each group of variables is described in detail in Section 2.3.3-6 in publication PII

2.2.2 Managing and controlling the risk of ship collision in winter navigation

The managing and controlling of the risk of ship collision in the introduced model focuses on the evaluation of common performance conditions (CPCs) that attempt to represent key elements for planning and supporting the tasks of the crew on the bridge. The CPCs are adopted from the Cognitive Reliability Error Analysis (CREAM). This method focuses on the
influence of the context on human performance and provides a cognitive framework for the analysis of this performance (Hollnagel, 1998). The method aims at seeking a good indicator for the probability of an interaction rather than a precise failure probability (Fujita and Hollnagel, 2004). The evaluated CPCs of the CREAM in the model are:

a) Adequacy of the organization: aspects represented in the management support provided by organizations to execute winter navigation operations, including the delegation of responsibility and management support.

b) Available procedures and plans: the efficiency of existing procedures and plans to perform operational tasks, including the availability of documented guidelines, plans, and procedures, and familiarizing the crew personnel with these.

c) Man-machine interface and operational support: the efficiency of the bond between the used technology to ensure the correct performance of the operation and the people responsible for executing the commands needed in the operations. This includes the assessment of the support provided by the utilized devices and technology on the bridge of ships and icebreakers and the review of the efficiency of bridge layout.

d) Available time: the management of the time to plan and perform the operations.

e) Training and preparation: the training provided for ensuring the adequate performance of the operations.

f) Collaboration quality: the quality of the internal and external cooperation and communication, and the job satisfaction among the bridge crew.

The CPCs have a link to proposed risk control options (RCOs) that aim to improve and support the performance of the bridge crew on ships or icebreakers. These RCOs are:

a) Adequacy of the organization
   - Improving organizational safety culture
   - Improving safety management
   - Improving personnel's satisfaction

b) Available procedures and plans
   - Improving emergency drills
   - Improving operational procedures

c) Man-machine interface and operational support
   - Improving the designation of responsibilities
   - Improving the electronic navigation support
   - Improving (modifying) ship bridge design

d) Available time
   - Improving time management in the execution of tasks

e) Training and preparation
   - Improving navigational training
   - Improving task planning
   - Improving safety and risk management skills

f) Collaboration quality
   - Improve internal and external communication

The included RCOs are very general in character in terms of managing the risk of ship collision in winter navigation. The aim is to initially detect areas of opportunity in the execution of the operations based on identified shortcomings in the functioning of the CPCs and then assessing the potential efficiency of the RCOs. The assessment of the CPCs and RCOs is executed by winter navigation experts from Finland and Russia. In particular, the RCOs are discussed in detail to look beyond the numbers to identify practical aspects in designated RCOs with
improvement potential. Details about this assessment are presented in Section 2.4 of publication PII.

2.2.3 The outcome of the risk management model of winter navigation operations

The integration and processing of different sources of evidence in the model provides different outcomes for understanding and managing the risk of collision in the analysed winter navigation operations. As an initial outcome, the model indicates that ship independent navigation and convoy are the winter navigation operations with the highest probability of collision (1.5E-04 and 1.4E-04, respectively); see Table 2 of publication PII. These are also the two operations that involve the highest probability of accidental oil spills. Table 7 in publication PII presents the probability of different sizes of accidental oil spills in each analysed operation.

Another essential outcome of the model is its capability to increase understanding of how collisions leading to accidental oil spills could occur. The elements related to the operational characteristics enable the detection of the angles and speeds utilized in the operations (see Appendix B in publication PII). Moreover, the integration of these elements into a collision damage model allows the calculation of the angle and speed of collision that would breach the ship’s hull, penetrating cargo or bunker tanks and resulting in oil spills. These calculations are presented in risk matrices in Appendix C of publication PII.

In the analysis of the CPCs and RCOs for managing the risk of winter navigation operations, the model is capable of representing the CPCs with the greatest need for improvement. Thus, the information presented in the model conveys the qualitative information collected from the consulted experts as probabilistic representations. In the model representing the experts from Finland, the available procedures and plans for managing and supporting winter navigation operations comprise the main CPC in need of improvement. While discussing this in detail, the experts expressed the need for safety management systems and processes with more efficient integration between safety regulatory and administrative demands and the demands of the operations. In the model representing the experts from Russia, the man-machine interface and operational support of the operations comprise the main CPC in need of improvement. This group of experts expressed the need for the more efficient implementation of devices and technologies for supporting the operations.

Based on the previous, the two groups of experts evaluated the improving of navigational training and safety and risk management training as the RCOs with the highest potential for efficiency in relation to risk reduction (see Table 6 in publication PII). The main aspects mentioned about the RCOs are the development of alternatives to provide adequate information to perform ship navigational operations in extreme ice conditions. To this end, Finnish experts particularly point out the need to develop methods to analyse and manage the safety and risks of winter navigation, focusing on enabling a clear understanding of the demands involved in the operations and the functions of the complete winter navigation system. Russian experts stated that there is a need to improve planning skills to enhance the quality and efficiency of the ship voyage plans, including enhancing cooperation and communication with other navigation stakeholders assisting with developing and controlling the operations as well as finding alternatives for supporting the cooperation between merchant ships, icebreakers, VTS centres, and pilots.

