ADVANCED RISK MANAGEMENT OF AN ARCTIC MARINE SEISMIC SURVEY OPERATION

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Abstract

This research is motivated by the lack of a robust risk management framework addressing the high risks in Arctic Marine Seismic Survey Operations (AMSSO), and the lack of transparent decision-making in Arctic shipping risk management globally. The literature review carried out herein reveals that the AMSSO and Arctic navigation involve significant risks caused by human elements and the unique features of this region. These known risk factors combine to constitute a ship-ice collision risk. This last represents the goal of the research investigation. With the complexity of the AMSSO system, three technical chapters are proposed to analyse and reduce the risks in the AMSSO. The first technical chapter deals with local risk analysis of the system. Herein, a Fuzzy Rule-based methodology is developed employing the probability distribution assessment in the form of belief degrees with Bayesian Network (BN) and Failure Mode and Effect Analysis (FMEA) for estimating the risk parameters of each hazard event using a computer-aided analysis. A case study of the application of the proposed risk model – Fuzzy Rule-based Bayesian Network (FRBN) –, in the Greenland, Iceland and Norwegian Seas (GNIS) AMSSO is carried out to identify the most critical hazard event in the prospect oil field. The second technical chapter deals with the global safety performance of the Ship-Ice Collision model dovetailing the Evidential Reasoning (ER) technique and Analytic Hierarchy Process (AHP) with the FRBN. A trial application of the global safety performance of the Ship-Ice Collision case in a prospect oil field is carried out to determine the safety level of AMSSO, measured against a developed benchmark risk. The outcome of the investigation reveals the Risk Influence Factor (RIF) of each hazard event in AMSSO. Since the risk level is far above the tolerable region of the developed benchmark risk, several Risk Control Options (RCOs) are investigated in the last technical chapter to reduce and control the critical risks. This technical chapter finalises the risk management framework developed in this research. In a trial application of reducing a critical risk in AMSSO, AHP-TOPSIS is utilised to find a balance between cost and benefit in selecting the most appropriate RCO at the heart of several RCOs and their associated criteria. The novelty of this research lies in the fact that it tackles the major concerns in risk analysis (concerns such as dynamic event risk analysis, hazard data uncertainties, and hazard event dependencies) of a complex system. More also, it adopts a hybrid methodology that offers a non-monotonic utility output to select the most

appropriate RCO amongst several RCOs and conflicting criteria, to reduce the critical risks in AMSSO, in an economically viable strategy.

Acknowledgement

I am grateful to God Almighty for the wellbeing and good health that were necessary to complete this Ph.D. research.

This Ph.D. research would not have commenced if my father and my beloved wife had not given me the initial support. It breaks my heart today, that my Ph.D. research is completed, and my father is no more, may your soul rest in peace Daddy. Special appreciation is also given to my mother, brother, and sisters for their prayers and support. I will not fail to appreciate my son, who constantly puts smiles on my face even in difficult times. I would not have succeeded without my beloved family.

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…GREGORY ASUELIMEN…

Table of Contents

Table of Figures

List of Tables

Nomenclature

AHP	Analytical Hierarchy Process
ALARP	As Low As Reasonably Practicable
AMSSO	Arctic Marine Seismic Survey Operation
BN	Bayesian Network
CI	Consistency Index
CR	Consistency Ratio
DoB	Degree of Belief
ER	Evidential Reasoning
ETA	Event Tree Analysis
E&P	Exploration and Production
FL	Fussy Logic
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode Effects and Criticality Analysis
FRB	Fussy Rule-base
FRBN	Fussy Rule-base Bayesian Network
FRBN-AHP-ER	Fuzzy Rule-base Bayesian Network-Analytical Hierarchy Process-Evidential Reasoning
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
GINS	Greenland Iceland Norwegian Sea
HAZOP	Hazard and Operability
IAGC	International Association of Geophysical Contractors
IDS	Intelligent Decision System
IEA	International Energy Agency
IMO	International Maritime Organisation
LJMU	Liverpool John Moores University
MAIB	Marine Accident Investigation Branch
MCDM	Multi-Criteria Decision Making
MSC	Maritime Safety Committee
NPC	National Petroleum Council
NSIDC	National Snow and Ice Data Centre
PC	Polar Code
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation

QRA	Quantitative Risk Assessment
RCA	Root Cause Analysis
RI	Risk Index
RIF	Risk Impact Factor
RPN	Risk Priority Number
R_h	Probability of risk evaluation
UNCLOS	United Nations Convention for the Law of the Sea
Vn	Relative weight of linguistic terms High, Medium, Low, Very Low
λ_{max}	Maximum eigenvalue of an n x n comparison matrix
2D	Two Dimension
3D	Three Dimension

Chapter 1– Introduction

Overview

In this chapter, the research background, justification of research, aim of investigation are presented, followed by the research objectives and the challenges of conducting the research. The research methodology and scope of this thesis are further discussed, followed by the research achievements. The construction of this thesis is drawn to demonstrate how the proposed risk-based methodologies can provide support for strategic decision making in AMSSO risk management.

1.1 Research Background

With the current technological advancements to reduce global warming – that is, by encouraging the use of renewable energy sources to replace fossil fuels –, it is apparent that the world at large still depends on natural oil and gas resources for energy production. (Patel et al., 2015). According to the International Energy Agency (IEA), global oil and gas demand could grow by more than 35% from the present time to 2035 (Eurasia-Group, 2018).

Currently, the world's rising desire for natural oil and gas, coupled with the retreating reserves of natural oil and gas in shallow waters, has prompted mariners among others to come up with solutions and expertise to carry out oil and gas exploration in the far regions of the earth (Foy, 2017, Appenzeller, 2019). This far region of the earth referred to as the "Arctic" is a poorly charted area (Mollitor, 2018). Consequently, navigation in this area could be very challenging not only because of the poor navigation charts but also because of the presence of other risk factors, such as sea ice, limited navigation system and infrastructure at high latitudes, and adverse weather conditions (National Research Council, 2011, Leppälä et al., 2019).

The Arctic waters, according to IMO guidelines 2002, is defined by a body of water having a sea ice concentration of 1/10 coverage or greater, and which has the potential to cause structural damage to ships (Willy Ostreng et al., 3013). Areas with Arctic waters are referred to as either the Arctic or the Antarctic region. The Arctic region, which is the subject of interest, is situated in the regions of the North Pole (see Figure 1). It is mainly dominated by the Arctic Ocean (Micalizio, 2016) and covers an area about 14.5 million square kilometres in extension. The Arctic sea ice extent for August 2018 averaged about 5.61 million square kilometres (NSIDC, 2018a). The Arctic region makes up about 8% of the Earth's surface (AMSA, 2009).

The Arctic region consists of the ice-covered Arctic Ocean extending to land regions, including Greenland and Spitsbergen, Canada, northern parts of Alaska, Norway and Russia.

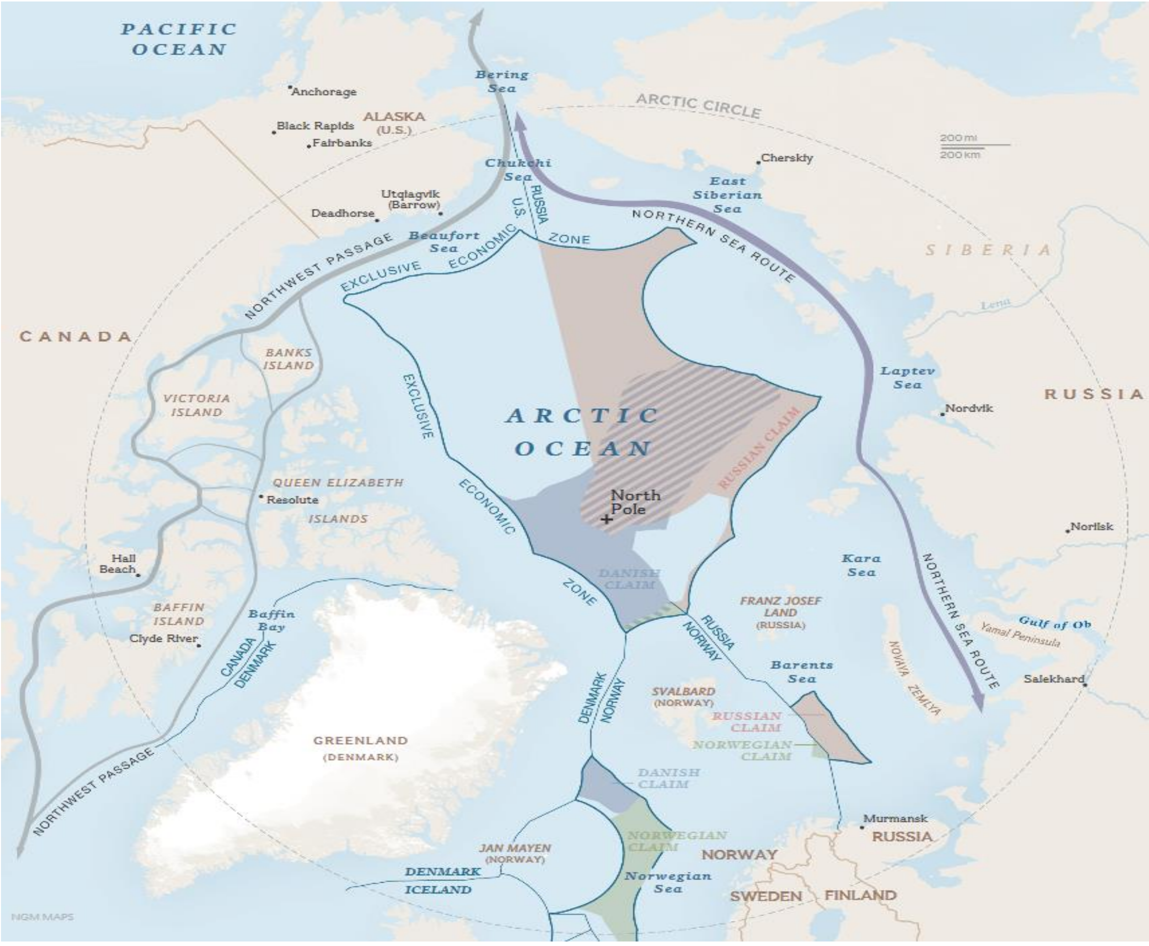

Figure 1: Location of the Arctic region (Shea, 2018)

Regions towards the North of the Arctic Circle according to a 2008 United States Geological Survey are believed to contain over 90 billion barrels of undiscovered and technically recoverable oil; this includes 44 billion barrels of Natural Gas Liquids in 25 distinct geological areas (Eurasia-Group, 2018). This region (the Arctic), represents 30% of the world's undiscovered gas and 13% of undiscovered oil (Eurasia-Group, 2018). The Arctic is believed to have the world's largest untapped resource of natural oil and gas (USGS, 2008). The energy and mineral assets distribution are represented in Figure 2, with Russia, Norway, the USA, and Canada topping the list in terms of mineral reserve deposits (USGS, 2008), (Desjardins, 2016).

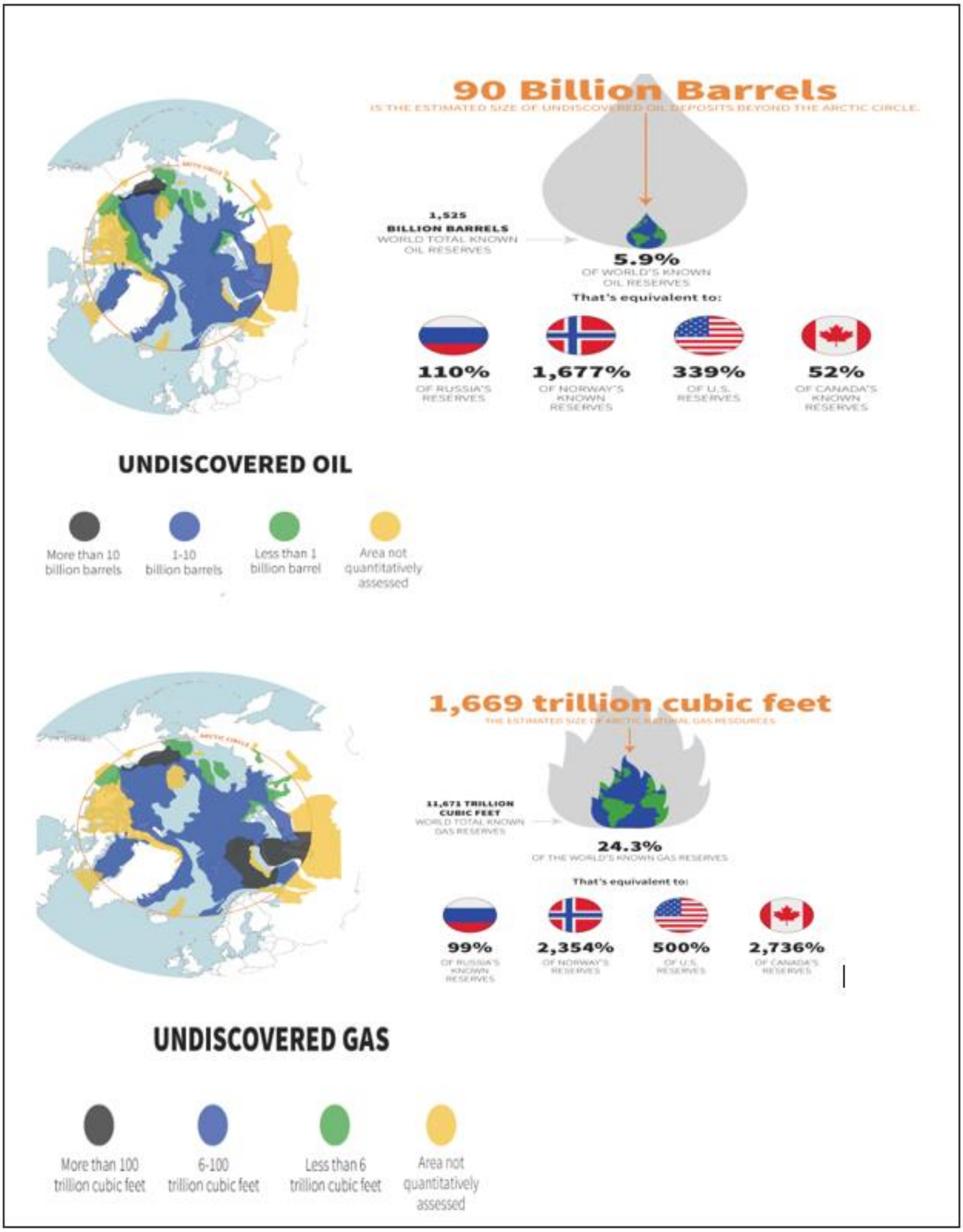

Figure 2: Energy and Mineral Assets of the Arctic (Desjardins, 2016)

The Arctic in overview is seen as a new frontier, undeniably one of the last on Earth, both in terms of its estimated economic benefits and as a poorly understood and fast-changing ecosystem (Hildebrand and Brigham, 2018). Despite the unique features of this region, such as the presence of ice, severe operating conditions, unpredictable climatic changes, and remoteness, oil and gas explorers are still relentless in exploring it because of the vast availability of natural hydrocarbon resources (Fu et al., 2018a).

Pinpointing the location of hydrocarbon resources (mostly oil and gas), in the Arctic seas, is in most cases a challenging task, because of the presence of ice. To overcome this challenging task, a seismic survey ship is desirable to carry out this operation efficiently and in a timely fashion (Hutchinson et al., 2009). This sophisticated vessel navigates about the surface of icy waters, letting off small explosions, which sends sound waves down to the rock layers, and recording the reflected sound waves with the aid of hydrophones to predict the possible location of natural oil and gas. The layout of the seismic survey vessel operation is represented in Figure 3.

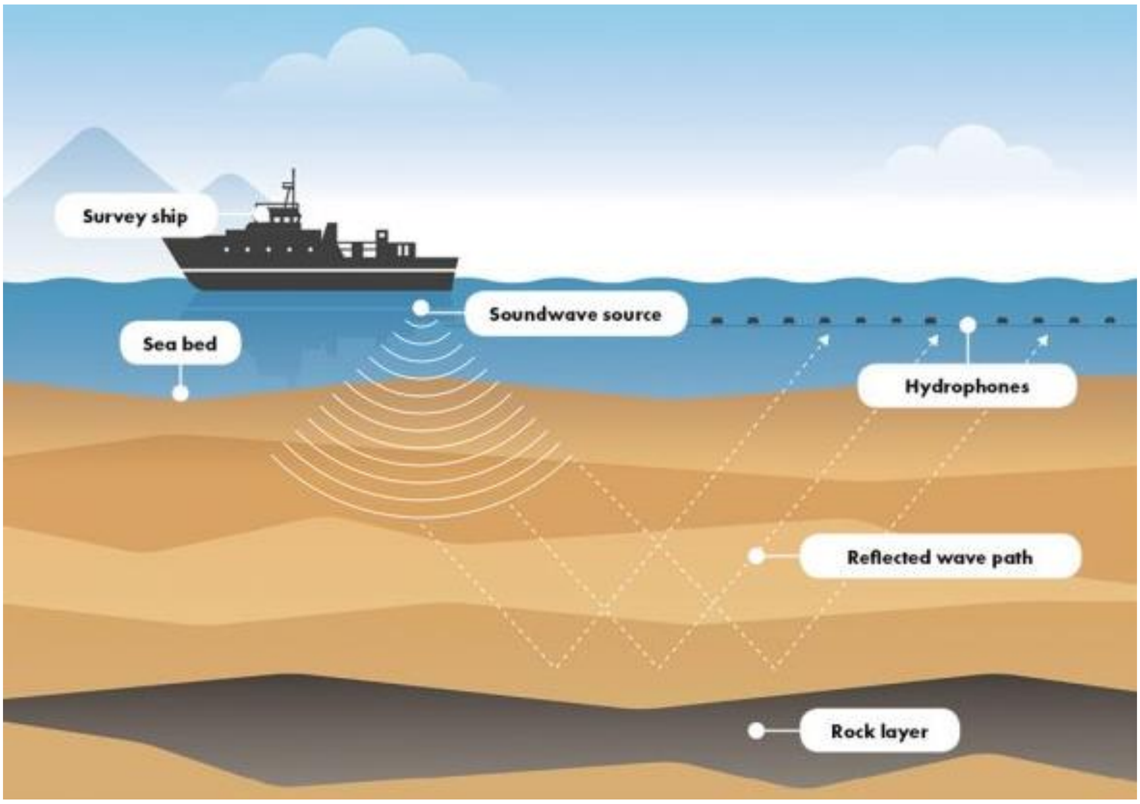

Figure 3: The layout of a Seismic survey vessel operation (EIA, 2019)

The sustained use of seismic vessels in Arctic oil and gas exploration is still very popular and cost-effective (Li, 2013a). Apart from the use of the marine seismic vessels in pinpointing the location of hydrocarbon, the use of these vessels can also be used to identify risks, and monitor and manage activities in the Oil and Gas Exploration & Production (E&P) life cycle (NPC, 2011). Marine seismic surveys remain a fundamental tool in Arctic oil and gas exploration, and presently one of the most sustained methods in pinpointing the location of oil and gas (Przeslawski et al., 2018, Daleel, 2019, NPC, 2011).

Seismic surveying in the Arctic is carried out with the presence of other shipping activities and offshore structures. With the recent trend in Arctic activities as a result of melting ice, there is a great likelihood of increased environmental and operational risks. In addition, there is a great likelihood of conflicts among traditional and new ocean users, and concerns of safety of life at sea (Hildebrand and Brigham, 2018). The 2009 Arctic Marine Shipping Assessment reported that there were around 6,000 vessels active in the Arctic in 2009 (AMSA, 2009). In addition to the negative impacts from the growing Arctic shipping activities, failure to plan for a robust risk management plan could potentially lead to loss of lives, assets, and damage to the environment (AMSA, 2009). Regardless of the complexity of things in the Arctic, all anticipated activities, whether oil and gas exploration, fishing and tourism must be done in a way that risks can be controlled to ‘As Low as Reasonably Practicable’ (ALARP).