The representation of the RCOs in the model enables a graphic description of the impact of each option on the expected improvement in human performance. This impact is represented by the effect of the RCOs on the probabilities of the CPCs, the human performance, and the final risk of collision in each operation. Another advantage of the model outcome is the
capability of representing the most effective combination of RCOs for improving human performance. Figure 6 presents two matrixes showing the respective percentages of expected improvement in crew performance with the combined implementation of two RCOs in each winter navigation operation. This expected improvement is categorized by the estimations made by the two groups of experts.

Figure 6 shows that based on the model, Finnish experts consider the improvement of safety and risk management training and the improvement of navigational training as the best combination of RCOs yielding a higher potential for efficiency with respect to risk reduction in ship independent navigation and icebreaker assistance operations. For example, the figure shows that combining RCOs 10 and 12 results in an expected improvement of over 40% in the efficiency of the execution of ship independent navigation.

In its detailed analysis of RCO 12, this group of experts refers to the need to have adequate formation and training to plan and implement more practical management of risk and safety. In particular, the experts consider that there is a need to combine operational and regulatory demands more efficiently. Regarding RCO 10, the experts see the potential lack of experience of navigation in sea ice conditions as one of the main hazards in the execution of the operations. The experts point out that any ship crews attempting to execute operations in sea ice conditions need to have adequate and accredited training.
In the case of the Russian experts, the figure shows that the improvement of electronic navigation support and improvement of navigational training are the best combination of RCOs yielding a higher potential for efficiency with respect to risk reduction in the execution of the four operations. For example, the figure shows that combining RCOs 7 and 10 results in an expected improvement of between 30% and 40% in the efficiency of the execution of convoy operations.

In its detailed analysis of RCO 7 and 10, this group of experts points out the importance of providing adequate training to the crew of ships and icebreakers in order to ensure efficient utilization of the technologies implemented in the development of the operations. The combination between training and technologies is particularly important for situational awareness.

Based on the outcome of the model and the RCOs that the Finnish experts identified as being potentially more efficient, the next section focuses on the development of proposals that offer alternatives to enable the more practical and systematic managing of maritime risk and safety.
3. Alternatives to support maritime safety management

3.1 An approach to interpret and adopt maritime safety management regulations

Today, safety management regulations aim not only to provide requirements to be fulfilled in order to ensure safety, but also represent initial sources of information that provide guidance for describing how to achieve a desired safety performance (Robson et al., 2007). Therefore, safety management regulations must be interpreted and adopted appropriately in the management practices of organizations. It is important to avoid the forced inclusion of regulations that are perceived as extra tasks in the common operations of organizations (Lappalainen, 2016).

3.1.1 Interpretation of maritime safety management regulations

The International Maritime Organization (IMO) is the main actor responsible for the applicable regulations for ensuring and managing maritime safety performance (IMO, 2015). The ISM Code is the main reference guidance available for the management of maritime safety. The code aims at ensuring safety at sea, preventing human injury or loss of life, and avoiding damage to the environment, in particular the maritime environment and property (IMO, 1993). Thus, the code represents the essential and minimum demands to be considered in establishing a maritime SMS. However, the interpretation of the content of the code and its potential to guide maritime safety management practices seem to be currently underutilized (Schröder-Hinrichs, 2010). This reflects the lack of methods to interpret and adopt this guidance, a problem that has already been pointed out in the analysis of managing and controlling the risk of ship collision during winter navigation presented in Section 2.2.3.

This section introduces a systematic method for interpreting and reviewing the requirements and guidelines of safety management regulations. The method is based on the structured review of policy programmes provided in the realist evaluation proposed by Pawson and Tilley (1997). This evaluation aims at reviewing the content of policy programmes in different stages of their applicability, going from conceptualization and adaptation to application. For this purpose, the content-mechanisms-outcome (CMO) process of analysis is applied, analysing aspects of the integration and adoption of these programmes:

- Context: assess and describe the conditions in which the programmes are introduced and applied.
- Mechanisms: assess the resources and practical applications that make the programmes work.
- Outcome: assess the intended and unintended consequences of the implementation of programmes.

In the context of the method proposed for the interpretation and adoption of maritime safety management, the programmes mentioned here consist of norms, covering regulations, guidelines, or any safety framework ruling the system. Thus, the implementation of the CMO is specifically considered as follows:

- Context: assess the form the requirement and guidelines included in the applied safety management norms are subjected to the reasoning and environment of the affected organization.
- Mechanisms: assess the use of resources to make the system functional and supportive to achieve the planned objectives through the implementation of the applied safety management norms.
- Outcome: assess the possible consequences arising from the application of these safety management norms, and how to adapt these to the plans and procedures of the system.

The CMO process represents the basis for developing a qualitative method for interpreting, reviewing, and adopting the requirements of safety management norms. Table 1 presents the method to interpret and review the requirements of norms.

Table 1. CMO applied to interpret, review, and adapt the requirements of regulations (publication PIII).