From a governance viewpoint, Arctic states and a growing number of non-state actors, are working together with the IMO and the Arctic Council on common Arctic issues, particularly on issues of sustainable development and reducing risk to ALARP levels (Hildebrand and Brigham, 2018). Apart from the IMO contribution to the safety of life in the Arctic region, the United Nations Convention on the Law of the Sea (UNCLOS) also has a vibrant presence in ensuring the safety of lives in the Arctic region. The UNCLOS provides a comprehensive legal framework for the Arctic Ocean activities. In addition to the diplomatic table, the IMO also identified and published an international code, named IMO Polar Code (IMO, 2018a).

The Polar Code culminates in the one of the latest recommendations of previous IMO documents (IMO, 2014). The contents of the Polar code are affiliated in a way that allows for rational integration into the parent IMO instruments. The IMO Polar Code uses the Formal Safety Assessment (FSA) guidelines in ensuring safety at sea according to MSC-

MEPC.2/Circ.1 (IMO, 2014). Up until now, the FSA guidelines and framework are still the state of the art for the rule-making process in risk management.

The recent introduction of several safety regulatory bodies in Arctic shipping operations to safeguard lives might be doing more harm than good, as there is wide speculation that the unification of these safety regulatory bodies might not be as effective in reducing Arctic risk. This speculation is documented in IMO Resolution MSC.385 (94) 2014 (Hildebrand and Brigham, 2018). Consequently, there is an urgent need for stakeholders and Arctic marine company managers to adopt the FSA framework in the IMO rule-making process to achieve a single fit-for-all in reducing risks whilst operating in the Arctic region.

This research framework/model can assist each individual risk management policy, to measure their progress and to make sure important steps are not overlooked in AMSSO and arctic shipping in general.

The modelling techniques used in this thesis will be organised using the FSA guidelines. The FSA guidelines will be adopted to achieve a reliable and systematic risk management framework in this thesis. The FSA methodology can offer desirable results by providing proactive ways to reduce risk and improve Arctic maritime safety. This is achievable because FSA has the ability to offer a systematic mechanism that enables decision-making based on risk assessment and, more importantly, the cost-benefit analysis of the risk control option (Wang and Trbojevic, 2007). The FSA guidelines have been used extensively by several maritime related industries, and other industries involved with risk management (Bai and Jin, 2016b, Wang, 2003). Therefore, in this study, the FSA method will be adopted to offer a clear and justifiable rationale for a risk management-based methodology in marine Arctic seismic survey operation.

With the current shortage of documented list of hazard events in AMSSO, this research will focus on analysing major risks (such as human error, loss of signal in the ship navigational system, loss of ship control, bad ice and weather conditions). In addition, this research will focus on taking vita risk information from primary (such as MAIB) and secondary (such as eyewitness) data with the aid of expert judgement and literature review. Lastly, with the lack of risk control measures in dealing with AMSSO risks, this research will focus on developing a methodology that minimises costs and maximises benefit through literature review and experts' knowledge. This is done to ensure effective solutions to manage the dynamic risk in AMSSO in a cost-effective manner.

The proposed risk management model will help to identify all those that are potentially high risks in AMSSO and evaluate the possible channel to mitigate such high risks to achieve a high standard of safety. The developed framework and model in this research will incorporate Quantitative Risk Assessment (QRA) techniques with uncertainty modelling techniques, such as evidential reasoning, Fuzzy Logic and BN, in order to assess and reduce the risk of data uncertainty in a more reliable manner.

Making appropriate decisions on selecting the most appropriate risk-based techniques are clarified in this research in order to achieve an advanced risk assessment and management framework that employs systematic reasoning and a variety of uncertainty techniques to solve complex safety concerns in AMSSO.

1.2 Justification of Research

This research is motivated by the lack of a suitable risk management framework addressing the high risks in marine seismic survey in the Arctic region, (with reference to search results from the web of science and Google scholar, 2019). The major concern that Arctic marine seismic survey operators are faced with is a lack of research upon which to base their safety procedures for their complex activities. In addition, there is a general shortage of robust risk management models in Arctic oil and gas E&P industry. Furthermore, there is a misinterpretation of uncertainty and methods capable of assessing risk from its root characterisation. The need to formulate a bespoke model that can address risk with all ramifications, and highlight the safety and work efficiency issues facing Arctic marine seismic survey operators, managers, stakeholders and safety officers, is eminent now.

A gap in knowledge exists regarding the applications of robust risk management in AMSSOs and Arctic shipping in general. In addition, there is a need for more practical research at the academic level, to advance the best practice of risk management methods, to ensure proper implementation of the risk management methods in AMSSO. Furthermore, the need for more practical research at the academic level will benefit the potential requirements of Arctic activities in the near future.

The following guiding questions have been generated to ensure that the objectives of this research are fulfilled and to provide a base for conducting this research.

- Considering AMSSO, what are the sources of accident or hazard events associated with AMSSO affecting safety and efficiency, and how can these hazards or sources of an accident be identified and grouped for further investigation?

- One of the most notable definition of risk is Likelihood (L) × Consequence Severity (S) (Stergiopoulos et al., 2018). With this definition, a low risk might mean high safety, but this might not mean high work efficiency. Hence, other risk parameters would need to be considered to ensure safety and efficiency in AMSSO. Therefore, how can the risk parameters capable of affecting the safety and efficiency level in AMSSO be identified?

- What are the most appropriate and useful tools for evaluating each identified risk factor with associated data uncertainties for AMSSO in real practice, and how can these tools be applied?

- How can the identified hazards or risk factors be prioritised and ranked?

- How can the identified hazard events or risk factors be mitigated and controlled in an economically viable manner?

1.3 Aim of investigation

An Arctic seismic survey ship navigates icy waters in grid pattern, with towed sensors and an escort vessel. The entire operation exposes the crew and the marine seismic equipment to additional risks. Additional risks such as a ship-ship or ship-ice collision can cascade to accidents such as machinery damage, grounding, and hull damage with catastrophic consequences. Given controlling and averting these risk factors, this research aims to investigate all catastrophic hazard events in AMSSO and address the issue of risk data uncertainty in AMSSO risk analysis. The data uncertainty arises from the unavailability of sufficient primary observations and consequent shortage of statistical data about hazard events. In addition, the research aims to estimate and control the risk level of the identified hazard events to a tolerable limit, and provide a cost-effective solution to manage the anticipated high-risk levels in AMSSO. The present study conforms to the International Maritime Organization's (IMO) probabilistically based FSA model.

1.4 Research Objectives

The following objectives shall be met:

I. To carry out a literature review on the subject matter and examine published materials on Arctic shipping, AMSSOs, and examine Polar Code regulatory guidelines.

II. Analyse the complex activities in the AMSSO in order to identify the unwanted events (hazards) including human factors influencing risks to AMSSOs.

III. Review the risk assessments and decision-making methods, that are capable of dealing with uncertainty and incompleteness of risk data both qualitatively and quantitatively, which have extensively been developed and used in the maritime domain.

IV. To develop advanced risk analysis models to support the proposed research framework employing techniques such as Fuzzy Logic (FL), Bayesian Network (BN) and Evidential Reasoning (ER), to deal with uncertainty and incompleteness in risk data, to fit in the scope of the research.

V. Apply techniques to achieve a risk reduction method that is practical and cost-effective.

VI. Collect and analyse data to validate the proposed framework and models via a trial application of the proposed framework and models.

1.5 Challenges of carrying out the research in the presence of uncertainties (Statement of the Problem)

The main challenge in the research is the lack of historical accident data. With the lack of historical accident data, it is difficult to precisely identify all accidents, or provide accurate failure data for a precise risk management plan. The aforementioned challenges are subdued by employing experts' knowledge and advanced risk management techniques, coupled with state-of-the-art computer models, to deal with the challenges and risks associated with AMSSO. This strategic risk management plan will contribute greatly to the improvement of the Arctic marine seismic survey operational safety and seismic data. In Chapter 2, various risk-based techniques will be looked into in order to subdue the challenges in achieving a robust risk management plan in AMSSO.

1.6 Methodology and Scope of the Thesis

A Risk management-based methodology is a continuous process to identify hazard events, estimate, and mitigate risks for any system or organisation by setting goals and strategies to control all potential sources of risks. The research risk management-based methodology conveys the path for solving the research problem in a systematic and rational approach.

The methodology and scope of this research are detailed as follows:

Stage 1: identify all possible hazard events in Arctic shipping and AMSSO through literature review and screen the identified hazard events through brainstorming meetings, in order to obtain a substantial list of all important hazard events in AMSSO.

Stage 2: develop a Fuzzy Rule Base (FRB) dovetailed with BN to analyse the most significant risk factors generated from the literature review and experts' knowledge.

Development of a benchmark risk will be achieved through the developed Fuzzy Rule-based Bayesian Network (FRBN) and experts' judgement.

Stage 3: develop a hybrid approach to the modelling of AMSSO safety performance measurement.

Stage 4: develop suitable means to select the most appropriate risk control option using Multi-Criteria Decision Making (MCDM) techniques such as the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

1.7 Structure of Thesis

An overview of the description of each chapter presented in the thesis is described as follows and is represented in Figure 4:

Chapter 1: corresponds to the research background and provides a clear justification for conducting the research. Research questions are generated to offer a guarantee that the research objectives are met. This chapter concludes by providing the risk management framework and structure of the thesis.

Chapter 2: starts by providing an explicit description of the Arctic marine environment and Arctic shipping in order to offer a grasp of the perception of risk in the Arctic offshore environment. This is followed by the introduction of AMSSO, here the risks in operating in the Arctic environment described earlier are narrowed down to the risks in AMSSO. The description of the IMO's Polar Code contribution to Arctic marine risk control and management is followed by a careful review of the widely applied risk management methodologies with consideration to marine and Arctic shipping. Risk, hazard, and uncertainty, all three of which are central terms used in the research risk-management process, are defined and differentiated. FSA, a popular tool used by the IMO in marine risk management is introduced to conclude this chapter.

Chapter 3: the first phase of chapter 3 acknowledges seven (7) major accident categories in Arctic operations and later combines six (6) risk factors common to the seven major accident categories to form the subject of investigation, termed Ship-Ice Collision risk factor. Hazard elements related to the Ship-Ice Collision scenario were identified through experts' knowledge and literature review in Chapter 2. The development of the FRBN model is described in the second phase of this chapter to analyse the most significant risk in the Ship-Ice Collision model. Finally, the sensitivity analysis method is developed and carried out to validate the new risk-based FRBN methodology.

Chapter 4: concludes the risk analysis process by focusing on assessing the overall risk estimate of the Ship-Ice Collision globally. Results from Chapter 3 are used to treat the issue of data uncertainty at the bottom level of the Ship-Ice Collision risk tree while AHP is employed to obtain the weights of all important hazard events at the intermediary level of the risk tree. Finally, the overall safety performance of the Ship-Ice Collision risk model is measured using the ER approach and the obtained results are measured against the developed FRBN benchmark risk. In addition, the sensitivity analysis method is developed and carried out to validate the new "FRBN-AHP-ER" risk analysis model.

Chapter 5: identifies different risk control options (RCOs) to mitigate the hazard event with the highest Risk Impact Factor (RIF) to the safety performance of the Ship-Ice Collision risk model. AHP is used here again to determine the weights of the identified RCOs, the outcome of the RCOs assessment is dovetailed with TOPSIS to arrive at the most cost effective RCO.

Chapter 6: provides the discussion. Knowledge contributions to AMSSO risk management are highlighted and areas for further research are highlighted.

Chapter 7: provides a recap of the risk management framework and models used in the study, this last shows how the aim and objectives of the research have been met.

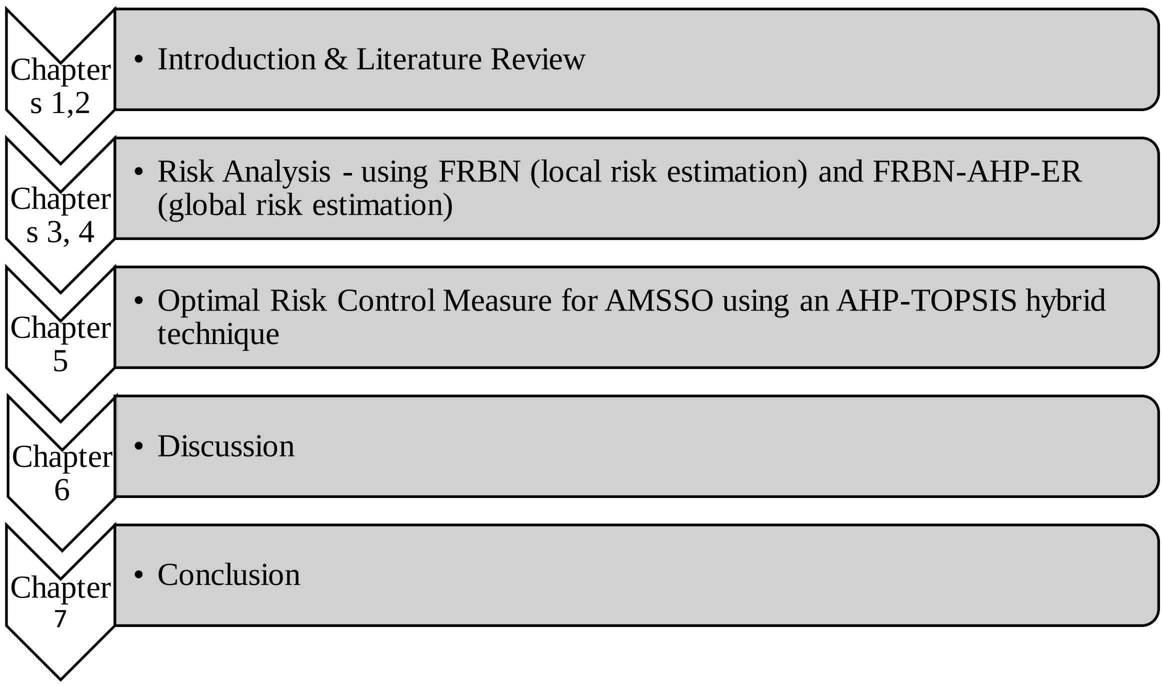

Figure 4: Research Structure

1.8 Conclusion/Research Achievements

This research develops an advanced, novel framework for the assessment of risks and vulnerability within Arctic shipping operation on a safety basis that allows industrial stakeholders and safety engineers to identify, assess, and mitigate the risk factors with the uncertainties that affect AMSSO. In addition, this research utilises risk-based methodologies in order to validate the theory of the strategic risk management approach. In addition, it reveals the effective execution of the risk management principle and integration to eliminate the concerns of uncertainty in risk evaluation in a complex AMSSO. For uncertainty treatment, FL, BN, AHP, ER and TOPSIS methodologies are applied in this research. The proposed models are anticipated to provide practical tools in the application and study of AMSSO risk management.

Chapter 2– Literature Review

Overview

This chapter starts by providing a broad description of the Arctic, and the extent of Arctic marine navigation. This is followed by a review and description of critical accidents in the Arctic region. Since, AMSSO involves both marine seismic survey operations and Arctic marine navigation, a careful review of risks related to Arctic shipping and marine seismic survey operations are highlighted. Several risk factors are identified capable of putting in danger AMSSO. Consequently, the lack of suitable risk assessment and management in AMSSO reveals a knowledge gap in reducing the critical risk factors in AMSSO. To analyse the risks in AMSSO, this chapter has reviewed seventy-five academic papers and printed books that have been utilised in other complex maritime systems, to fit in the risk analysis of AMSSO. The knowledge of the studied academic papers and printed books are dovetailed to reveal a proposed model to analyse the intricacies of risk analysis in the AMSSO system. The proposed model is capable of taking into account, the unavailability of statistical accident data as well as uncertainty in risk data.

2.1 Introduction

Seismic surveys are one of the primary ways mariners and oil companies learn about a site's production potential. Seismic surveys in the Arctic region can be challenging and even more difficult, especially when the seismic ship needs to tow in-water equipment and a number of streamers in the presence of ice. The process of gathering seismic data in the Arctic Seas has been carried out in various Arctic regions for over 5 decades (Rice et al., 2015), and it is still very much in practice these days (Eurasia-Group, 2018). The marine seismic vessels with towed sensors have continued to experience risks such as collision, grounding, machinery damage and hull damage. The aforementioned risks are because of floating ice packs, and increased traffic, which are partly as a result of global warming (The Independent News, 2018). Significant parts of the Canada Basin in the Western Arctic Ocean, for example, have remained a high-risk zone because of the presence of multiyear ice (Hutchinson et al., 2009).

Although sea ice seems to be melting gradually, however, the record of the melting ice extent in the Arctic Sea and the effects of global warming for the past 2 years has increased the level of risk in sailing through this region (The Independent News, 2018). Furthermore, discrepancies in the rate of global warming are a contributing factor that adds to the complexity of events occurring in the Arctic Seas. For instance, on September 15^{th}, 2007, it was reported that the Arctic ice cap was 23% below the previous record set in 2005 (NSIDC, 2018b). Also, the 2007 record exceeded the computer model predictions that were used to prepare the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report in the same year (NSIDC, 2018c). This last means that, with the volatile nature of the Arctic Seas, it is believed that new risks will arise and the reduced sea ice would likely result in an increase of traffic (Molenaar, 2009), and probably increase accidents (Kum and Sahin, 2015).

In addition to the level of risks in the Arctic region and in Arctic operation, exploring this region can be an expensive stake (Li, 2013b), both in terms of capital investments and time. With project costs rising every year, an oil company cannot stand to lose a huge amount of money developing a prospect oil field, that fails to yield hydrocarbons in commercial rates (RigZone, 2019). Also, a seismic survey project can take a protracted length of time for completion; for example, a 3D- marine seismic survey of 500 km^2 would take about 8 months for completion (RAG Austria, 2019).

Although AMSSO has been in practice for over for over 5 decades (Rice et al., 2015), there is still a concern that accidents and/or incidents are not properly reported and documented. This last is leaving safety engineers and stakeholders with inaccurate failure data measurements. The uncertainties in the failure data are amplified in situations where human judgement is taken as primary input data in risk analysis and management (Zhang et al., 2016). Consequently, the uncertainty of events and risk measurements often leads to disruption of operation, or an unwanted chain reaction requiring strategic risk control. The consequences of high risks in AMSSO have prompted stakeholders to employ advanced risk management strategies, to aid in making decisions regarding the allocation of scarce resources.

In order to support the safe and efficient AMSSO, efforts have been made to review the monthly descriptions and records of ice and weather conditions for all Arctic states, both during the summer and in the winter season. The combination of the information contained in the meteorological institutes and published related papers, has provided essential support for developing a safe and efficient AMSSO.

A limited number of academic papers have in one way or another described AMSSOs; for example, Gagliardi et al. (2018) described in full details the operational plan of carrying out an AMSSO, while Dudley et al. (2000) and Toennessen (2008) described a seismic survey vessel and included the layout description of the vessel. However, none has been able to venture into addressing the complexity of risks or propose a technically sound risk-management plan to carry out AMSSO in a safe and efficient manner. Nevertheless, several academic papers have been able to describe the root cause of accidents in the Arctic, have analysed safety and risks in Arctic shipping, and have discussed the occurrence of accidents in Arctic voyages. For example, Kum and Sahin (2015) discussed a root cause analysis for Arctic Marine accidents from 1993 to 2011, Eguíluz et al. (2016) carried out a quantitative assessment of Arctic shipping in 2010-2014. Khan et al. (2018) discussed an operational risk analysis tool to analyse marine transportation in Arctic waters. While Mussells et al. (2017) analysed the risks and identified the hazards for winter resource-based shipping in the Canadian Arctic. Jalonen et al. (2005) and Goerlandt et al. (2017) carried out a preliminary risk analysis of winter navigation. Valdez Banda et al. (2015) carried out a risk analysis of winter navigation in Finnish sea areas. However, Afenyo et al. (2017), (Fu et al., 2018b) and Serdar and Bekir (2015), provided useful information on addressing the uncertainty of failure data in Arctic shipping/navigation.

Several other studies have addressed the types of accidents occurring in a specific maritime area. For example, Hänninen et al. (2014) linked the safety management to the maritime traffic safety indicated by accident involvement; Mullai and Paulsson (2011) designed a conceptual model for analysis of marine accidents; Rambøll (2006) investigated the registered groundings, collisions and navigational traffic patterns between Danish and Swedish territorial waters.

In terms of towing in-water equipment, a seismic survey can be compared to a fishing vessel. Therefore, a risk and safety analysis for fishing vessel operation carried out by Wang et al. (2005) and Jin and Thunberg (2005), is likewise taken into consideration in this present study. Furthermore, descriptive information concerning safety and risk management strategies implemented to support AMSSO is rarely considered in Arctic operations. Hence, this chapter will start by describing the impression of the Arctic and describing the following: 1) the extent of Arctic navigation, 2) various risk factors in Arctic shipping and AMSSO and 3) critical review of safety and risk assessment as it relates to AMSSO. Next, the operational characteristics of ship independent operation in ice conditions and icebreaker assistance are presented. Based on the lack of a systematic risk management plan, FSA is introduced with the contribution of the IMO Polar Code in ensuring safety in Arctic operations.

The main purpose of this Chapter is to gain a high-level insight into AMSSO, as it poses a high risk to life, assets, and the environment. Furthermore, the conditions under which accidents occur are examined. Such a detailed investigation is significant for identifying which scenarios or hazard events should be prioritised, in developing a strategy for risk reduction and control in AMSSO.

2.2 An impression of the Arctic

The most basic and common definition of the Arctic describes it as the land and sea area north of the Arctic Circle (that is, a circle of latitude of approximately 66.34° North) (Harriss, 2016). There are just eight countries having territory north of the Arctic Circle, they are: Canada, United States (Alaska), Russia, Denmark (by virtue of Greenland, a member country of the Kingdom of Denmark), Norway, Finland, Sweden, and Iceland (O'Rourke, 2018).

The Arctic region also consists of the ice-covered Arctic Ocean. The Arctic Ocean is the smallest and shallowest of the world's five major oceans, namely Atlantic, Arctic, Indian, Pacific and Southern Oceans (Pidwirny, 2009). It is partly covered by sea ice throughout the year, and in winter, it is almost completely covered by sea ice. The Arctic Ocean's salinity and surface temperature vary seasonally as the ice cover freezes and melts (Rudels, 2016, K and A, 2006). Out of the five major oceans, the Arctic region has the lowest salinity on the average; this is due to the heavy freshwater inflow from streams and rivers, low evaporation, and discharge to surrounding oceanic waters with high salinities and restricted connection. From June to September, the shrinking of the ice is envisaged to be at 50% (Pidwirny, 2009).

Under present international law, the North Pole position and the region of the Arctic Ocean surrounding it, are not owned by any country (The Telegraph, 2013, Harriss, 2016). The Arctic countries only have limited access to an Exclusive Economic Zone (EEZ) of 200 nautical miles (that is, 370 km or 230 miles) adjacent to their coasts as documented in Article 76(1) of UNCLOS (MRAG Report, 2013). The waters beyond the territorial waters of the coastal states are known to be the "high seas" (*i.e.*, international waters). The sea bottom further away from the EEZ is known to be the "heritage of all mankind", and is managed by the U.N. International Seabed Authority in the UNCLOS-Convention (Guo, 2018).

Huge areas of Arctic shorelines remain without satisfactory geographic data. Arctic countries and their international state agents are faced with the urgent need to quicken the provision of Search and Rescue (SAR) services and reachable coastline seaports. Extended periods of extreme cold in winter time (see Figure 5), winter darkness, icebergs, and summer hurricane-strength storms (see Figure 6), are just some of the serious threats to all human and commercial activities in the Arctic.

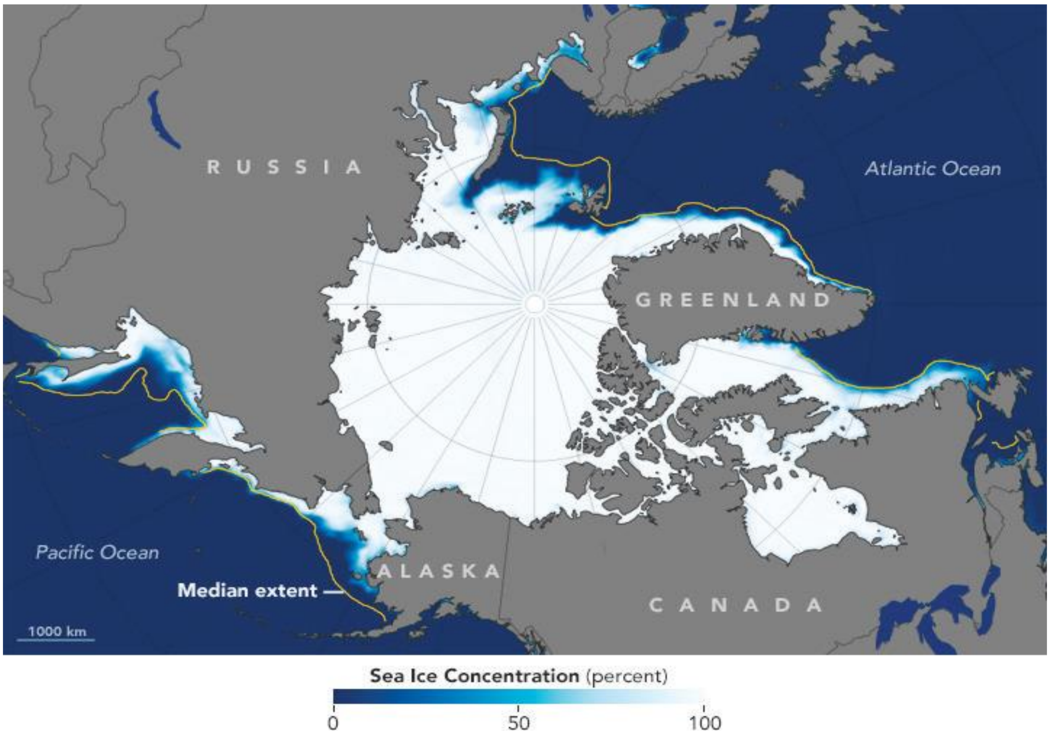

Figure 5: Winter growth of sea ice in January 2016 (Harriss, 2016)

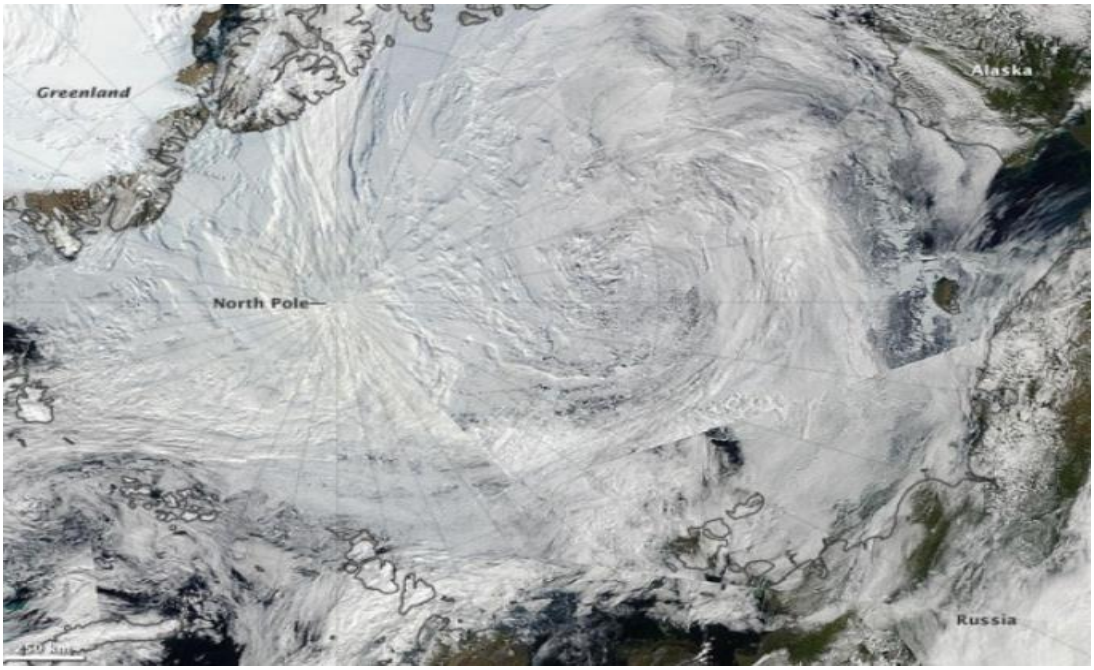

Figure 6: A summer storm over the Arctic– NASA's Aqua satellite captured this natural–, colour image of the storm in the Arctic on August 7, 2012. The storm that appears as a swirl is directly over the Arctic in this image. NASA image by Schmaltz (2012)

2.3 Extent of Arctic Navigation

New Arctic shipping and marine operations are evolving, but significant challenges persist with the presence of ice (Stephenson and Pincus, 2018). From October to June, most parts of the Arctic region remain ice locked thereby making navigation impossible for most vessels (Drewniak et al., 2018). Sea ice grows in thickness year in and year out (Hodges, 2015). Even with the receding sea ice coverage, it is nearly impossible for ships to make their way through a region infested with multi-year ice (Dewitz et al., 2015).

This last demands specially designed vessels and navigational skills, as ships operating in the Arctic Ocean are subject to significant obstacles, posed by the presence of ice in all its forms (Jensen, 2007). Contrastingly, as parts of the Arctic regions are becoming increasingly accessible in recent time, shipping traffic, in turn, could be put at risk.

Therefore, while the warming of the Arctic may indicate the need for fewer icebreakers, the growth in shipping traffic and unpredictable environmental conditions require nations to strengthen their icebreaking fleet.

Icebreakers are a vital means to clear and maintain Arctic navigation, necessary for oil and gas exploration. In Arctic navigation, the icebreakers can serve as multifunctional platforms to support Search and Rescue (SAR) and mass rescue operations (Drewniak et al., 2018). Hence, additional investments in new construction of icebreakers and/or escort vessels are required to support the growing need of Arctic marine activities. Consequently, the introduction of icebreakers along with well-trained crewmembers in carrying out Arctic operations can be essential in order to navigate/operate safely in the Arctic.

Modern Arctic navigation is further faced with geopolitical concerns amongst several countries with a stake in this region. For several countries, the Arctic offers an investment opportunity to raise its strategic and economic importance as well as to boost their international status (Kossa, 2016). Although the political aspect of the Arctic industry is not within the scope of this thesis, this is only mentioned herein to provide the latest developments in Arctic navigation.

2.4 Information on bergy bits, iceberg and growlers

Icebergs are different from sea ice in the sense that they are formed from freshwater-ice originated on land. Bergy bits were once defined by the Canadian Coastguard as a piece of glacier ice appearing from 1m to about 5m above the sea level (ECCC, 2016), having lengths between 5m and 15m (Canadian Coast Guard, 2019a). The smaller pieces of the glacier are the growlers appearing less than 1m above sea level, having a length of not more than 5m. Growlers in most cases are transparent, showing greenish or blackish colour on the water surface; as a result, it is difficult to detect them.

Icebergs are glacier ice pieces bigger than bergy bits; the growlers and bergy bits are formed by calving from the icebergs (O'Connell, 2013). The little ice pieces in the growlers and bergy bits can amount to large forces upon impact with structures; hence, it is of importance to obtain information about the possibility of sailing into these tiny pieces, drifting close to the parent iceberg.

In relation to the relative velocities between the little ice pieces and the parent iceberg, the little ice piece has a maximum distance it can travel before melting to a trifling size; this negligible size lacks the capacity to cause damage in case of impact (O'Connell, 2013).

Prediction of the origin of a drifting iceberg can be obtained from ice temperature measurements, since the temperature of the parent glacier is stored in the heart of the iceberg (Høvik, 2015).

A study on an iceberg drifting in the Kara and Barent Sea was carried out from 1987 to 2005 (Keghouche et al., 2010). In the study, Novaya Zemlya, Franz Josef Land, and Svalbard were the core sources for icebergs capable of causing structural damage to ships in this region. Also in Keghouche et al. (2010), estimation of calving rate based on the average size of icebergs were made on the average number of icebergs on the loose each year from diverse sources. Assuming that the estimation is accurate, the yearly number of icebergs calved each year would amount to around 19,000 to 20,000 pieces.

Also based on the study, approximately 77% of the calved icebergs each year become grounded, with icebergs spending about 42% of their lifetime stationary. From the study, about 20% of the icebergs endured more than one year and only 3.3% endured more than two years. The possibility of running into an iceberg is highest close to its calving source, and slowly drops with the distance from the source (Keghouche et al., 2010).

The solid light blue circles in Figure 7 represent the diverse sources of the iceberg and the main ocean currents; the arrowhead represents the ocean currents where the icebergs float.

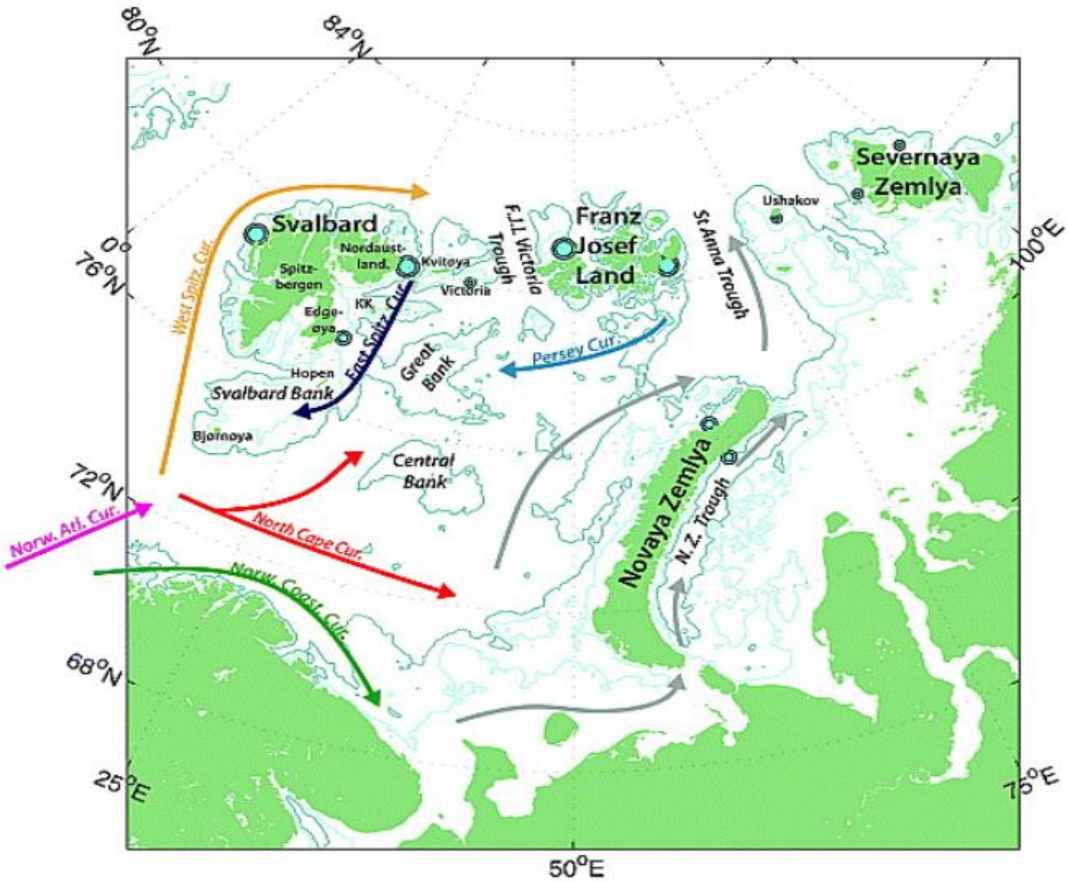

Figure 7: Iceberg sources, Svalbard and Franz Josef Land (Keghouche et al., 2010)

The probability of running into an iceberg within a year in the domain from 1987 to 2005 within a 25×25 kilometre grid cell is graphically represented in Figure 8. The scale is logarithmic. The thick grey line shows the northern boundary of the model. The red and black colouration on the map represents areas with a high probability of running into icebergs about Svalbard to Franz Josef Land. These are areas open to seismic surveying and other shipping activities. Wave erosion of materials at the waterline and thermal stress caused because of solar radiation, are some of the diverse calving processes from the iceberg. Icebergs are easily detected on the ship radar, but the objects in the bergy bits and growler size range can sometimes be difficult to detect. For the sake of precaution, care is being taken upon sighting or identifying an ice piece.

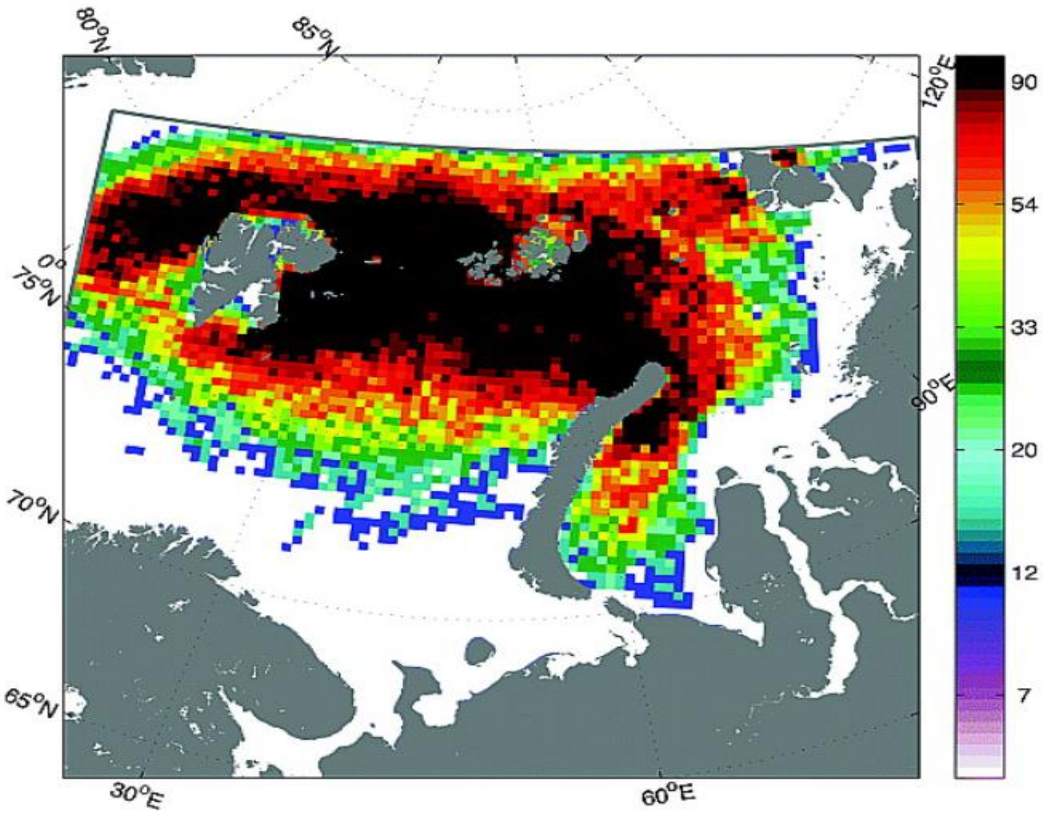

Figure 8: Probability of encountering an iceberg (Keghouche et al., 2010)

2.4.1 Ice Navigation and Pathways

Ice is a hindrance to any ship, even an icebreaker, and it is the responsibility of the Navigation Officer (NO), to understand the latent power of ice and its destructive strength. Nevertheless, it is possible for well-found seismic ships to develop their pathways and navigate successfully through an ice-covered prospect project.