<table>
<thead>
<tr>
<th>Realist evaluation</th>
<th>Application for the analysis of the regulation’s requirements</th>
</tr>
</thead>
</table>
| **Context**        | - What is (are) the main organizational aspect(s) analysed by the requirement?  
- Which is (are) the current task(s) developed in the organization linked to the requirement?  
- What is the status of the organizational conditions influenced by the requirement?  
- What and who are responsible for ensuring the requirement implementation and its maintenance?  
- What is the current link of the requirement with similar requirement(s) in other implemented norms? |
| **Mechanisms**     | - Which are the main organization’s means for the implementation?  
- How is the requirement currently communicated inside and outside of the organization?  
- How is the organization able to ensure that the importance of the requirement is understood?  
- How are the skills and capabilities of the responsible person(s) evaluated?  
- How is the organization able to ensure that the requirement is linked with other implemented norms and regulations? |
| **Outcome**        | - What is the current level of fulfillment of the requirement?  
- What are the expected results derived from the application of the requirement?  
- What are the possible negative aspects (internal and external) that could affect the implementation of the requirement?  
- What kind of improvement can be obtained after implementing the requirement? |

### 3.1.2 Integration of maritime safety management norms into safety management systems

The proposed CMO method is applied to review the content of two main guidelines sources in the management of maritime safety: the ISM Code by IMO and the Tanker Management Self-Assessment (TMSA) by the Oil Companies International Maritime Forum (OCIMF, 2014). The ISM code is selected to cover the essential demands of maritime safety management and the TMSA is selected to strengthen the essential demands of the code with safety management guidelines from the best practices implemented in maritime oil transport. The aim is to incorporate the interpretation and adoption of the two mentioned norms into the structure of an SMS. To this end, the proposed CMO method presented in Table 1 is executed, and the review of the generated information is performed together with experts in maritime safety management in Finland. Section 3.2.2 in publication PIII presents detailed information about the characteristics of the consulted experts.

Tables 3 to 5 in publication PIII present examples of the application of the CMO in the analysis of three requirements contained in the mentioned regulation and guideline. The aim is to utilize the proposed process to support the understanding about the functioning of the regulations and the guidelines included in it. This makes it clear to whom the benefits of their application should be represented. A coherent balance can thus be achieved between the actual functioning of the organization, the resources available for the management of safety, and the requirements of the regulations. Furthermore, reasoned expectations can be derived from the adoption of the requirements and the regulations in general.

The method aims at supporting either the constitution and installation of a new SMS or the review and adoption of an additional regulatory framework into an existing SMS. This supports the development of systems with a more proactive approach to control and ensure the safety of maritime organizations.
3.1.3 Establishing a systematic analysis of the system performance

The application of the proposed method to review the mentioned safety management regulation and guideline has the additional aim of providing guidance for defining key performance indicators that are capable of monitoring and reviewing the functioning of the requirements and the functioning of the entire SMS. For this, preliminary measures for monitoring and reviewing the functioning of the requirement have been selected; see step one in Section 3.2.2 of publication PIII. The relevance of these measures is assessed based on the analysis of the requirements with the proposed CMO method. The aim is to select KPIs for the analysis of the requirements contained in the analysed regulation and guideline, creating a reasoned basis for representing the complete aspects of the system that are behind the reported output of each KPI. This is represented in the third column of Tables 3 to 5 of publication PIII where the justification of the final selected KPI is presented.

The selection of KPIs after the application of the proposed CMO method facilitates the comprehension of the complete scope covered by the KPI. This enables an analysis that supports understanding of the evaluated requirement and facilitates the definition of KPIs for the requirement. Table 6 in publication PIII presents a list of 53 defined KPIs for reviewing the requirements of the ISM code and TMSA. These KPIs are categorized into three types of indicators defined by Reiman and Pietikäinen (2012):

- **Drive indicators**: applied to change, maintain, and reinforce different elements of the system. These indicators act to direct the sociotechnical aspects of the system by motivating certain safety-related activities.
- **Monitor indicators**: applied to monitor the functioning of the system, including but not limited to the efficacy of the control and development measures. These indicators measure the internal dynamics of the sociotechnical system.
- **Outcome indicators**: reflect a temporary end result of a process and/or an activity. These indicators present the result or consequence of the main tasks or processes in the organization.

Finally, an analysis for identifying and defining the main components of maritime safety management in Finland is executed. The selected KPIs are individually analysed by the same group of experts described in Section 3.1.2. The analysis of the selected KPIs is described in detail in Section 3.2.3 of publication PIII. This resulted in a list of the 23 defined components of maritime safety management in Finland, which is presented in Section 4.3 of publication PIII. These elements can be considered to be a first step towards an integrative, comprehensive, and simple description of the aspects considered in the management of safety in the Finnish maritime industry. Moreover, these components have been implemented as a starting point for examining the inner mechanics of maritime safety management for relevant key stakeholders in the Finnish maritime industry; see Hänninen et al. (2014).