The first principle of successful ice navigation is to maintain freedom of manoeuvre (Canadian Coast Guard, 2019b). A detailed description of the most important pathways based on the experiment carried out from 1988 to 1992 in the Arctic Circle, shows that the spreading of icebergs inside the domain is complex and chaotic. The most important pathways from the experiment agreed to a high degree with the one described by Abramov (1992), and it is presented in Figure 9.

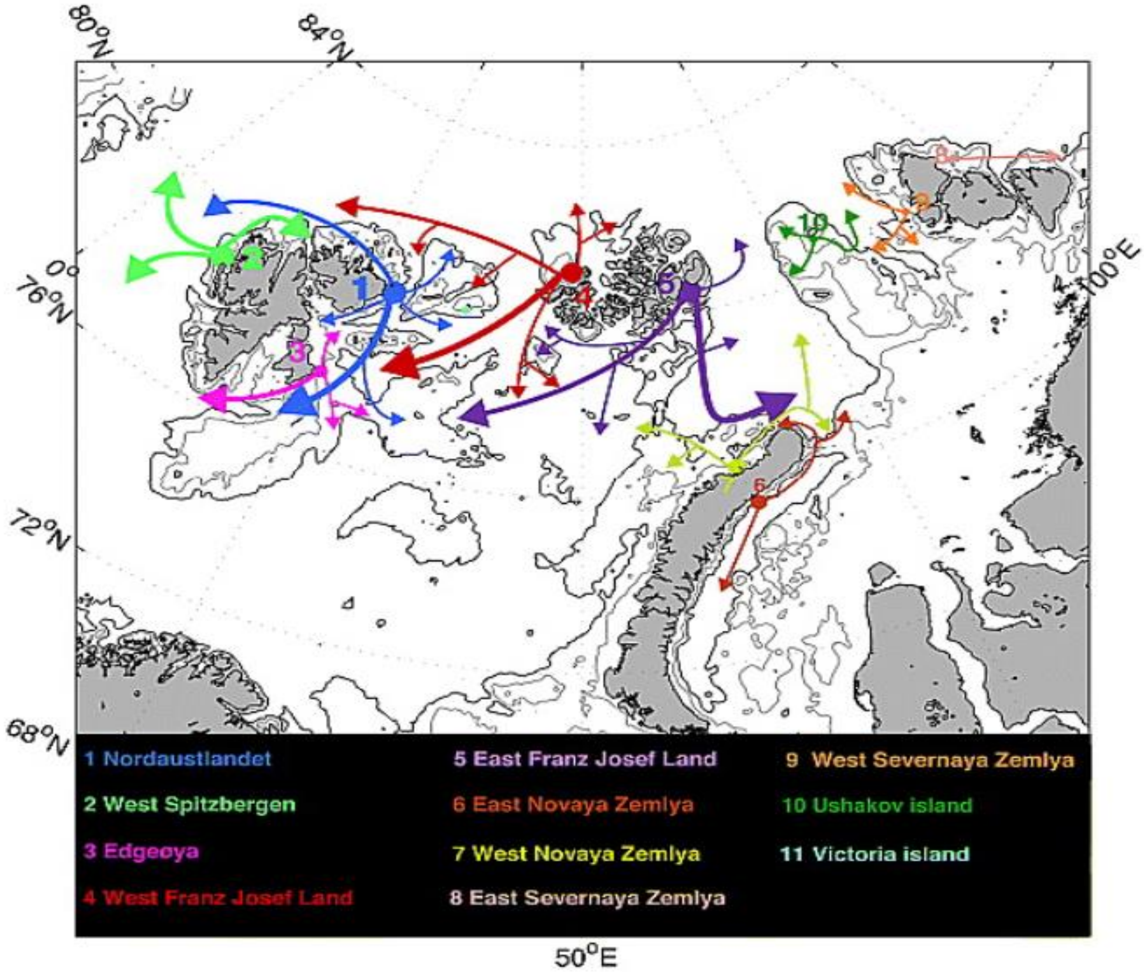

Figure 9: Pathways of icebergs from their calving site based on the model runs covering the period 1985-2005. Main pathways are shown with larger arrows(Keghouche et al., 2010).

The growlers, bergy bits and icebergs will flow in the direction of the ocean current as shown in Figure 9. The growlers and bergy bits will drift with a higher velocity than the icebergs because of their smaller masses. This assumption is dependent on the direction of flow of the Ocean and the wind (Keghouche et al., 2010), where the smaller ice pieces are more affected by the wind than the iceberg, which moves in line with the current flow. Apart from the growlers and the bergy bits, other smaller pieces of ice will also be formed from the calving.

The smaller pieces of ice, lesser in size to the bergy bits and growler, do not pose a significant threat to the approaching vessel hull, but would pose a threat to the seismic survey in- and/or on-water equipment. When a vessel navigates through the current, it is in a hazardous position, as there might be a high possibility of running into bergy bits and growlers. Crewmembers working on board could be put in a dangerous position, if the ice pieces are not identified in advance. For a seismic survey vessel navigating in grid pattern, it will be necessary to reduce speed in the event of running into an area with bergy bits (Canadian Coast Guard, 2009). An impression of the correct approach to an oil field in presented in Figure 10. It is noteworthy that the sizes of the different items shown in the drawing can differ from a real situation.

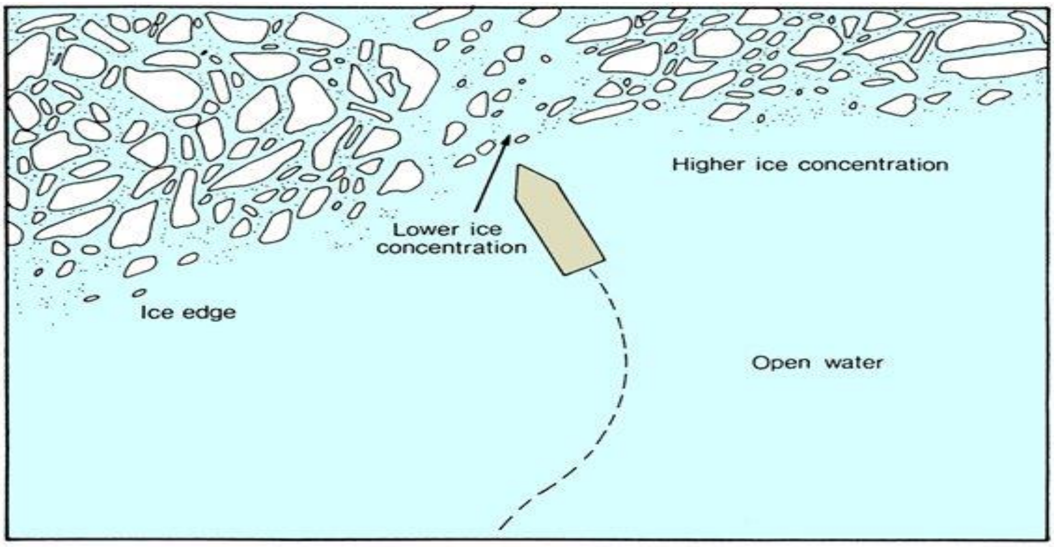

Figure 10: Ice Navigation and Pathways model (Canadian Coast Guard, 2019b)

For a seismic survey vessel approaching packed ice, the vessel should reduce speed and navigate at right angles to the edge of the packed ice. This approach is preferred to avoid glancing blows. In addition, the ship should be ballasted down to ice draft, if suitable, or to such a draft that would offer protection to a bulbous bow, rudder, or propeller (as applicable) (Canadian Coast Guard, 2019b).

2.5 AMSSO– An Overview

A seismic survey is a geophysical survey technique employed to map the geology of the rock subsurface. The key driver of this type of survey is to identify possible petroleum traps – located in the subsurface –, where petroleum can be located. An image of the subsurface can be obtained by employing seismic data. Geologists use the data to interpret the rock's subsurface, and identify areas where petroleum may have accumulated (Rice et al., 2015)

The gathering of seismic data has been carried out in the various Arctic regions for over 5 decades now. The earliest AMSSO included 2D seismic profiles (refraction and reflection), using both land acquisition equipment for wintertime, and a towed marine streamer in the summertime. Gathering of the towed 2D streamer data was usually done during the open water seasons, where the equipment and vessels could operate in ice-free zones.

Since the improvement in data gathering methodologies and 3D technology in the 1980s, there has been a great advancement in data acquisition, including time lapsed or 4D seismic. The advanced technologies have been known as one of the most notable developments to deliver a step change improvement in seismic image quality (Wilson and Dutton, 2019). The advanced technologies have also been known to improve drilling and production success in the E&P industry.

With the exemption of the orthodox 2D offshore Arctic Exploration and Development Technology (EDT), many of these advanced seismic methodologies and technologies have not been suitable for use in the Arctic (Efnik and Taib, 2011). There could be a number of reasons for this, including but not limited to the higher risk prospect in the Arctic region, and the lack of technological development to suit the Arctic operations, considering the overall cost of exploration and production of oil and gas offshore in the Arctic.

2.5.1 Brief history of Arctic seismic surveying

Until now, AMSSO has been on a small scale (Heide-Jørgensen et al., 2013). The efforts made so far have been carried out on the borders of the Arctic, using conventional methodologies and technologies whilst taking advantage of open water seasons (Rice et al., 2015). However, as stated in section 2.6, a seismic survey operation in Arctic waters has metamorphosed since the early 1980s. In the 1980s, Arctic seismic survey operations were divided between the E&P industry in pursuit of possible hydrocarbon resources, and data gathering operations backed and funded by academic and government research groups and consortiums (Rice et al., 2015).

Early Arctic seismic survey operations in the Sverdrup Basin of Northern Canada were carried out using land seismic technology, positioned on top of the ice (Masterson, 2013). This method was later used in Alaska in the 1990s, where the offshore operation was carried out in late winter season on the sea ice to plot possible near shore prospects. These on-ice procedures are limited to conditions of landfast ice (also called shore-fast ice) or stable ice. An old-fashioned marine 2D streamer was collected offshore in the Canadian Beaufort Sea in the period of 1980 to early 1990. From early 2006, a wide regional 2D streamer seismic data (including Ocean Bottom Cable (OBC)), was collected throughout the Chukchi and the Beaufort Sea, employing primarily the old-fashioned acquisition methods.

Up until 2009, there have been approximately three exploration grade 3D streamer surveys and at a minimum, two smaller 3D OBC developments carried out over specific lease blocks (Rice et al., 2015). These developments or projects produced more than 8,000 square kilometres of seismic data.

In Eastern Canada, Norway, Russia, and Greenland, there have been comparable type efforts to collect seismic data north of the Arctic Circle, using mostly the old-fashioned technology, and taking advantage of the old summer open water seasons. For comparison, there was no activity in the North American Arctic in 2014, while recently in 2015, there are about eight 3D surveys going on in the Kara and Barents Seas (Rice et al., 2015).

2.5.2 AMSSO– Procedure

The first stage of AMSSO is supplying the seismic survey vessel with all necessary fuel, water, food, seismic equipment and crew (IAGC, 2002). The overall Arctic marine seismic survey system consists of an escort and a survey vessel that traverse a pathway to perform marine seismic surveying in a marine Arctic environment This AMSSO uses equipment and techniques described in Gagliardi et al. (2018) and in subsequent sections.

Seismic surveying in the Arctic or the Antarctic has unique challenges; hence, the data acquisition procedure requires particular techniques for operating in ice regimes. To that end, Figure 11 illustrates a set of procedures for performing AMSSO. This set of procedures gives a general outline of the AMSSO, with the description as follows in chronological order:

1. From the beginning, operators carefully plan a track for surveying the desired area of the ocean where ice exists or may be located. Unlike the orthodox marine surveying where the survey vessel can simply traverse the area without much hindrance, here the operators plan the survey track in the icy region with specific consideration to weather conditions, current and historical regimes. Concurrent with the planning of the survey track, operators select the required vessels and

equipment of the system to conduct the planned survey. These selections are made with respect to the environment of the icy regions likely to be encountered. The same considerations apply to the selection of the streamer(s), the source(s) and other seismic equipment.

2. Once the vessel and the system devices (equipment) are chosen, operators prepare the vessel and install the system equipment. These preparations can incorporate outfitting the vessel with particular equipment for conducting the seismic survey in ice, such as installing ice skegs on the vessel, modifying decks on the vessel, and upgrading other equipment as required.
3. Once the vessel has been selected and installed with suitable equipment, operators can begin the planned seismic survey by taking the vessel and installed equipment out to the start of the planned track. If required, the seismic vessel can be accompanied by an escort vessel (an icebreaker). Even the travel of the vessel to the desired region requires particular planning when the region has ice. For example, an initial route may need to be planned to bring the seismic survey vessel to an appropriate starting location, so that the equipment of the AMSSO system can be deployed without much interference from ice.
4. Once at the planned start position, operators then begin deploying the equipment to commence the seismic survey. Because these procedures are carried out in or near icy waters, operators use deployment techniques different from the overall conventional deployment procedures used in normal open waters.
5. Finally, operators carry out the seismic survey with the equipment deployed by traversing the planned survey track. Since the icy region changes dynamically and has a number of potential dangers and impediments, operators repetitively

monitor for threats, manage ice, modify the track if required, and handle emergencies.

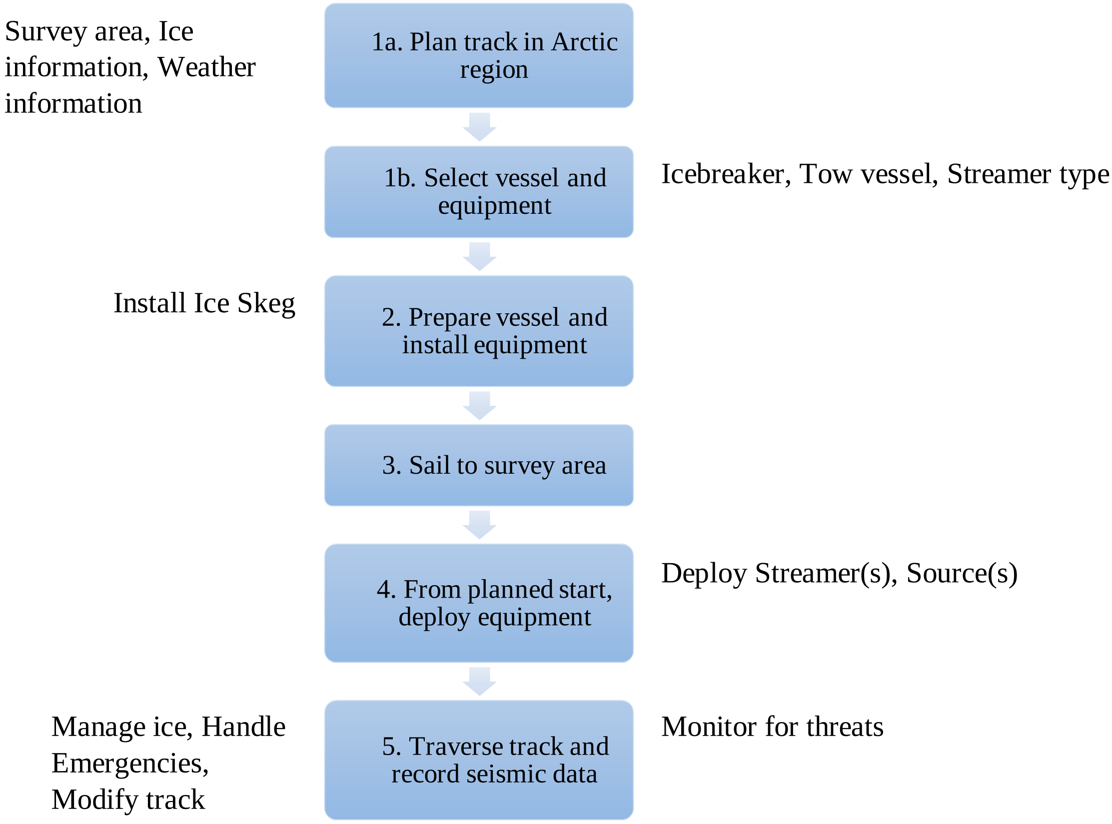

Figure 11: Procedure for performing AMSSO

2.5.3 Key risk associated with AMSSO

AMSSO comes with additional risks compared to other Arctic shipping activities. The challenges in Arctic seismic survey can be summed up in two major categories, that is, the environmental sensitivity and metocean conditions (ice included) (Rice et al., 2015, Hänninen and Sassi, 2010). The operating conditions in the Arctic all shorten the time window for conventional seismic operations; such conditions are limited or no daylight, extremely cold temperatures, high winds and seas, and variable ice conditions (Ayele et al., 2015). These conditions pose great risks to crewmembers, the vessel, and the in-water seismic equipment.

Hence, operating in this dangerous zone requires a careful selection of marine vessels of a suitable ice-class. In addition to the harsh operating conditions, remoteness of this region introduces attendant logistical issues.

Section 2.6 and its corresponding subsections describe in detail the selection of marine vessels for Arctic operation as well as the concerns and state of established practice for AMSSO "in" and "under" ice conditions.

2.6 The state of the established practice in Arctic seismic surveying

2.6.1 Current Practice in AMSSO

The conventional towed seismic streamer arrangements make use of either fluid or solid filled streamers. In order for the towed seismic streamer to maintain a suitable positioning of the airgun and streamers, it uses surface referenced floats. To achieve a suitable positioning, the arrangements would include floats on the paravanes, which are employed to form the lateral spread of the streamers and the airgun as shown in Figure 12. The tailbuoy floats the tail of the streamers, which could be 150m apart, while the headbuoy floats the streamer lead-ins, and lastly the airgun floats the airgun arrays, which could be 75m apart in the layout.