The provided CMO method to interpret and review norms enables coherent integration between the requirements of regulations and the functioning of organizations. This represents an essential pillar for interpreting and adopting regulations into the function of an SMS. Figure 7 presents the elements covered in this analysis; these are essential for establishing an SMS in the maritime industry. The elements included in the figure are the actual functioning of the organization, the regulatory frameworks applied or adopted by the organization, and the monitoring and reviewing of their performance by utilizing KPIs. Thus, the figure represents the interpretation and adoption of regulatory demands based on the description of the current functioning of the organization. The next section focuses on the elaboration of an alternative for designing a maritime SMS that enables a systematic integration of the three mentioned elements.
3.2 Designing functional maritime safety management systems

As discussed in Section 3.1, safety regulations are essential for the functioning of the SMS of maritime organizations. However, a clear understanding about the functioning of the organization is also essential to establish an SMS. This is necessary to capture the actual management practices utilized in the organization more efficiently. In order to efficiently combine the regulations and the functioning of the organization for implementing and operating an SMS, processes for designing SMS have to be elaborated.

In the maritime industry, the regulations for managing the safety of maritime organizations include different types of demands that vary depending on different aspects, including the context of the operation and/or the industry involved. This creates exhaustive regulatory demands and complexity in their implementation and management (Knudsen, 2009).

For understanding the functioning of organizations, a solid theoretical foundation that enables the representation of the practices and aims of the system at different hierarchical levels of the organization needs to be defined (Hollnagel, 2014; Leveson, 2011; Roland and Moriarty, 1990). As graphically represented in Figure 1, the FSWNS is a multi-hierarchical one. Thus, it is crucial to understand and represent the boundaries of the system levels and identify the links between levels and their dynamic interactions.

The monitoring and reviewing of system performance must also be included, starting from the system design phase. In practice, performance monitoring and reviewing are commonly executed by implementing KPIs (Reiman and Pietikäinen, 2012). KPIs measure the levels of operational and organizational safety that are reflected in the performance of the SMS (Øien et al., 2011; Swuste et al., 2016). Therefore, the definition of the KPIs of the system and their practical implementation need to be performed as the last task of the design phase.

3.2.1 A method to systematically design maritime safety management systems

This section introduces a process to design an SMS for organizations within the maritime industry. The process is guided by the application of a methodology for integrating safety into system engineering based on the structure of the safety intent specification presented as part of the Systems-Theoretic Accident Modelling and Processes (STAMP) (Leveson, 2011).

STAMP is an approach to depict and review the function of safety from a systemic perspective. The method assesses the function of safety in complex sociotechnical systems. To this end, it
attempts to face the fast pace of technological change, increase the ability to learn from experience, understand the changing nature of accidents, and especially to deal with the complexity of interaction among diverse system components. For this last aspect, the foundations of the method are based on emergence, hierarchy, communication (feedback), and control. Emergence is the representation or model of complex systems, hierarchy describes different levels of an organization, communication transmits the understanding about the hierarchy and its emergent properties, and control imposes constraints on the system behaviour.

The safety intent specification in STAMP is organized into hierarchy levels that provide information about the decisions for assembling the management of organizational safety. Section 3.1.2 in publication PIV presents the original structure of the safety intent specification. This structure consists of seven defined hierarchy levels:

0. Defines the initial conception between the planning goals and the existing management practices.
1. Defines the foundations of the SMS, representing the safety components to be analysed and included in the initial structure of the SMS.
2. Provides details about the designs and the scientific and engineering principles of the system.
3. Defines the system architecture and represents the interface between system engineers and component engineers.
4. Reviews the system user needs.
5. Reviews the implementation issues based on the reviewed user needs.
6. Reviews the system operations and performance.

Based on the hierarchy levels, a process to design a maritime SMS is elaborated (see Table 2).

The process focuses on identifying the elements contained in the management of safety in the different hierarchy levels of the organization from an early design phase. The tasks included in Level 0 enable a systematic representation of the management practices in the organization, starting with an understanding of the managerial structures and practices already adopted in the organization. The tasks included in Level 1 support the definition of the core safety elements that the system must manage, representing the basis of the SMS. The tasks included in Level 2 define the details of the logic principles behind the interaction of the requirements of the SMS under design, reviewing and redefining these requirements and the safety constraints designed in the previous level. The tasks included in Levels 3 to 5 define the approach to making representations of the structure and the requirements of the SMS for facilitating the analysis of these with any system stakeholder. Finally, the task included in Level 6 provides means and tools for monitoring, reviewing, and updating the functioning of the SMS.

The process is utilized to design the structure of an SMS for VTS Finland. The designed structure attempts to represent the functioning of the controls utilized to ensure internal safety management at VTS and the management of the safety of ship navigation in Finnish sea areas. To this end, the SMS is designed by differentiating the services provided during the spring-summer-autumn season and the winter season, i.e. when the FSWNS is active. The application of the process presented in Table 2 provides the definitions of nine requirements for the management of safety in the spring-summer-autumn season and four additional requirements for the winter season. Together, these 13 requirements and their respective safety constraints are generated for managing internal safety at VTS Finland and the external management of the safety of navigation in Finnish sea areas. The complete outcome of the application of the process is presented in Section 4 of publication PIV.
The requirements produced by the application of the proposed process provide a systematic structure that enables the definition of the safety management tasks at VTS Finland. This includes the identification and definition of the system environmental assumptions (EA), the safety constraints (SC) implemented to ensure the functioning of the system, the hazards (H) mitigated by the system, and the indicators (KPI) utilized to monitor and review the performance of the system. Figure 8 presents examples of these aspects in the systematic structure of the requirement Req./G2/6 “Vessels navigating in a route where complex ice conditions can be foreseen must be informed about this situation and re-recommend the following of the waypoints”. Section 4.2.2 in publication PIV describes the other 12 designed requirements.