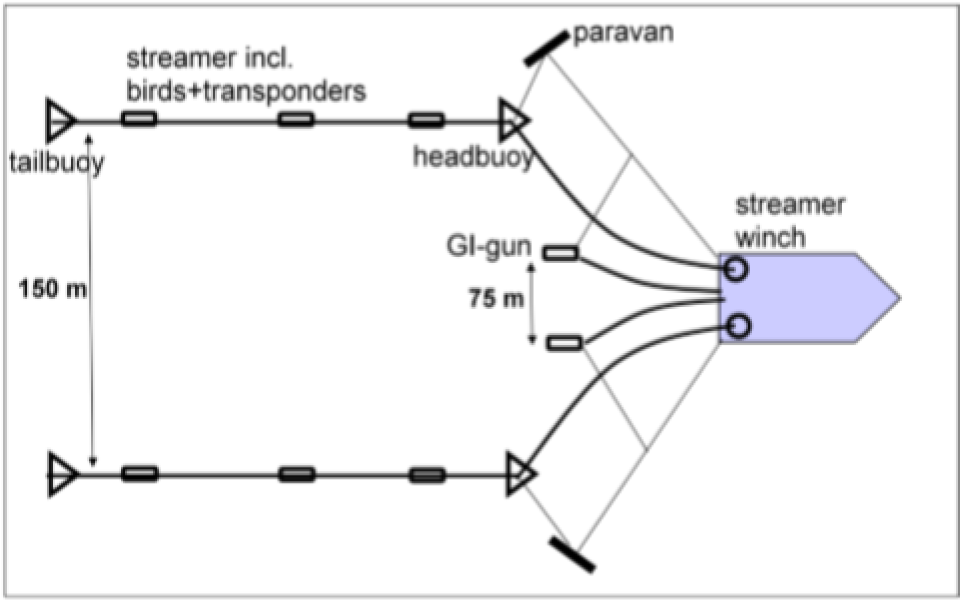

Figure 12: Schematic illustration of a 3D towed seismic streamer arrangements (Damm and Badewien, 2014)

All or any of these arrangements may have acoustic positioning equipment or GPS for maintaining exactness of positioning, in the course of data acquisition (Rice et al., 2015). As mentioned previously, the presence of ice poses a significant risk to the vessel and other in-water equipment as it navigates the hostile environment. Contact between the vessel and the sea-ice, and/or any other in-water equipment or cables, can potentially have severe consequences resulting in equipment damage, injury, or loss of life. Some of the more recent Arctic data acquisition methods have utilized a number of special risk mitigation measures, including but not limited to, ice classing of vessels and distinctive environmental consideration, in a way to reduce any potential risk from the sea ice.

With these risks and restricted technology to challenge the recorded and envisaged risks, Arctic seismic surveying has been conducted using the open water methods in “ice-free" conditions.

Most of the AMSSOs to date have been carried out in “ice-free" conditions, and have used the conventional seismic methods and equipment (Onarheim et al., 2018). These conventional methods are subject to the limits of the equipment and vessel used, and the conditions of the prospect area – including the extent of the presence of ice – at the scheduled time of the operation (Rice et al., 2015). While these types of surveys are organised to reduce risk to the lowest minimum, the underlying assumption is that, if there is a bad ice year or rare conditions, the opportunity to collect data for any given project, will be at the mercy of the present ice conditions during the scheduled operating window.

Recent examples of “ice-free” data acquisition projects are as follows:

- The 2D seismic exploration in the Russian Arctic which was conducted by Russian Geophysical Companies (such as MAGE, SMNG, and DMNG), on behalf of Gazprom, Rosneft.
- The 2D regional agenda in the United States Arctic (2006-2009) carried out by TGS and ION Geophysical, using a conventional seismic airgun array and a towed marine streamer.
- The 2D regional agenda in the Russian Arctic carried out by ION Geophysical (2010-2012), using a conventional seismic airgun array and a towed marine streamer.

Some other recent projects have been carried out in the presence of ice but the key precaution is avoidance of the several growlers, icebergs and bergy bits that were seen in the prospect area. The surveys carried out in the presence of ice may use the traditional seismic vessels with some ice-class and/or winterisation features, with modified in-water seismic devices, on-board ice management systems, personnel, and other support facilities to reduce catastrophic failure in the event of incidental contact with sea ice.

Examples of data acquisition carried out in the presence of ice include:

- The Shell Chukchi and Beaufort Sea exploration (2006-2007), carried out by WesternGeco,
- The Statoil Chukchi sea exploration (2010), carried out by Fugro-Geoteam,
- The Western Greenland 3D exploration (2012), carried out by Polarcus on behalf of Shell, using on-board ice forecasting tools and two conventional multi-streamer seismic vessels operating in tandem,
- The 2D regional agenda in Labrador (2013), carried out by ION Geophysical using a conventional airgun source, and a 2D streamer with an icebreaker escort vessel,

For the successful completion of the above projects, the key focus was avoidance of the several icebergs, growlers, and bergy bits that were present in the prospect area.

There have been a number of executed "under ice" data acquisition projects, but the number of completed projects is very limited because of the huge ice contact risk. The success of the completed projects has been a result of advanced technology and methodologies. These advancements include a conventional 2D seismic vessel with some ice-class features. Here, the equipment is deployed in such a way as to ease, but not to eliminate the surface footprint of the in-water seismic device; this is done by using a technology-based approach, which focusses on the development of new equipment. Thus, providing a means for the total elimination of any surface footprint of the towed in-water seismic device.

Recent examples of "under" ice data-acquisition projects include:

- 2D Regional seismic projects, carried out in northeast Greenland from 2009 to 2011; this project was conducted by ION Geophysical using a conventional Ice-classed seismic vessel, equipped with under-ice technology, and an ice breaker, and
- 2D Regional seismic project – an UNCLOS project in 2011 – carried out in the Russian High Arctic with ION Geophysical, by outfitting the Arctic classed icebreaker with under-ice seismic equipment, and with a nuclear icebreaker as an escort vessel.

Since the 1990s, there has only been a small number of additional "under-ice" surveys carried out, but the majority were academic/government based and these utilized a very short streamer and a very small source. Hence, the applicability of the data acquired for E&P exploration purposes is limited.

2.6.2 Ice-Classed vessel

Vessels operating in the Arctic region require special considerations in their design and construction, to ensure they are designed against the harshness of the Arctic region (Deggim, 2013). In designing special vessels for Arctic operations, the basic parameters to consider are the safety of the crewmembers, the vessel, and associated equipment, since these are exposed to ice, and low air and sea temperatures (Rice et al., 2015).

The classification of vessels for use in ice is a vital reference in choosing vessels for such harsh operations. The machinery rating and the hull strength of a selected ship should be compared with the ice conditions that such a vessel is expected to navigate in. One of the regulatory bodies with the responsibility for setting rules for ice classification is the Classification Societies (CS) (Girba et al., 2015). Although there are different CSs with similar criteria and requirements, however, caution should be taken in selecting the most appropriate criteria and requirements that include structural and machinery classification.

A set of unified requirements as developed by the International Association of Classification Societies (IACS) for Polar ships prescribes for example, that Polar ships navigating in ice-infested waters should be constructed of steel. Vessels (or ships) that conform to IACS requirements, under the Polar criteria, are suitable for a Polar Class (PC) notation. Vessels designed to operate with an icebreaker notation, have additional requirements and often receive special consideration.

An icebreaker vessel is designed to work with an escort or ice management functions, with the powering and dimensions that would allow the vessel to carry out rigorous operations, offshore in the Arctic. This icebreaker has a class certificate notation, and without this notation, vessels are only allowed occasional ramming. See Table 1 for Polar class notation and the corresponding description.

Table 1: Polar Class notation and description (Amin and Veitch, 2017)

Polar Class	Ice description based on WMO Sea Ice Nomenclature
PC1	Year-round operation in all Polar waters
PC2	Year-round operation in moderate multi-year ice conditions
PC3	Year-round operation in second-year ice which may include multi-year ice inclusions
PC4	Year-round operation in thick first-year ice which may include old ice inclusions
PC5	Year-round operation in medium, first-year ice which may include old ice inclusions

Polar Class	Ice description based on WMO Sea Ice Nomenclature
PC6	Summer/autumn operations in medium first-year which may include old ice inclusions
PC7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

Table 1 is adapted from IACS Machinery Requirements for Polar Class Ships (IACS-UR-I3), 2006, and from Amin and Veitch (2017).

Poor selection of vessel with fitted ice-class and winterization level could risk the safety of operators, assets, and the success of the operation. Additionally, operating the vessel above its ice-class standard could possibly render the vessel out of class, and overturn its insurance. There are a limited number of seismic vessels built to navigate in ice-infested waters; such seismic vessels would be in the PC7 class or in most cases less than the PC7 ships. This means that only a few seismic vessels are up to-date and suited for Arctic ice conditions. Although the proposed IMO Polar Code excludes non-Polar Classed Vessels from operating in waters South or North of 60° S or 60° N, respectively.

Ice Class consideration is essential for ships utilised in ice-covered waters. As a result, seismic survey operation in Polar waters requires judicious consideration of support, escort, and/ or ice management vessels, to safeguard the operators and the intended operation or project.

2.6.3 Seismic Survey Ship

Seismic survey ships needed to operate in Arctic waters must be designed to have the physical capabilities to withstand the harshness of the Arctic environment, and be able to maintain high safety standards. State-of-the-art and fit-for-purpose technology can be employed to reduce risk and ensure operational capabilities.

Ice class ship type is selected to operate in this environment with key considerations to powering and control systems, sea suction layout, fuel capacity, and the ability to make satisfactory fresh water in the course of operation in cold sea water. The fuel and fuel systems must be able to work in low temperatures, and be able to avoid clouding and waxing issues (Canadian Coast Guard, 2019a).

Other key ship components suited for this operation are ice management and ice information support systems. Like the conventional seismic survey operation, here, the physical environment must be wholly assessed to make sure that the vessels selected for ice avoidance, “ice-free” or “under ice” conditions are matched to the demand of the project. In addition to the conventional assessment, the winterization assessment ensures that the escort ship(s) and seismic vessel(s) are suited to the project requirements, and the intricacies of the ice, et cetera. A higher classed vessel means more confidence to reduce the risk from ice and other environmental hazards.

The powering of a selected ship for Arctic marine seismic survey must be sufficient to tackle the rigours of harsh weather, ice resistance, and to provide the required amount of bollard pull (force) for the in-water seismic equipment. In addition to the selected powering requirement, the control features and the hull strength must be suited, to provide for sufficient manoeuvrability and stability in both open waters and ice-infested fields. The in-water equipment must be protected by a means of an ice skeg. This special protection offers a subsea towage point close to or below the bottom of the keel, and offers protection to the streamers and umbilicals, from these tow-points to the streamer deck and to the airgun.

Ocean Bottom Cable (OBC) operations in ice equally require an approach concerning risk assessment and environmental elements. The deployment of an armoured bottom cable by ships suitable to this kind of ice seismic operation also needs to be well founded and capable in ice. The operational use of seismic vessels in “under-ice” or “ice avoidance” seismic projects, together with Ice-classed vessels tailored for this role, must require the help of an escorting ice management vessel. This collaboration offers a pre-break or an ice-escort for the main ice features like ridges and other ice that would hamper the continuous forward advancement, required of the seismic vessel. This collaboration of the seismic vessel with an Ice-classed vessel and an escort ice-management vessel helps to avert loss, injury, or damage to assets, environment, and human lives.

2.6.4 Escort/Guard Vessels

Ice classed seismic vessels are generally provided with an escort ice-management vessel to support the towed streamer and bottom cables. In most cases, the choice of an ice management vessel depends on its availability (since a small number of icebreakers are selected for such work).

The seismic survey vessel and the icebreaker will both work together closely, in order to tow streamers and to complete a fully integrated and coherent operation. The choice of a suitable ice-management vessel is focussed not only on the physical harsh environment, but also upon the selected ice-seismic escort vessel, and other factors such as ergonomic, et cetera. The selection of an ice-seismic vessel and the escort/guard vessel must be compatible to work coherently; that is, the two-ship system must be able to navigate in all ice conditions mapped for the survey mission.

The ice-seismic escort vessel is important in AMSSO because it helps the seismic vessel not to halt in the ice, but also to slow down below the minimum stipulated speed. The collaboration between the ice-seismic survey ship and the ice-breaker vessel, demands a very high level of coordination in terms of both system coordination and navigation (Gagliardi et al., 2018). See Figure 13 for the various systems coordination between the ice-seismic survey vessel and the ice-seismic escort/guard vessel.

The icebreaker is assigned to lead in a way quite different from the traditional ice-escort operation, as it is now expected to break ice along a defined track, so that the seismic survey vessel can navigate and tow the streamer over the required pre-plotted tracks, without halting the forward navigation of the seismic survey vessel. An appropriate selection of an escort icebreaker will be considered based on icebreaking capabilities, bow and hull forms, redundancy protection, directional stability, displacement, track clearing characteristics, propulsion type, manoeuvrability, draft, surplus power management, and control systems.

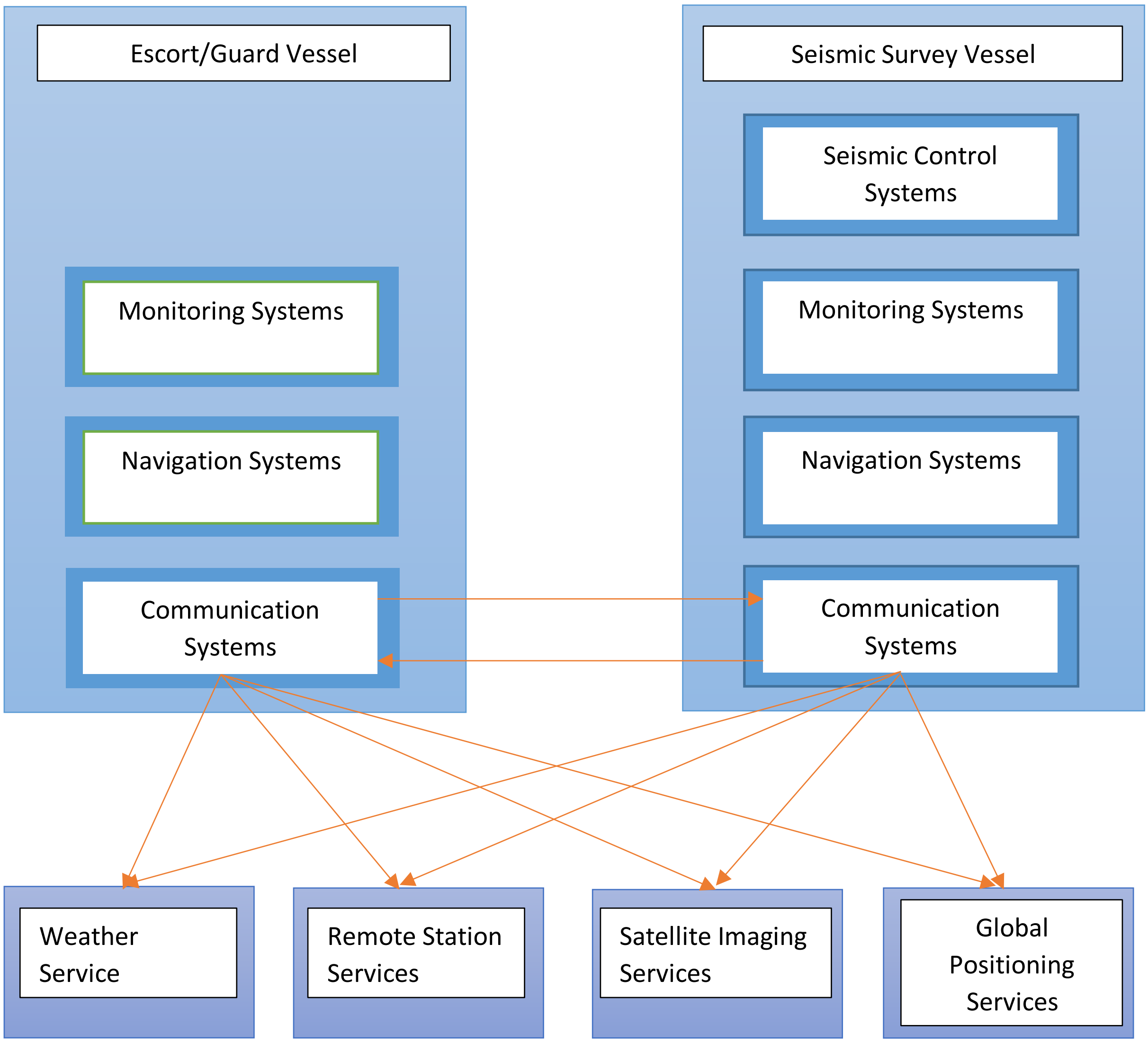

Figure 13: Various systems coordination between the ice seismic survey vessel and the escort/guard vessel

2.6.5 Specialised Equipment Handling Systems

Like in open water seismic survey, all seismic surveys involve a configuration of sensors or receivers and a source. In order to manage these collections of equipment, a careful arrangement of dedicated procedures, handling equipment, and vessels are expected to be deployed and be recovered from the field. AMSSO can be categorised into two main operations centred on their popularity, namely the two-dimensional (2D) and the three-dimensional (3D) seismic survey operations. In a nutshell, 2D can be fairly described as an old survey method which is quite simple in its underlying assumptions, this method is still in practice as it offers an effective way to locate oil and gas (Rice et al., 2015). The 3D, which can be described as a complex survey method, involves the use of sophisticated equipment and much more investment, compared to the 2D. The 2D marine seismic survey requires a single streamer and a single sound source towed behind the seismic survey vessel, while the 3D seismic survey requires multiple sources and streamers (IAGC, 2011).

The 3D survey operation requires a significant amount of in-sea equipment and a vessel capable of towing 16 or 20 streamers with lengths ranging from 96 to 120 Kilometres. Subsequently, the back deck of a seismic survey vessel becomes very busy because of the activity connected to the handling equipment, such as sound sources, streamers and the related control devices. Diverters or paravanes spread the streamers' cables. This can be pictured as a type of mid-water trawl door, extending to over 500 meters in width. On the ends of each streamer is a tailbuoy, which carries flashing lights and radar reflector. The various arrangement of the handling equipment at the back deck of a marine seismic survey vessel has been represented in Figure 12.

Organising and working in a survey field, needs to be safe and efficient with the help of highly skilled personnel. The major concern in Arctic Marine Seismic Surveying is the risk of in-water equipment making contact with sea ice. The most common of the risks is the possibility of snagging and sorting out the auxiliary equipment, such as Streamer Recovery Devices (SRD). There is a high possibility of losing all of the source array and streamer(s). With the risk of streamer fluid leaks or spills, the use of solid streamers can offer protection against such leaks. Source umbilicals and lead-ins provide a better shield against separation by ice contact.

The use of an ice skeg on the vessel provides a solution to some of the problems that are usual under sea ice operations. Therefore, the use of an ice skeg and submerged source floats should be encouraged, in order to achieve success in any marine seismic survey arranged for under-ice mission (Rice et al., 2015).

2.6.6 Ice management system

Ice management is another important key factor to enhance a safe and efficient operation in the Arctic. Factors of ice management required for seismic acquisition are detection and prediction of ice hazards. Seasoned ice management professionals implement the detection and prediction of ice. These professionals provide support from ashore, with the help of a host of remote sensing technologies (Rice et al., 2015).

However, with limited communication systems, the safety engineer or stakeholders embark on icebreaking and ice dispersal techniques (Gagliardi et al., 2018). In the icebreaking procedure, the icebreaker breaks up high concentrations of mobile packs or large floes ice into small pieces. The resulting broken pieces can then flow around the survey vessel's hull, whilst the ice skegs protect the deployed cables and lines for the streamers and sources. In the ice dispersal procedure, the supporting ice classed vessel breaks and spreads out large floes by using propeller wash and/or high-speed manoeuvres. Various ice breaking patterns can be used to clear ice so that the survey vessel can traverse the survey path. These icebreaking patterns are illustrated in Figures 14 to 17.