The result of the process application provides a set of analyses for managing safety in a systematic manner. This enables linking all information processed in the system, supporting its transmission to manage safety at all hierarchy levels of the organization.

Furthermore, the review of the system performance tests the functionality of the system based on KPIs that monitor the internal functioning of the SMS and the level of efficiency of the SMS when managing safety in relation to external stakeholders. This systematic review process for the analysis of system performance is presented in detail in the following section.
3.2.2 Systematic monitoring, evaluating, and updating of system safety performance

Section 3.1.3 outlined the importance and actual role of KPIs for monitoring, reviewing, and updating the performance of SMS. This section focuses on representing how this can be executed in practice. For this purpose, an elaborated performance monitoring tool is presented.
The performance monitoring tool is the result of the implementation of the last task included in Level 6 of the process for designing the maritime safety management systems represented in Table 2. In particular, this tool is applied to review the performance of the SMS designed for VTS Finland.

The KPIs to be represented in the tool are defined through reviewing the 13 requirements of the SMS with the CMO method presented in Section 3.1.1. This produces the definition of 31 KPIs for monitoring and reviewing the performance of the requirements of the SMS. Annex 6 in publication PIV describes these KPIs. Table 3 presents the practical content and functionality of the KPIs for monitoring and reviewing the requirement Req./G2/2 “A vessel approaching to a point of contingency has to be informed about the situation and recommendations (guidance) have to be provided”.

The monitoring tool is structured in a BN model. The tool is divided into three sub-models, each with a specific role:

- Sub-model one. Contains the KPIs of each requirement and collects their input information
- Sub-model two. Displays the level of efficiency of the requirements
- Sub-model three. Contains the actions to be executed based on the levels of efficiency

The functioning of the tool is structured based on a commonly used Plan-Do-Check-Act (PDCA) paradigm (Meyer and Reniers, 2013). Figure 9 presents a portion of the monitoring tool for presenting the application of the PDCA process for exemplifying the functioning of the tool with the review of the requirement presented in Table 3.

<table>
<thead>
<tr>
<th>Req./G2/2</th>
<th>A vessel approaching to a point of contingency has to be informed about the situation and recommendations (guidance) have to be provided.</th>
</tr>
</thead>
</table>
| Status and input information | KPI/Req./G2/2(1) Warnings emitted to vessels regarding contingency points (OI*):
- Status A: Less than 5 warnings reported (in a determined time period)
- Status B: Between 5 and 15 warnings reported
- Status C: More than 15 warnings reported
KPI/Req./G2/2(2) Vessels affected by registered contingency points? (MI*)
- Status A: Less than 3 vessels (in a determined time period)
- Status B: Between 3 and 6 vessels affected
- Status C: More than 6 vessels affected |
| Conception of current safety level of the requirement | States for defining the current safety level:
- Efficient
- Inefficient |
| Actions connected to the efficiency of the requirement | - Action A: Periodically review the requirement and the safety constraints linked to it.
- Action B: Make a review of the requirement, including the analysis of the assumptions made to formulate it. Review the control structure established for the analysis of the hazards to make updates that improve the transmission of warnings.
- Action C: Make a detailed review of the preliminary hazard analysis to re-evaluate the relevance of the detected hazards and discuss other potential threats connected with the function of the requirement. Complement this with the execution of the STPA. |
| Actions from Drive KPIs | KPI/Req./G2/2(3) Actions developed to strengthen the skills of VTS personnel in the provision of guidance (DI*)
- Action A: Organize meetings and workshops to discuss issues influencing the effectiveness in the provision of warnings and navigational assistance.
- Action B: Request for training to improve the emission of warnings and the provision of navigational assistance, analysing potential conflicts in the emission of warnings and provision of navigational assistance. |

*OI: Outcome Indicator, MI: Monitoring Indicator and DI: Drive Indicator
In the “Plan” phase, three probability sets must be defined. In sub-model one, the probabilities of the defined statuses included in each KPI must be estimated. In sub-model two, the probabilities of efficiency and inefficiency of the requirement(s) analysed by the indicator(s) must be estimated, considering the statuses of each KPI included in the assessment of the requirements. In sub-model three, the probabilities for each recommended action must be estimated based on the expected efficiency level of the requirements.

In the “Do” phase, the outcomes of the measured KPIs should be reported by including the evidence for the statuses after the actual measuring of the KPIs. Evidence should be assigned to each variable representing the KPIs of sub-model one.

In the “Check” phase, the levels of efficiency and inefficiency of the requirements should be reviewed in sub-model two once evidence is included in each KPI. Moreover, the produced probability levels in the recommended actions designated for each requirement also need to be reviewed.

The “Act” phase is represented in sub-model 3. The actions with higher obtained probabilities in each requirement are presented to the user as suggested courses of action.

In general, the process created to design maritime safety management systems enables the adoption of the safety management practices of the organization, systematically transferring these into the functioning of the SMS. The process provides guidance to design an SMS with a
solid structural foundation and based on a state-of-art theoretic accident model. The inclusion of the CMO method (see Section 3.1.3) to define the indicators of the SMS supports the analysis of the assumptions behind each KPI. Thus, the foundations of the SMS are systematically strengthened. Figure 10 presents the elements that are essential for establishing an SMS in the maritime industry in a graphical representation, adapting Figure 6 by including the process proposed in this section, thereby representing the effect produced with the use of the process for designing a maritime SMS. The figure depicts the integration of the elements for designing, establishing, controlling, and maintaining an SMS.

Figure 10. The elements integrated in the design of a maritime SMS
4. Discussion, contributions, limitations, and future research

4.1 Thesis contribution and reached objectives

This section discusses the contribution of the thesis to the FSWNS in view of the stated objectives in Section 1.3. Figure 11 presents a graphical representation of the input of each objective into the functional scope of the FSWNS. The contribution of the executed analyses and the proposed alternatives to manage the risk and safety of the system are assessed.

4.1.1 Maritime risk management with focus on winter navigation

Risk management focuses on the development of methods for detecting, analysing, mitigating, and controlling the risks threatening the safety system. Following this definition in Figure 11, the accomplishment of Objective 1 provides understanding and evidence about the risks threatening the safety of the FSWNS, thereby detecting the main hazards and risks of winter navigation, and representing in detail the different risk scenarios in the output of the system.

Objective 2 is defined based on the outcome of the first objective. Its accomplishment provides concrete understanding about the operative context that involves the highest risk of navigation in ice conditions, i.e. ship to ship collision. This objective includes a review of the potential catastrophic consequences of such an accident, giving insights about the different sizes of potential oil spills.

In the analysis of the risk of ship collision in winter navigation, Objective 3 assesses potential options to control/mitigate the risk of ship to ship collision. To this end, the objective initially focuses on the analysis of the common performance conditions of personnel responsible for executing the operations, identifying shortcomings and needs in those conditions. The accomplishment of this objective highlighted several options aiming at controlling, mitigating, and improving the risk of collisions in winter navigation. This review indicated that the strengthening of navigational training for the crews of ships operating in sea ice conditions, the improvement of electronic navigation support to efficiently guide ships operating in sea ice conditions, and the improvement of safety and risk management practices for planning and supporting winter navigation operations are the options with the highest potential for producing positive results in controlling and improving winter navigation operations.

The accomplishment of these three objectives has provided essential elements for analysing and managing the risk of winter navigation. The analysis of the performance of the FSWNS presents a positive output in terms of accident occurrence: accidents have low frequency and the severity of these accidents is commonly low. In the analysis of ship to ship collisions, the probability and severity of this kind of accident are also low. This indicates that ship independent navigation and ships in convoys are the operations with potentially more severe consequences. This positive output of the system allows the implementation of proactive approaches to further strengthen the functioning of the FSWNS and this is reflected in the three risk control options that are estimated as being potentially more efficient.

4.1.2 Maritime safety management with focus on winter navigation

From the three options evaluated as being potentially more efficient, the improvement of safety and risk management practices for planning and supporting winter navigation operations is the option that was developed further. A particular focus was the development of alternatives to tackle the need for developing coherent safety management practices capable of transferring the actual operational needs into the functionality of the safety management in the organization. Apparently, this is not an exclusive need in managing the risk and safety of
winter navigation as it has been previously detected in the context of other maritime operations (Ek and Akselsson, 2005; Lappalainen et al., 2014; Ol tedal, 2009). Thus, in order to cope with this detected need of the FSWNS, two complementary alternatives are formulated into Objectives 4 and 5.

**Objective 4** provides a methodology to interpret and adopt safety management regulations. The method is applied to provide guidance for interpreting and adopting two main norms of safety management in the maritime industry, with the Finnish maritime industry as the context of application. Moreover, the method supports the systematic setting of KPIs for monitoring and reviewing the performance of identified elements of safety management in the Finnish maritime cluster. In Figure 11, the input from this objective is represented in the connection between the main responsible organizations (shipping companies) for fulfilling and incorporating the requirements of these norms in the actual execution of their operations and the responsible organizations (IMO and FTSA) for developing and implementing the norms in a certain framework. Thus, the accomplishment of this objective facilitates the systematic incorporation of the requirements of the norms into the actual practices of maritime safety management in Finland.

**Objective 5** strengthens the functioning of the FSWNS by providing a detailed process for designing an SMS in the maritime industry. The process prioritizes the value of designing safety management practices that aim at ensuring the internal functioning of the organization and the functioning of the system to which it belongs. In Figure 11, the input of this objective is given to the application of this process for designing the framework of an SMS for VTS Finland. The influence of this application is represented in the connection that VTS Finland has with the organization (FTA) responsible for its operations and the main organization (IALA) offering guidance on the functioning of VTS, and the link VTS has with other winter navigation stakeholders (pilot, shipping companies and icebreakers). The designed controls of the SMS are capable of managing safety at different organizational levels within VTS and define particular links to promote and execute the systematic management of safety together with other FSWNS stakeholders.