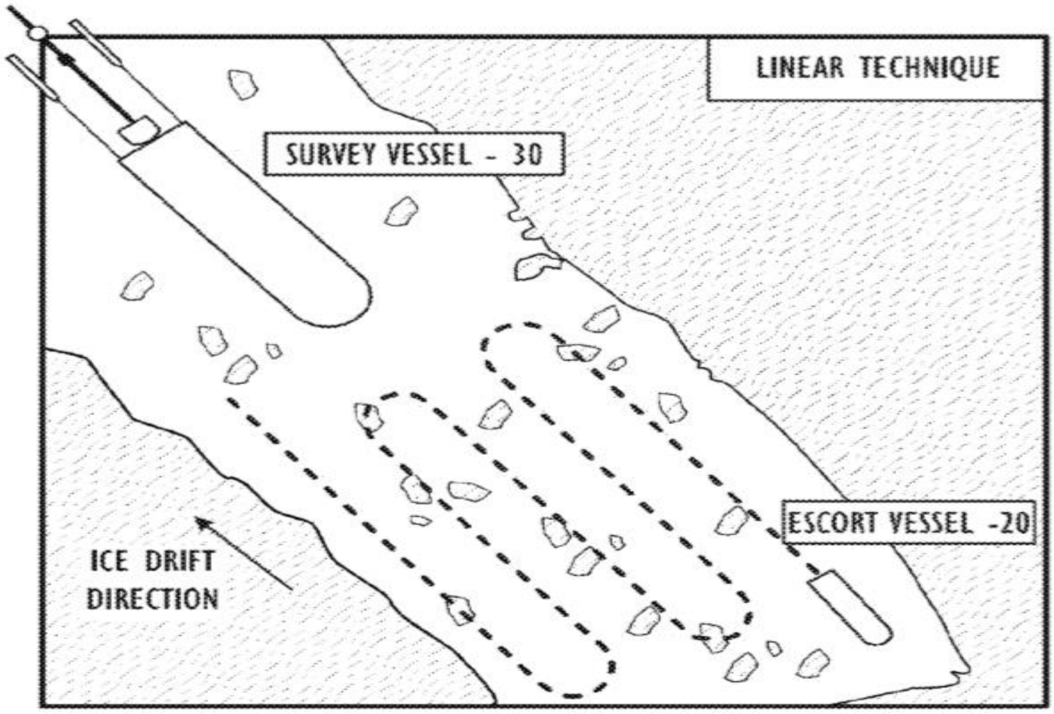

Figure 14: Linear icebreaking pattern (Gagliardi et al., 2018)

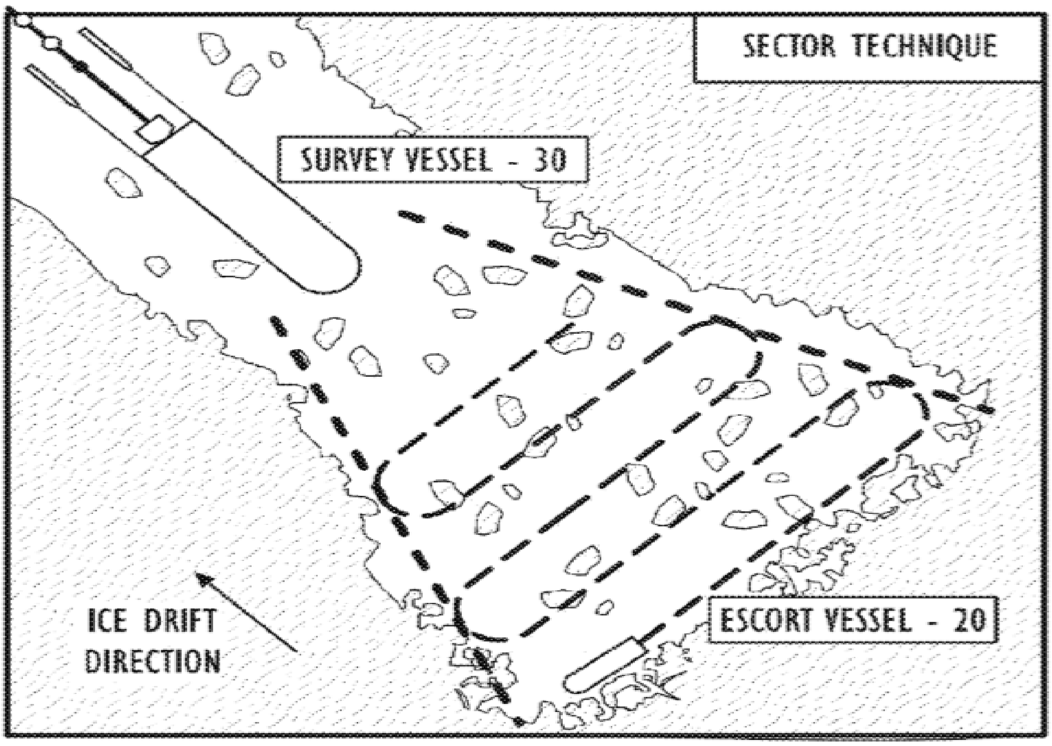

Figure 15: Sector icebreaking pattern (Gagliardi et al., 2018)

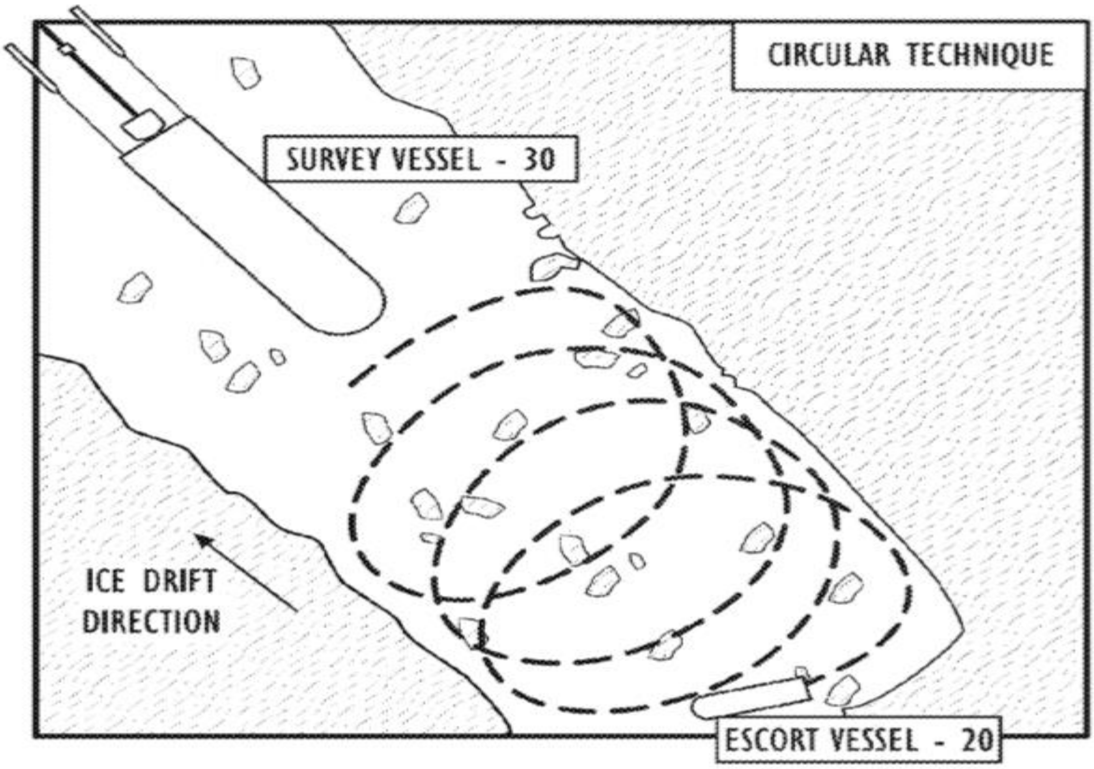

Figure 16: Circular icebreaking pattern (Gagliardi et al., 2018)

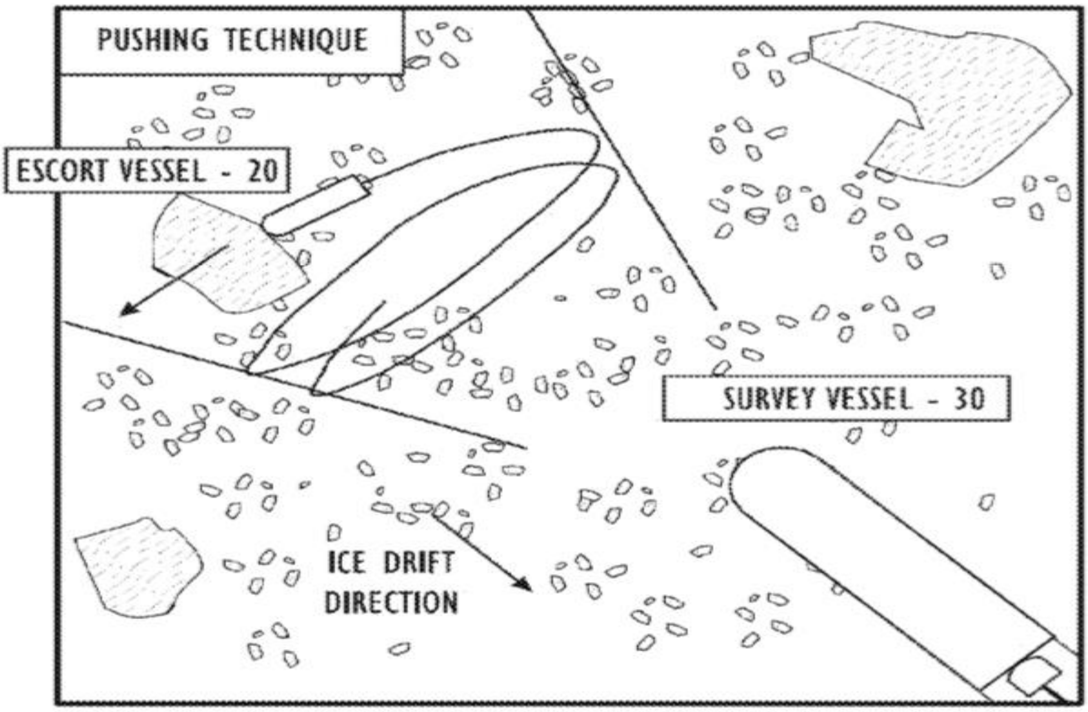

Figure 17: Pushing icebreaking pattern (Gagliardi et al., 2018)

Other sections to acknowledge regarding the concerns and state of established practice for AMSSO "in" and "under ice" conditions are: Integrated Multi-Vessel Navigation System (IMVNS), Communications, Geophysics for Shallow Hazards, Marine Mammals, Marine Sound, Ice Experienced Maritime Professionals, Extended work sets and Fitness for Duty etc. More details on the above can be found in (Rice et al., 2015, Gagliardi et al., 2018).

2.7 Some drawbacks on replacing the conventional seismic survey using a survey vessel

Knowing the negative effects that surface ice conditions contribute to the marine seismic acquisition, several alternative technologies have been discussed to circumvent these negative effects. A promising way out of these negative effects or problems might be related to keeping above or below the ice (Rice et al., 2015). A recognisable alternative to towed marine streamer would be the launching of OBCs or Ocean Bottom Nodes (OBNs). Each of these relies on launching either seismic cable, autonomous recording nodes or a hybrid solution of autonomous nodes mounted on a cable. These solutions have their drawbacks. The major drawback of an OBN is power supply, whereby batteries have to be replaced at certain time intervals, usually less than 60 days (Daleel, 2019).

Quite a lot of seismic contractors are trying to modify surface streamer equipment to work below the ice, employing fully submerged seismic devices. The seismic gear is typically mated with the modified surface streamer equipment to provide near neutral buoyancy with control surfaces to offer trim buoyancy. Nevertheless, this can be problematic because GPS cannot be employed in the positioning of the seismic receivers. The alternative is to use a fully submerged acoustic solution but data collected in this way might be of limited value (Björn Heyn et al., 2018).

To shrink the effects of seismic acoustic pulses on sea life, alternative sources can be selected that either stretch out the acoustic amplitude over a longer time period (marine vibroseis) or control the frequencies that are produced by airguns (IAGC, 2011). Each has some drawbacks and needs further development, but could be used both in ice obstructed and non-obstructed waters (Rice et al., 2015).

The use of Autonomous Underwater Vehicles (AUV's) or submarines to pull streamer cables has been deliberated on for over 20 years now but their use is still viewed as impractical or cost prohibitive.

One possible alternative to replace a seismic survey vessel in pinpointing the location of oil and gas resources in the Arctic is the use of Unmanned Aerial Vehicles (UAV's) (IAGC, 2011). However, this technology is mature enough to go on full-scale application but it is still not extensively used in the Arctic today as GPS does not work under water and surfacing is a difficult task in the Arctic (Björn Heyn et al., 2018).

All of the different kinds of suggestions to replace seismic survey ships generally only collect specific data types. Consequently, one methodology might not completely replace others. The arctic geological survey, therefore, depends on financing the various available means of reaching this remote region of the earth and making use of economic, military, political and scientific interests alike.

2.8 IMO's contribution to Safe Arctic Shipping Operations

Shipping operations in the Arctic (and the Antarctic) regions such as marine seismic surveying, fishing, tourism, and other marine and offshore operations are exposed to a number of unique risks. Bad weather conditions, poor communication systems, short daylight, and lack of updated navigational charts and remoteness of this area (IMO

Document, 2019), are a few examples of the unique risks that mariners and other key players in the Arctic oil and gas E&P lifecycle face.

All the aforementioned concerns and more are the major focus of the IMO to safeguard life, property and the Arctic environment. IMO's requirements, provisions, and recommendations have been developed over the years (IMO, 2018a). Over the past 27 years, the IMO has established several requirements, guidelines, and recommendations concerning Polar ice-covered waters covering the Arctic and the Antarctic areas. These requirements, guidelines, and recommendation are concerned with the certification of seafarers on ships operating in Polar waters.

The guidelines for ships operating in Arctic ice-covered waters are planned to tackle those additional provisions thought necessary for consideration outside the existing requirements of the SOLAS Convention (IMO Document, 2019). The IMO has accepted the International Code for Ships Operating in Polar Waters (Polar Code), and associated amendments to the International Convention for the Safety of Life at Sea (SOLAS) to make it mandatory, marking a notable milestone in the Organization's work to protect ships (Jensen, 2016).

The introduction of ship classes by the IMO-Polar Code also forms an integrated approach to ensuring the safety of life, operation, asset, and the Arctic environment. The classification of ships differentiates between Polar class and Non-Polar class ships with design preferences. The IMO guidelines have also introduced a system developed to show the different levels of strength and capability for vessels navigating in Arctic waters as discussed earlier in section 2.6.2.

In parallel to the development of the IMO guidelines, the International Association of Classification Societies (IACS) has established a set of Unified Requirements, which, integrates suitably with the general classification society rules, addressing all essential aspects of construction for ships of Polar Class (IMO Document, 2019).

The Maritime Safety Committee, at its seventy-fourth session in 2001 and the Marine Environment Protection Committee (MEPC) in 2002, approved the Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process, at its forty-seventh session (IMO, 2015, IMO, 2018b). The Maritime Safety Committee (MSC) deals with all matters related to maritime safety and maritime security which fall within the scope of IMO (MSC Document, 2019). The FSA methodology is a structured and systematic methodology, aimed at enhancing maritime safety, as well as protection of life, health, the marine environment, and asset, by using risk analysis and cost-benefit assessment (IMO, 2015).

The method of foreseeing hazards and addressing them before they occur is incorporated in the FSA proactive risk-based methodology in conjunction with the use of expert judgment (IMO, 2018b). The introduction of expert judgement not only contributes to the proactive nature of the FSA methodology, but it is also an essential part in risk analysis where there is a lack of historical failure data (IMO, 2015).

The IMO, with the responsibility of dealing with all phases of maritime safety and protection of the marine environment, has acknowledged FSA as an alternative proactive safety approach known as Goal Based Standards (GBS) (Hermanski and Daley, 2005).

2.8.1 Marine Risk Management and the Polar Code

Generally, all ships whether new or existing, operating on international or local passages within IMO defined boundaries of Polar waters must adhere to the Polar Code. The implementation of the Code came into full force on the 1st of January 2017 (IMO, 2018a), while existing ships still have until their renewal survey or their first intermediate after the 1st of January 2018 to conform (IMO, 2018a). As with most IMO's rules, government vessels that are not involved in commercial business are exempted from the Polar Code regulations but there is no room for laxity as government and academic researchers are strongly advised to act in a consistent manner, to an extent as reasonable and practicable to agree with the requirements of the Polar Code.

The Polar Code manages the risks of Arctic shipping by defining objectives and functional prerequisites relating to watertight and weather-tight integrity; ship structure; stability and structural subdivision; operational safety; fire protection and safety. Other risks managed are machinery installations; navigational safety; life-saving arrangements and appliances; communications; vessel manning and personnel training; voyage planning; and prevention of pollution by the garbage disposal, noxious liquid substances, oil, and sewage (Ghosh and Rubly, 2015).

According to the Polar Code, vessels wishing to operate in Polar waters shall be required to apply for a Polar Ship Certificate, which classifies the vessel as either a Category A or B or C vessel (Ghosh and Rubly, 2015).

2.8.1.1 Ship Categories

The idea of splitting ships into different categories was initially introduced in the Polar Code for the sole purpose of organising their requirements against the classes of ship. For an ice class notation, there exist three Polar Ship categories namely, A, B, and C. These categories provide a general indication of a ship's worthiness to sail through in an ice-infested environment. Ships meant to sail through Polar water will usually fall into one of these categories, namely (IMO, 2016b):

1. Category A

The ships under these categories are designed to operate in at minimum a first-year ice, with nominal ice thickness greater than 70cm. The medium first-year ice may include old ice inclusions. Category A ships, in general, will be purpose-built having primary responsibilities and design features for operating in hostile Polar ice conditions, and having the capability to work independently. The standard dimensions for parts of the ship structure must be compliant with IACS Polar Class PC 1 to 5 (or at minimum the IACS Polar Class PC5). If the structure can comply with any other standard that is equivalent to an acceptable level of safety, then the ship can operate as a category "A" ship.

2. Category B

The ships under this category are not included in category A; they are designed to operate in at minimum thin first-year ice, with nominal ice thickness greater than 30cm. The thin first-year ice may include old ice inclusions. A typical category B ship will navigate in the Polar ice conditions independently or with an escort icebreaker on a seasonal basis. The standard dimensions for parts of the ship structure must be compliant with IACS Polar Class PC 6 to 7 (or at minimum the IACS PC7). Alternatively, the flag state can consent to another ice class notation, for example, the Finnish-Swedish Ice Class 1A super (or IA), if an acceptable level of safety can be proved.

3. Category C

The ships under this category represent any other ship operating within the Polar waters. These ships do not necessarily need to be ice strengthened hence they can operate in open water or light ice conditions. Even in light ice conditions, the flag state can demand that the ship must be ice strengthened to meet up with an acceptable standard.

The appropriate selection of an ice-class as well as the subsequent Polar ship category would be judged based on the predicted ice conditions of the planned sailing area. Other vital information on the ship's drawbacks will need to be documented in the Polar Water Operational Manual (PWOM) and the Polar Ship Certificate.

2.8.2 POLARIS

To ensure safe navigation in ice, IMO came up with a harmonized methodology for evaluating the operational setbacks in ice-infested environments through the Polar Operational Limit Assessment Risk Indexing System (POLARIS). In 2016, this methodology was published as a recommendatory IMO Circular through the Maritime Safety Committee (MSC) (IMO, 2016a).

Experience and best practice from the Russian Ice Certificate concept and Canadian AIRSS system are incorporated into this methodology with additional input supplied by the rest of the coastal administrations having the experience to regulate Arctic marine traffic. The purpose of POLARIS is to evaluate the environmental risk on ships employing the ship assigned ice class and the World Meteorological Organisation (WMO) nomenclature.

POLARIS can be used before embarking on an Arctic voyage or can be used on board in making a real-time decision on the bridge, like any other methodology. POLARIS is not intended to substitute for experienced master's judgement. It evaluates ice conditions centred on a Risk Index Outcome (RIO). Results can be gotten by carrying out the following simple calculation:

$$RIO = (C_1 \times RV_1) + (C_2 \times RV_2) + (C_3 \times RV_3) + (C_4 \times RV_4) \qquad 1.1$$

Where;

$C_1, \ldots, C_4$ = concentration of ice types within ice regime.

$RV_1, \ldots, RV_4$ = Corresponding risk index value for a given ice class.