The accomplishment of these two last objectives provides alternatives to strengthen the planning, implementation, and monitoring of safety management in the FSWNS, and thereby takes advantage of the current performance of the system in order to develop more proactive safety management practices in the maritime industry in Finland.

### 4.2 Limitations of the utilized data, methods, and thesis output

In the development of **Objective 1**, the analysis of the current output of the FSWNS covers the analysis of accident and expert data. The main limitation of the accident data is the lack of details about the accidents that occurred. This limitation is mainly due to the type of accidents reported, as most of them are less serious and do not require a far-reaching investigation. This is a problem often detected in maritime accident databases; the issue has also been discussed in work by Hänninen et al. (2014), Hassel et al. (2011), Lappalainen et al. (2011), and Qu et al. (2012). The expert data represents the view of the three most relevant stakeholders of the FSWNS. However, this view is limited to a relatively low number of interviewed experts.

The elaborated model as part of **Objective 2** conveys arguments based on available evidence, and this results in the quantification of uncertainties that are represented as probabilities. However, the model does not claim to represent the “true” probability of collision and potential oil spills. The model is focused on the estimation of probabilities of observable events (ship collisions), aimed at highlighting the relative importance of the proposed RCOs. Furthermore, the strength of evidence utilized for the functioning of the model is mainly
assessed as medium. Thus, the strength of the evidence is represented as high in the analysis of the traffic conditions and as medium in the analysis of operational characteristics and human factor. Appendix E in publication PII presents the strength of the evidence base utilized in the model.

In **Objective 3**, the analysis of the options to control the risk of collision in winter navigation is limited to six common performance conditions involved in the planning and executing of operations on the bridge of ships and icebreakers. For this purpose, human error quantification is performed by combining the CREAM and BNs methodology. Error probabilities are used to detect a good indicator for the probability of interaction between the common performance conditions and the proposed risk control options, keeping in mind that
the model makes no claims about precise failure probabilities. Again, the probabilities are utilized to represent trends and guide the decisions for supporting risk management. Also, the analysis of the RCOs is limited to the views of a certain number of interviewed experts in Finland and Russia. Another limitation is represented by the exclusion of the cost-benefit analysis of the proposed RCOs as demanded in the FSA. This represents a known limitation that comprises an area of opportunity for future research.

The method proposed in Objective 4 represents a qualitative process that aims at executing an exhaustive analysis of the context, mechanisms, and expected outcome for interpreting and adapting requirements demanded in safety management regulations. The main limitation of the proposed method concerns the resources that need to be invested to execute the method. These resources need to be aligned to the defined scope of the method application, balancing this aim and the resources invested.

The previous limitation is also reflected in the process proposed in the accomplishment of Objective 5. The limitation of the STAMP methodology and particularly the development of the safety intent specification is the definition of the level of detail that the process aims to cover. This level of detail has to be defined based on the safety goals and strategy of the organization, requiring a clear agreement between the system designers and system engineers about the resources available in the design phase of the SMS.

Finally, the last two objectives have another limitation: the lack of means to validate the efficiency of the output generated after the application of the method and process proposed. Procedures should be developed to provide concrete evidence about the actual benefits of developing and implementing an SMS.

4.3 Future research

This thesis points out two main aspects to continue the research developed. The first is the development of appropriate frameworks for validating the importance of the design phase and the general implementation of an SMS. The author sees a need for more pragmatic means to confirm that the SMS has a representative effect on controlling and improving the safety performance of organizations. An SMS must achieve a concrete balance between the invested work force, time, money and other type of resources and the actual monetary and organizational advantages obtained with its implementation.

The second main aspect is the continuation of the implementation of safety management approaches focusing on the functioning of the complete system. In the case of the FSWNS, this particularly means continuing with the implementation of safety system engineering and approaches to develop safety and risk management strategies and practices that strengthen the functioning of the system. Thus, the internal practices of risk and safety management in each organization covered by the system must be adapted to develop truly systematic management of risk and safety. This should create a harmonized approach for planning, implementing, and reviewing the management of risk and safety, improving cooperation and knowledge sharing among the stakeholders of the FSWNS, and compare this systematic approach against the safety and risk management practices implemented in other sea areas where navigation in ice conditions is executed.
5. Conclusions

The general aim of this thesis has been to assess the safety performance of winter navigation, in particular by reviewing the functioning of the FSWNS, with a view to understanding the risk and safety management practices implemented in the system, extracting details about the system output in terms of accident occurrence, and detecting areas of opportunity to strengthen the potential of the system. This aim is extended to provide safety and risk management alternatives supporting the planning, implementing, reviewing, controlling, and improving of winter navigation.

Publication PI has provided an updated and detailed review of the output of the system in terms of accident occurrence, presenting descriptions of the types of accidents that occurred to vessels when they navigated in ice conditions in the Finnish sea area and the actual context of these accidents. Moreover, this publication presents information about the severity and likelihood of these accidents.