From the above, if a small value ($0 \leq 10$) is obtained for RIO, then it shows an acceptable risk level, hence the operation may go on, whereas, a large RIO value greater than 10 shows an elevated risk level; hence, the operation might be stopped, reassessed or continued with caution, by reducing speed, et cetera.

The Risk Values (RVs) depend on ice-class, operational state (whether operating alone or with an escort icebreaker) and season of operation. POLARIS offers RVs for seven IACS Polar Classes, four Finnish-Swedish Ice Classes, and non-Ice-classed ships (IMO, 2016b). More details on POLARIS Risk Values for Winter Ice navigation can be found in IMO (2016b), and the general theory proves that an increase in ice thickness and reduction in ice-class increases the risk level of ice navigation.

2.8.2.1 Operational Assessment for Arctic Operations

Under the umbrella of Polar Code, ship owners and stakeholders are expected to carry out adequate operational checks before entering Polar waters (IMO, 2016b). The results of the operational checks are vital and are directly related to other regulations in the Polar Code. The operational checks include operational limitations of the vessel, its capabilities as described in the PWOM and sited on the Polar Ship Certificate.

Other items to consider in the assessment is the life-saving facilities. Ship owners and stakeholders are strictly advised to carry out an internal risk assessment, which contributes significantly to their internal safety management systems. Risk assessment given in the Polar Code is not intended to substitute the company's existing risk management culture, rather it helps to validate best practices. The outcome of the assessment should at least cover the following items:

- Work carried out in low air temperature, high latitudes, and ice conditions
- Possibility for abandonment on ice or on land
- Polar Code hazards and other identified hazards

The Polar Code does not include any stipulated format for risk assessment, but it provides guidance on how to carry out such operational assessment. In defining the scope of operational assessment, ice-class can provide a basis for definition, and in all cases, expert opinion is required to provide a full operational assessment. Assessment from the early stage of ship design is recommended so that outcomes can be integrated into the construction and operation procedure in the PWOM. According to Polar Code, the following basic steps are recommended to be taken (IMO, 2016b):

1. Hazard identification centred on a review of the proposed operations. Operations in ice conditions, low air temperature, and high latitudes should be in consideration.
2. Develop a risk model for analysing the probability and consequences of a potential hazard event.
3. Carry out risk ranking to determine acceptability and non-acceptability of risk.
4. Carry out risk control options to reduce the frequency and consequences of an unwanted event.
5. Take decision by incorporating the risk control options as desired.

2.9 Developing a strategy to manage difficult operational risk in a poorly understood environment: AMSSO Case Study

2.9.1 Introduction

The term "risk" is often used in our everyday life, the accurate definition is hard to capture but according to Garrido and Saunders (2019), risk can be defined as the likelihood and consequence of a hazard. It can also be described as the likelihood and impact of unexpected hazard events that adversely influence any part of a process system, leading to operational, tactical or strategic level failures or irregularities (Baryannis et al., 2019). Operational risk herein, summarises the uncertainties and hazards that crewmembers face when they attempt to carry out their day-to-day business activities in marine and offshore environment.

There is an element of risk inherent in most, if not all engineering inventions (Engineering Council, 2011). Therefore, managing such risks and unexpected events leading to system failures and/or loss or injury to human life is vital in engineering practice.

From the definition of risk, the basic elements of risk are “likelihood” and “consequence” of an unwanted event (Garrido and Saunders, 2019). The Risk Index Value (RIV) which is consequence multiplied by likelihood can be obtained if the information on likelihood and consequence are known. Nevertheless, where there is lack of sufficient data and information for identification of the risk influencing factors in a poorly understood environment, it becomes difficult to manage such risks (Fu et al., 2018a). Hence, the immediate need to tackle the complexities of risk assessment. This process of tackling the problems of risk assessment has led to the development of risk measurement disciplines such as Advanced Risk Assessment, Advanced/Robust Risk Analysis, and Strategic Risk Management.

Presently, strategic risk management techniques for improving safety in the maritime industry are quite expensive and in most cases, the methods might not be suitable or precise due to inadequate applicable risk related data and the associated high level of uncertainty involved in the available data (Sing Sii et al., 2001). As a result of this, the main objective of section 2.10 is to review all relevant risk analysis techniques that address uncertainty and carefully examine suitable criteria and alternatives in controlling complex risks in an economically viable strategy.

2.9.2 A review of Advanced Risk Analysis and Management techniques

Risk assessment and risk analysis are interchangeably used in marine risk reduction/ management disciplines. For clarity, risk assessment involves processes and technologies that identify, evaluate and report on risk-related concerns while risk analysis involves system description– a process of estimating the probabilities and anticipated consequences of an identified hazard. Whereas risk management is the continuing process to identify, analyse, evaluate, and treat loss exposures and monitor risk control and financial resources to mitigate the adverse effects of loss or accident.

In simple terms, risk management describes the Identification, Analysis (or Measurement), Reduction and Monitoring of risk (Health Guard Security, 2015). Therefore, from a hierarchical perspective in Figure 18, risk Analysis is part of Risk Assessment, which in turn is a part of Risk Management.

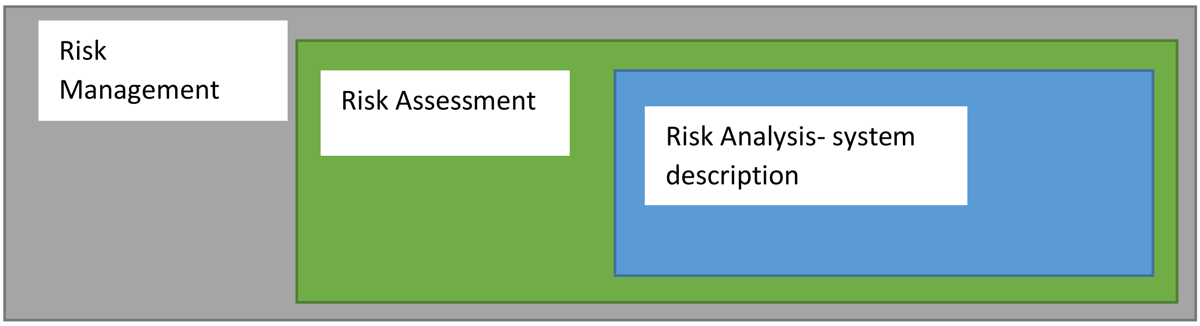

Figure 18: Relationship between Risk Management, Assessment & Analysis (Health Guard Security, 2015)

A limited number of advanced risk analysis models have been developed to lower risk and improve safety in AMSSO and Arctic shipping in general, with reference to the web of science and Google scholar search. Criteria for the concerned topic search via an advanced Google search on the 8th of January 2019 included:

- all these words: accident analysis, risk analysis of Arctic operation
- this exact word or phrase: "Arctic seismic exploration"
- any of these words: Arctic geo-data acquisition OR Arctic oil and gas exploration.

Approximately 600 academic material were obtained in the review of risk management in Arctic operations. However, most of the results mainly focussed on Arctic shipping and operations, Arctic drilling and Arctic navigation but none dealt with the risk management in AMSSO. Hence, there is an urgent need to take into account the unique risks of AMSSO due to icing, ice loading, low temperatures, remoteness, wind-chill effects, limited daylight, etc.

Another search was carried out to identify the various risk factors and hazard elements in Arctic operations, which gave approximately 33,208 websites and PDFs results, reordering these results via Google scholar, presented 75 academic papers. The 75 academic papers included journals papers and company research reports from science databases namely: sciencedirect.com, semanticsscholar.org, Viewlt@LJMU, researchgate.net, bibsys.no, core.ac.uk, Arctic-council.org, lu.se, sandia.gov, and springer.com.

The Presentation of the literature results both from the Google scholar search and studied books from LJMU library will follow the chronological order of the Polar Code– and FSA–, steps in managing Arctic risks (IMO, 2016b). It is worth noting that before commencing any risk management study, it is important to have a preparatory stage, here, the goals of the study are defined, and boundaries are set out.

Consequently, one of the reviewed papers revealed that identification of the risk factors or hazard events in Arctic operation, which is the first step in risk analysis, can be challenging due to the limited shipping activities in the Arctic Ocean (Fu et al., 2015). Moreover, there is a lack of sufficient statistical accident data to thoroughly identify hazard events of Arctic shipping operations (Fu et al., 2018a). The problem of uncertainty of failure or hazard event data, which emanates from lack of experience in the field and the limited shipping activities in the Arctic Ocean, brings enormous challenges to managing risks in AMSSO.

In order to improve safety in AMSSO through advanced risk analysis and management techniques capable of dealing with data uncertainty, it is important to first identify possible hazard events in the system. From the 75 relevant papers and the studied books from LJMU library, it is revealed that Arctic operations are complex and dynamic in nature with several risk factors originating from the environment, human, technical, management and political factors (Ehlers et al., 2014, Ayele et al., 2015).

Studies that are more recent also support the aforementioned risk factors (Fu et al., 2018b, Rahman et al., 2019, Khan et al., 2018). Experts including academia, industrialists, related field managers, and stakeholders are also considered in the hazard identification stage of the risk management study.

Although there is no best method for hazard identification, experts can apply any methodology to identify the causes and effects of accidents and the relevant hazards (Asuelimen et al., 2019, Loughran et al., 2002). With the limited availability of historical data on seismic vessel accidents/incidents a more detailed risk identification method such as Checklist, Hazard and Operability studies (HAZOP), Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) might be well suited (Leimeister and Kolios, 2018, Ericson, 2015, Fuentes-Bargues et al., 2017).

A detailed risk identification method will also involve the question of how and why accidents occur just like the HAZOP technique. Consequently, Kum and Sahin (2015) investigated into the subject of how and why Arctic accidents occur by including expert knowledge in their Root Cause Analysis (RCA) to identify and investigate the causal factors in Arctic marine accidents taking data from Marine Accident Investigation Branch (MAIB) from 1993 to 2011. Ship-ice collision and grounding were selected as the most common accidents in the Arctic region.

Consequently, the presence of ice is a major threat to Arctic operations, and there is an urgent need for academic researchers to propose a recommendation to reduce the occurrence probabilities of ships colliding with ice (Fu et al., 2018b).

Risk analysis of Arctic operation including AMSSO is a function of (i) ice and weather conditions, geographical positions (ii) traffic patterns (iii) previous marine accidents (iv) traffic and ice class regulations as well as ice breaker assistance (Serdar and Bekir, 2015). In addition, it remains that the most significant risk factors faced by mariners working in the Arctic region include drifting ice and extremely low temperature (Valdez Banda et al., 2015, Goerlandt et al., 2017, Johansen, 2013, Khan et al., 2018). Moreover, a very prominent risk factor experienced in the Arctic is the inaccessibility of the region and as such rescue response in the Arctic can be delayed (Jensen, 2007).

Although it is perceived that accidents are rare in the Arctic, this could be because of the lack of documented incident/accident records. The lack of sufficient accident data does not negate the need to develop a robust risk management model since accidents in this region often result in high consequences (Zhang and Thai, 2016). Despite the lack of sufficient accident data in the Arctic region, the Polar code painstakingly highlighted a comprehensive list of hazards for ship operations in Polar waters (IMO, 2014). Low temperature, poor hydrographic data and information, potential lack of ship crew experience and the presence of ice were not left out of the comprehensive list.

With the prolong darkness condition in the Arctic, it is revealed that the number of accidents happening during this condition were found to be approximately twice the number happening in daylight conditions (Akten, 2004).

The human element, a special kind of risk factor in Arctic shipping, is scantily discussed in Arctic accident topics but (Marchenko, 2013) investigated ship-ice collision accident model and associated ship-ice accidents with human error, weather and ice conditions.

Whereas, (Kum and Sahin, 2015, Serdar and Bekir, 2015) identified collision and grounding as the most frequent accident scenarios in Arctic operations and linked human element as the highest priority for root causes of Arctic marine accidents. Other Arctic risk management bodies and authors such as American Bureau of Shipping (ABS Advisory, 2014a), Canadian Coast Guard (Canadian Coast Guard, 2013), and Khan and Kum (Khan et al., 2018, Kum and Sahin, 2015) have identified weather and ice conditions, human error and faults in navigation systems as possible risk factors in Arctic shipping.

As reported by Lloyd's Marine Intelligence UFnit Sea Searcher Database, Canadian Transportation Safety Board (Marine) and Canadian Hydraulics Centre and Arctic Ice Regime System Database, there exist 293 marine incidents which have occurred in the Arctic region between 1995-2004 (Serdar and Bekir, 2015). And from 2004 up till 2017, it is believed that more accidents/incidents have happened as a result of the increased shipping activities in the Arctic and the melting of sea ice (Afenyo et al., 2017).

Since Arctic accidents are composed of constant and unsteady parameters, understanding the chain of reaction or failure path of each risk factor is important. In order to simplify each risk factor, identifying the root cause(s) of an unwanted event plays a significant role in risk analysis. However, reports, summaries and important data of marine Arctic accidents/incidents are just not enough to reveal the failure path in AMSSO. To this end, experts' experiences are consulted to discuss failure paths and deliberate on the probabilities of all risk parameters and predict accidents that might occur in the future.

Since the presence of ice and ice loading is a major concern in Arctic operation (Ayele et al., 2015), it is still very difficult to obtain information on actual ice load. To counter the unavailability of actual ice load data, Ehlers et al. (2014) focussed on various parameters such as estimating ice loads with expert judgement, taking maximum loading into consideration, assessing structural concerns of the loading events, establishing a risk-based design framework and assessing related potential environmental consequences.

Risk-based design methodologies using first principle methods offered a better way to achieve safe navigation within and outside of the Arctic. Kjerstad and Skjetne (2014) also investigated the impact of ice load on marine vessels, and from the experiment, it was revealed that the ice loads affected several major elements of the system.

Since the risk factors in Arctic operations are a result of several combinations of hazard elements, it is pertinent to carry out effective means to predict the occurrence probability of events occurring in this dangerous zone to account for the risk estimation and data uncertainties.

2.9.3 Uncertainty Analysis

Risks, fuzziness, and uncertainties penetrate every aspect of the exploration of petroleum resources in the Arctic (Hasle et al., 2009). To address risks, fuzziness and the uncertainty of failure data in a complex operation including AMSSO, most researchers have in most times incorporated fuzzy set theory in their risk analysis techniques. Fuzzy set theory has successfully been used in novel Probabilistic Risk Assessment (PRA) approaches for safety and reliability evaluation under conditions of uncertainty (Zolotukhin and Gudmestad, 2000, Kabir and Papadopoulos, 2018).

Bayesian subjective probability approaches have attempted to solve the problem of subjective data uncertainty but recently an alternative method has been proposed that involves interval probabilities along with fuzzy sets (Aven, 2016). The fuzzy set, apart from having interval distribution probabilities, also has the qualitative feature to express the strength of an expert's knowledge to inform the risk analyst or decision-makers. The risk analysis results are then summarised in not only probabilities P but also the pair (P, DoB), where DoB provides some qualitative measures of the strength of the knowledge supporting P. The fuzzy set is compatible and popularly used today, with the conventional risk analysis techniques.

Ferdous et al. (2013) analysed system safety and risk under high uncertainty using a bow-tie diagram. Since the traditional bow-tie technique does not take account of uncertainty in failure data, the author introduced expert knowledge to make up for the missing data, and incorporated fuzzy set theory, and evidence theory to assess the uncertainty in the system's risk analysis. Other advanced risk analysis techniques used with fuzzy set theories include FTA (John et al., 2017), AHP (Sahin and Yip, 2017), PROMETHEE with variation of fuzzy set (Tian et al., 2014), BN (Eleye-Datubo et al., 2008) and FMEA (Hajighasemi and Mousavi, 2018).

Risk Models play an important role in risk analysis and management. Nowadays, we see elements of integrative thinking, where risk analysts and decision-makers use different techniques to obtain something new and wider ranging. For example, John et al. (2017) and Alyami et al. (2019) developed an integrated fuzzy risk assessment technique for seaport operations. In the study, the weight of risk factors was determined using the fuzzy AHP methodology while ER methodology was used to synthesise the analysis. Validation of the developed model was completed using Sensitivity Analysis (SA).

Again, Zhang et al. (2016) developed an integrated fuzzy risk assessment technique for inland waterway transportation systems (IWTS). In the study also, a hierarchical structure for modelling IWTS hazards (hazard identification) was utilised to screen the hazards before ER was utilised to synthesise the risk estimates from the bottom to the top along the hierarchy through an Intelligent Decision System (IDS) Software. With these innovative advancements, it is speculated that this integration would enhance the resilience of the system in question, in a systematic approach.

2.9.4 Decision-Making Strategies

Once the question of how and why accidents occur, and the most appropriate method to treat uncertainty is answered, the next question is, how to achieve the most suitable risk control option for decision-making? There are several risk reduction techniques leading to an adequate decision-making process in risk management discipline, but the choice of selection depends on several criteria such as costs, legal factors, benefits, risk reductions, political and environmental factors (Ayyub et al., 2002). Other criteria can include the availability of risk data, or time span taken to install a risk barrier.

Several mathematical techniques have been used to synthesise the most appropriate option for risk reduction with the associated criteria such as listed in (Ayyub et al., 2002). For a simple decision-making on the most appropriate risk control option, safety engineers and stakeholders can use the Cost-Benefit Analysis proposed by IMO (Wang and Pillay, 2003). That is if cost and benefit (risk reduction) are the main criteria to be considered in decision-making. However, in a complex system with several criteria and alternatives, safety engineers and stakeholders can use multi-criteria decision-making (MCDM) techniques.

Recently, a review of MCDM applications was carried out to identify the most widely used and efficient MCDM technique. Approximately, 128 peer-reviewed papers were published from 1995 to June 2015 in flood risk management. It was also observed that the number of flood MCDM publications has exponentially grown during this period, with over 82% of all papers published since 2009. Consequently, AHP was the most popular method, followed by TOPSIS, and Simple Additive Weighting (SAW) techniques (de Brito and Evers, 2016).

In another study to identify an efficient MCDM, a review of 176 papers published between 2004 and 2015, from 83 high-ranking journals relating mostly to Management Sciences and decision-making was carried out. The results of this study indicated that more papers on VIKOR (VlseKriterijuska Optimizacija I Komoromisno Resenje) technique were published in 2013 than in any other year (Mardani et al., 2016). The application of several MCDM, Multi-Objective Decision Making (MODM) techniques can be found in (Mardani et al., 2015). In Decision-making applications and theories, several modelling techniques are available but selecting an appropriate technique depends upon the decision-maker, desired goals, available information, time, etc. The most important advantage of the MCDM methods is their capability of addressing the problems that are marked by different conflicting interests (Mardani et al., 2015, Kittur et al., 2015)

Although there is greater interest in MCDM, uncertainty analysis remains an issue. To address the issue of uncertainty in decision-making, several stakeholders have initiated the introduction of a fuzzy set into MCDM techniques. Torfi et al. (2010) used two Fuzzy MCDM methods to solve an MCDM problem. First, the Fuzzy AHP (FAHP) technique was applied to determine the relative weights of the evaluation criteria and the extension of the Fuzzy TOPSIS (FTOPSIS) technique was applied to rank the alternatives. Empirical results show that the proposed methods are viable approaches especially when data are vague and imprecise (Kusumawardani and Agintiara, 2015).

With the lack of systematic risk management methodology, Formal Safety Assessment (FSA) methodology as approved by IMO in conjunction with other international and national regulatory authorities and class societies (Hermanski and Daley, 2005) will be synthesised into AMSSO risk management. Consequently, the FSA methodology will enhance the strategic risk management of both documented and envisaged risks posed by the ever-changing and dynamic Arctic environment.