Based on the outcome from publication PI, ship to ship collision has been identified as the accident with the highest risk of occurrence and with potentially more severe consequences. Publication PII has focused on the analysis of the risk of collision in the most common operations of ships and icebreakers during winter navigation. The publication provides a model for analysing and managing the risk of winter navigation. The model reviews technical characteristics of these operations, characteristics of ship traffic, and potential oil spills caused by ship to ship collisions in ice conditions. As output, the model indicates that ship independent navigation and ships in convoys are the operations with the highest risk of collision and the ones with potential for triggering accidental oil spills.

The model also includes the evaluation of specific options to mitigate the risk of collision, focusing on the development of actions that support the roles of the people who are responsible (in practice) for the operations of ships and icebreakers. This analysis has identified three particular needs for supporting the planning and executing of bridge personnel tasks. The first is the strengthening of the skills and knowledge of the ship crew involved in the planning, executing, and monitoring of winter navigation operations. The second is the need for developing risk and safety management practices that enable the integration of the practical demands of the operations and the demands coming from regulatory frameworks of safety and risk management. The third is the need for having electronic navigation support on-board to provide real-time information about the ice conditions of the operations and thereby enable the optimization of ship routing in wintertime.

From the above findings, the thesis provides alternatives focusing on closing the gap of the lack of coherent risk and safety management practices for transferring the needs of the actual operations performed on-board and integrating this into the interpretation and adoption of safety management regulations and the functioning of the SMS of the organization. To this end, publication PIII provides a method for executing a review and integration of requirements of safety management regulations into the functioning of organizational safety management. The method is applied to review the most common regulatory reference for maritime safety management (the ISM Code) and the guidance provided in the TMSA. The aim is to depict their application and interpretation in the maritime industry of Finland. This supports the definition of the main components of maritime safety management in the mentioned industry and the provision of key performance indicators for monitoring and reviewing the performance of those components.

Publication PIV proposes an additional step in closing the cycle of the tasks demanded for coherent safety management in maritime organizations. This publication introduces a
framework for designing safety management systems. The aim is to guide the design phase of an SMS for defining safety management requirements and controls at the different hierarchy levels of the organization. These requirements and controls are the product of the interpretation and integration of operative and management practices that have already been implemented in the organization. Thus, this publication provides guidance for creating an SMS with a coherent and reasoned foundation and exemplifies this with the application of this framework to one of the main stakeholders of the FSWNS, thereby systematically strengthening the entire system.

Overall, this thesis has presented the importance of executing the management of risk and safety of winter navigation in Finnish sea areas from a systematic perspective. To this end, the thesis has provided an integrated implementation of different data and scientific methods for understanding, reviewing, and consolidating the functioning of the FSWNS. While several research limitations are detected and additional research is recommended to confirm and advance the outcome of the work presented, the overall objectives of the thesis have been achieved.
Hänninen, S., & Rytkönen, J., 2004. Oil transportation and terminal development in the Gulf of Finland (p. 151). VTT.


Montewka, J., 2009. Predicting Risk of Collision for Oil Tankers in the Gulf of Finland. J. Konbin 11–12, 17–32. doi: https://doi.org/10.2478/v10040-008-0128-1


Oil Companies International Maritime Forum (OCIMF), 2014. Tanker Management Self-Assessment (TMSA). 2, 208th edn. OCIMF, Bermuda


Errata

Publication PI
On page 102, Section 3.2, first paragraph: “The navigational operation begins once a merchant vessel enters the areas covered with sea ice and starts navigating under these conditions without any operational assistance from...” should read “The navigational operation begins once a merchant vessel enters the areas covered with sea ice and starts navigating under these conditions without any on-site assistance operation from...”

On page 111, Section 5.5, last paragraph: “The risk of other events in Fig. 13 and other figures in this section is similarly represented” should read “The risk of other operations as the ones presented in Fig. 13 are similarly represented in this section”

Publication PII
On page 243, Section 2.1.2, first paragraph: “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.” should read “Ship independent navigation is described as the navigational operation that begins when a merchant vessel enters areas covered with sea ice and navigates in these without on-site assistance of any other type of vessel.”

Publication PIII
On page 244, Section 3.2.2, last paragraph: “The selection of the most relevant and final KPIs is conducted by applying the CMO queries presented in Table 1.” should read “The selection of the most relevant and final KPIs is conducted by applying the CMO queries presented in Table 2.”
Maritime transport is commonly categorized as one of the riskiest industry sectors. In Finnish sea areas, the risks increase during winter navigation when ships have to navigate in sea ice conditions. In order to support and ensure the integrity of people, ships and environment during winter navigation, different safety and risk management strategies are developed.

This thesis provides a review of the current safety performance of winter navigation in Finnish sea areas and it proposes alternatives to control and improve it. For this, it provides understanding and evidence of the risks threatening the safety of the Finnish-Swedish winter navigation system.

The thesis offers methods for executing a systematic application and performance measurement of the requirements contained in maritime safety management regulations. Moreover, the thesis introduces processes for designing maritime safety management systems based on a system engineering approach.