2.10 Formal Safety Assessment (FSA)

Originally introduced in the response to the Piper Alpha disaster in 1988, FSA is currently being used in the IMO to support the rule-making process (Sames, 2009). The FSA framework can best be described as a balanced and a systematic process of assessing risks associated with shipping operations and for evaluating costs and benefits of diverse options for identified risks reduction (Hermanski and Daley, 2005). Most modern risk assessment studies related to shipping activities are often faced with the following four challenges, and these four challenges are dealt with in the FSA framework:

1) Being systematic: the ability to be implemented using a formal and structured process.
2) Being proactive: the ability to predict hazards rather than respond after accidents have occurred.
3) Being transparent: the ability to be clear in the safety level achieved.
4) Being cost-effective: the ability to find a balance between risk reduction and economic benefits, for the key stakeholders of the proposed risk control measures.

A part of a study under the European Union's Horizon 2020 titled "Formal Safety Assessment of a Marine Seismic Vessel Operation, Incorporating Risk Matrix and Fault Tree Analysis" has also proved the application of the FSA methodology to be systematic, proactive, transparent and able to provide risk management decision making using a cost-benefit approach (Asuelimen et al., 2019). The inclusion of expert judgement in risk analysis of a poorly understood system such as Arctic operations as included in FSA studies also proves its proactive step in addressing complex risks (Stanton, 2017). However, the basic steps of the FSA methodology elaborated into the following steps:

1. Preparatory step
2. Identification of hazards
3. Risk estimation
4. Identification of risk control options

5. Cost-Benefit Analysis (CBA)
6. Recommendation for decision-making.

Details regarding these six (6) steps can be found in section 2.11. It is worth noting that the proactive approach included in FSA Guidelines remains deeply imbedded in probabilistic methods to risk assessment. This is reflected throughout the “2013 version of the FSA guidelines” (Stanton, 2017). In the “2013 version of the FSA guidelines”, paragraph 3.2.3, for instance, highlights that a "proactive approach is reached through the probabilistic modelling of failures and development of accident scenarios". This objective can be argued whether it is realistic or not.

However, this is not a question for this research. Appendix 3 of the FSA Guidelines contain recommendations for approaches to be employed during hazard identification. Most of them are qualitative and quantitative risk assessment (QRA) tools such as Event Tree Analysis (ETA), Fault Tree Analysis (FTA), FMEA, etc.

The same is related to methods recommended for the consideration of human factors. The main tool to be used for that purpose is the Human Reliability Analysis (HRA), as recommended in Appendix 1 of the 2013 FSA Guidelines.

In general, the use of FSA in the shipping industry whether in the Arctic region or in open water areas, represents a fundamental cultural change, from a generally reactive approach to a structured, proactive and systematic approach that employs risk evaluation, that is integrated, and effective (Stanton, 2017, Wang, 2003).

2.10.1 Qualitative Risk Assessment

The risk description generated by a qualitative risk assessment, while ideally centred in numerical data for exposure assessment and hazard representation, will generally be of a descriptive or categorical nature, that is not directly tied to a more precisely quantified measure of risk (WHO, 2009). Qualitative risk assessments are generally used for screening risks to determine whether they deserve further investigation, and this can be useful in the 'preliminary risk management activities'. In Risk assessment, qualitative risk assessment is undertaken initially, with the intention of following it up with a QRA if it is subsequently understood to be necessary or useful.

A risk profile or qualitative risk assessment is suggested if a quantitative assessment is underway. This can be useful to identify the data presently available, the uncertainties about that data, and uncertainties surrounding the exposure pathways, and to decide if quantification is both achievable and likely to add information to the present state of knowledge (WHO, 2009). A good example of a qualitative risk assessment is represented in Table 2.

Table 2: Qualitative Risk Table (Asuelimen et al., 2019)

Risk factors	Operational stage			
	Crew embarking	Manoeuvring (harbour)	At sea (coastal)	Crew disembarking
Collision/ Contact	Very Low	High	Medium	Very Low
Man Overboard (MOB)	Medium	Low	Low	High

There are about 31 qualitative risk assessment techniques according to ISO/IEC 31010:2009 (Brocal et al., 2018) although some techniques do cross over one another. Out of the 31 methods, the Brainstorming technique is preferred and used in the qualitative aspect of this research. The brainstorming method involves a group of experts working together to identify potential risks, causes, hazards, criteria and failure modes for decisions and/or options for risk reduction/control. Brainstorming should motivate free-flowing conversation amongst experts without criticising or rewarding ideas. This is one of the most appropriate and popular ways to identify both risks and key controls of risk (Harb, 2018).

2.10.2 Quantitative Risk Assessment (QRA)

In simple terms, a QRA is a formal and systematic approach to estimating the likelihood and consequences of hazard events and expressing the results quantitatively as a risk to people, the environment and the organisation. A QRA can also be referred to as Probabilistic Risk Analysis (PRA) or Probabilistic Safety Analysis (PSA). QRA is being applied to many industries, including transportation, construction, energy, chemical processing, aerospace, the military, and financial planning and management (Tim and Roger, 2003, Voeller, 2010).

A QRA is an effective means to capture an extensive picture of the risk of accidents and has the ability to (Khan et al., 2018):

- be described in terms of probabilities and expected values of hazards and,
- treat uncertainties related to the risk obtained for the desired event.

Essentially, QRA answers the following three questions (Voeller, 2010, Kaplan and Garrick, 1981):

- What can happen?
- How likely is it to happen?
- Given that it occurs, what are the consequences?

The key QRA results are the probabilities of various consequences of accidents, the identification of the most likely scenarios (event sequences) that may lead to the consequences, as well as the most important (from a risk perspective) structures, subsystems, and components. This information is very valuable to designers, operators, and regulators because the responsible parties can focus on what is actually important to the safe operation of the system (Voeller, 2010).

The QRA sets out to define, measure, predict and provide a confidence level of likelihood and occurrence of threat impacts (Glenn et al., 2015). QRA are rarely used alone – they are typically used in collaboration with qualitative analyses, operational experience reports, and expert judgement –, their use includes the use of numbers or quantitative data and provides quantitative results (Rae et al., 2014). Hence, this method is more precise and more objective. More importantly, the quantitative results can be greatly affected by the validity and precision of the input parameters. Therefore, the quantitative outcomes within the risk analyses do not necessarily have to be exact numbers, but as estimates or approximations, with a variable scale depending on data quality.

2.11 Application of FSA in risk management research

2.11.1 The preparatory Step

In any risk management project, it is important to understand the definition of the problem under study, with respect to the system, goal, and operations. The reason for defining the problem is to have an understanding of the task with respect to risk regulations under review; this in turn will assist in determining the scope and depth of the risk management process. It is important to include the preparatory step in any risk management project because a misguided definition of a problem such as a vessel design or operation etc., may lead to insufficient recommendations, which in turn may exclude major risk factors from the system being assessed. This preparatory step in risk assessment and management helps to simplify the objective of the assessment.

2.11.2 Hazard Identification (HAZID)

After the preliminary phase of outlining the goal and aim of the risk assessment, the first and most important phase is the HAZID process (Sutton, 2014, IMO, 2002, HSE, 2014). For many managers, the identification of hazards may well be the most difficult part of the risk assessment process. The rest of the process is relatively simple maths, depending on the analysis and method chosen, and combined decision-making technique (Tucker, 2014).

HAZID process is satisfied with a combination of creative and analytical exercises that aim to identify all significant hazards. The creative part (mostly brainstorming) is to ensure that the process is proactive and not restricted only to hazards that have happened in the past (Kontovas and Psaraftis, 2009). The process should be carried out to ensure that all circumstances with the likelihood to cause harm to people, and/or damage to assets and the environment have been identified, and the risk factors as a result of these causes are defined as well (Bai and Jin, 2016a).

In engineering and other industrial sectors, HAZID is a universal term used to describe a practice whose aim is to identify all significant activities that have the likelihood to result in significant consequences (Wang et al., 2005, Wang and Trbojevic, 2007). The HAZID process can vary depending on evaluated system/facility characteristics, such as an operation's complexity, workforce, activity magnitude, equipment and available resources.

Different techniques are used to perform HAZID, including qualitative and quantitative approaches, which includes literature review and research, physical inspection, checklist, brainstorming, flow charts, What-If Analysis/Structured What-If Technique (SWIFT), organisational charts, safety audits, HAZOP, Task Analysis (TA) and FMEA (Brocal et al., 2018).

A literature review as one of the HAZID process can provide a high-quality analysis where the hazard based data have been searched and justified for a related topic, which can be used in conjunction with the other qualitative and quantitative methods (Quinlan et al., 2019, Saunders et al., 2009). Brainstorming phases are generally used to analyse technical systems and thereby generate the main qualitative results. A team of experts is called upon to determine the potential consequences of a deviation in a system in the HAZID phase. The concerned team should represent a cross section of disciplines and functions, including maintenance, operations, engineering, process design, and management, to ensure that all hazard situations are detected and discussed (Sutton, 2015, Bai and Jin, 2016a).

Once hazards have been identified through literature review and/or brainstorming session, the method of hazard presentation is also important in the risk management process. Identified hazards could be represented in an overlapping, non-linear or linear manner. The linear representation involves the use of a novel divisive hierarchical clustering technique to identify failures/hazards in a large system such as the Arctic system.

The purpose of clustering is to reveal an event’s dependency and to partition the hazards into hazard groups (clusters), such that hazard elements within the same cluster are more similar to each other than to hazard elements in a different cluster. Clustering is a non-overlapping complete set of clusters. This has been used in the medical field to identify clinically interesting subpopulations in a large cohort of Olmsted County, Minnesota, USA (Kim et al., 2014). The hierarchical clustering dendrogram would be such as presented in Figure 19.

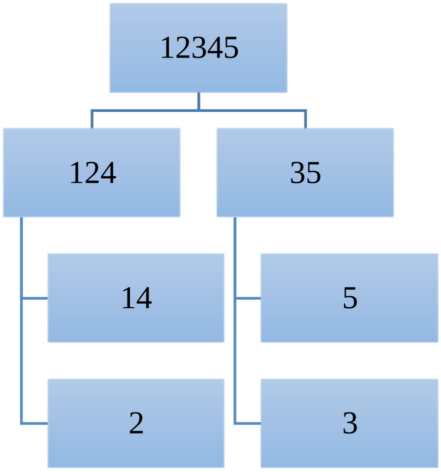

Figure 19: A Linear dependable representation of events

2.11.3 Risk Analysis

The main objective of carrying out risk analysis is to provide an explicit investigation of the causes and the consequences of the most significant scenario. The purpose of this is to give proper attention to high-risk areas and focus on factors, which affect the level of risk.

Risk is often measured using two-risk parameters (that is, frequency or likelihood and consequence). Analysing risks simply in terms of probability of a hazard occurring (or frequency) and the impact of hazard (or consequence) with methods such as FTA, Event Tree Analysis (ETA), Risk Matrix, Cause-Consequence Analysis (CCA) and bow-tie techniques are effective. However, moving on to a more complex and expensive operation, these methods might not be suitable, as they tend to miss the much richer detail that can be uncovered if the costly and expensive operation are examined in greater detail. Examining other risk parameters such as the ability to detect the harm/hazard (detectability) also factors in the estimation of risk (Stavrou and Ventikos, 2016, Stavrou et al., 2018, Lo and Liou, 2018).

Any other risk parameter that can interfere with the risk level of an event can be considered in the risk analysis phase. Therefore, detectability as a dependent metric can be included as a risk parameter since it reduces the probability of occurrence of an event (Speer, 2015). Another factor that can be included in the risk parameters in a risk evaluation phase, is costing (Lo and Liou, 2018) or impact on the operation.

In order to introduce more than two risk parameters in the risk analysis phase, a forward-looking risk-management technique such as FMEA, FMECA can be utilised. FMEA has been utilised in various industries for promoting the reliability and safety of processes, structures, systems, and services (Lo and Liou, 2018).

Again, moving on to a rare and extreme risk, the risk analysis process becomes even more complex with intricacies such as probability and uncertainty of hazard information (data). The problem with assigning a probability figure in an environment with little or no historical accident record can be an issue. Uncertainty in data is due to the combination of incomplete knowledge about a process and its expected or unexpected variability (Ayyub and McCuen, 2016, Snidaro et al., 2015).

Therefore, moderating the probability value can provide a solution even when decision-makers are not sure of their probability data (Liu et al., 2017, Liu et al., 2016, John et al., 2017). This works in a way that the decision-maker might conclude that there is a 50% probability of the risk happening with 20% deviation, giving a possibility range of 70% to 30%. Which eventually means that the decision-maker does not think it is very likely or unlikely to occur, but the probability is in the middle somewhere. Evidence of this technique to solve uncertainty in data can be seen in a number of studies (John et al., 2018, Alyami et al., 2019, Yang and Wang, 2015).

A more advanced risk analysis, which takes account of the multi-faceted nature of the risk, can include both qualitative and QRA techniques or a combination of several QRA techniques. A variety of QRA techniques which have been introduced by academic bodies and used in the maritime industry include but are not limited to Failure Mode Effects and (Criticality) Analysis (FMECA), FMEA, BN, VIKOR, FTA, ETA, Preliminary Hazard Analysis (PHA), Cause-Consequence Analysis (CCA), ER and Human Reliability Analysis (HRA). All these techniques have been used or mentioned in a number of studies (Bai and Jin, 2016a, Sutton, 2015, John et al., 2018, Liu et al., 2015).

The mentioned techniques may differ in structure and may have qualitative or quantitative output. Nevertheless, they share a commonality in that they involve identifying hazards, analysing the risk associated with each hazard and evaluating how significant the risks are (Sandle, 2015).

2.11.4 Risk control/ Decision-making

To investigate risk control options, it is necessary to first identify high-risk areas from step 3, which needs to be managed. Thereafter, identification of the risk control/reduction options otherwise known as RCOs or alternatives can be carried out through literature review and expert consultation, including non-professionals from the workplace (Asuelimen et al., 2019, HSE, 2010). Risk control embraces decision-making to reduce and/or accept risks. The number of resources used for risk control should be proportional to the significance of the risk. The process of controlling risk might focus on the following questions (Sikdar, 2017, Byrn et al., 2017):

- Is the risk level acceptable or not?

- What can be done to control or eliminate risks?
- What is the suitable balance among benefits, costs, and resources?
- Are new risks introduced in the course of controlling risks?

The marine industry and regulators assess and manage risk using recognised risk management tools such as MCDM, MADM, and MODM (Mardani et al., 2015). Decision makers could use a single tool or a combination of MCDM tools to arrive at a suitable option to answer the above four questions. The selection process could be in the form of benefit-cost analysis (Basten et al., 2010), for understanding the optimal level of risk control. In addition, MCDM can provide a useful tool in deciding a balance between cost and benefit from the risk control options associated with their several criteria.

Whichever tool is adopted to reduce or manage risk, there are two important points to bear in mind, namely:

- There is no such thing as "zero risk" and therefore, a decision is required as to what is "acceptable risk" and this must be qualified before the risk analysis begins;
- Risk management is not an exact science as different people will have a different perspective on the same hazard (Sandle, 2015).

2.12 Conclusion

The IMO Polar Code provided the boundaries for the review and techniques of risk management practices. The scientific assessment methods adopted by the IMO can be used to enable HAZID and risk/safety management of AMSSO under high uncertainty. This chapter has provided the knowledge background to identify the most suitable risk-based methodology to analyse the risks in AMSSO both locally and globally. The comprehensive list of hazard events and risk factors obtained from this present chapter would be included in the data set of the subsequent chapters.

Chapter 3– Enabling Fuzzy Rule-Based Bayesian Network (FRBN) Methodology in AMSSO Risk Evaluation and Prioritisation

Overview

One of the several problems in Arctic shipping and AMSSO risk assessment research is the unavailability of sufficient primary observations and consequent shortage of statistical hazard data. The insufficient availability of hazard data adds to the uncertainty of events in this region, leading to the possibility of unpredicted catastrophes such as hull damage, ship-collision, grounding etc. In addition to the complexity of the AMSSO risk analysis, a careful literature review revealed that: human factors contribute more than 50% of the marine and offshore accidents, and risk is often not primarily within the vessel operating in marine environment but by other issues involving efficiency, political, legal, social-economic and environmental element.

Several scholars have offered a wide range of risk analysis techniques such as Risk Matrix, FTA to solve complex risk analysis, utilising either the idea of the probability of a failure event occurring or the likelihood of a hazard event occurring and the likely consequences of such a hazard event. However, those models very often fail to account for other significant parameters of risks such as Impact of failure (I) and the probability of detecting a failure in the system (P). This in turn limits models' capability to analyse the risks in a complex system, as P and I are simply not put into consideration.

In order to analyse risk confidently and ensure safety in AMSSO, this chapter starts by first carrying out a qualitative risk assessment by identifying the most significant hazard *events in AMSSO. Then it combines two QRA techniques– i.e. FMEA and BN approaches with fuzzy logic–, to establish a novel Fuzzy Rule-based Bayesian Network (FRBN) hybrid methodology.*

The FRBN is capable of accounting for the issue of data uncertainty and taking into consideration other vital parameters of risks in order to prioritise risk in AMSSO in a more confident manner. Compared to conventional FMEA, the new technique integrates (Fuzzy Rule-Base) FRB and BN in a complementary way, in which the former provides a realistic and flexible way to describe input failure/hazard information while the latter allows easy update of risk analysis results and facilitates real-time safety evaluation and dynamic risk-based decision support in AMSSO.

The Sensitivity of the developed model can be an additional issue in the risk analysis studies, however, this can be dealt with by incorporating a sensitivity analysis technique to link practical design formats. The proposed approach can be tailored for wider applications in other engineering and management systems, especially when instant risk ranking is required by the stakeholders to measure, predict, and improve their system safety and reliability performance.

3.1 Introduction

Risk can be described as the probability or likelihood (L), high or low, that somebody or some asset or environment could be harmed or damaged (C) by a hazard (HSE, 2017). Risk analysis plays an important role in the entire risk management cycle from identifying, evaluating, reporting and controlling to monitoring risks. The role of risk assessment helps decision-makers to rank and manage risks in order to avoid potential hazards and to form the basis to reasonably allocate remedial options (Mirzaei et al., 2018).

Some risk assessment methodologies assess risk qualitatively (e.g. PHA) or with the combination of qualitative and quantitative approaches using probability assignment (e.g. FTA, ETA) (Rausand, 2013, Cox Jr, 2009). However, a more suitable approach that addresses risk qualitatively and quantitatively from its root definition is the risk matrix technique (Duijm, 2015). The risk matrix technique remains popular and often utilised in the informative sections of several international standards such as IEC (2006) and ISO (2010) (Asuelimen et al., 2019). In the risk matrix approach, qualitative data, such as that obtained from interviews and questionnaires, can be used to identify possible improvements, while quantitative data, such as that obtained from historical data can assist to evaluate risk or failure in a system.

In line with the description of risk, the probability of occurrence (*L*) and the consequence severity (*C*) of damage/impact can be expressed as two input variables in the risk matrix. The combination of "*L*" and "*C*" formulates an index to classify and distinguish different risks. The logical interpretation of the combination of "*L*" and "*C*" can be described as "IF probability is "*L*" and consequence severity is "*C*", THEN risk is "*R*" (Markowski and Mannan, 2008). Generally, qualitative scales in the risk matrix describe both input and output variables. The probability of occurrence (*L*), for example, can be split into five levels, such as remote, unlikely, likely, high likely and almost certain, while the severity of impact (*C*), for example, can also be categorized as negligible, minor, moderate, serious and critical.

Concisely, each risk is measured by the risk matrix mainly from two dimensions. However, as many practical (real-world) systems are becoming gradually more complicated, along with the appearance of unexpected events and changes, the two-level measurements of the probability of occurrence (*L*) and consequence severity (*C*) are incapable of entirely capturing the whole behaviour of a risk (Janasová and Strelcová, 2018). It is problematic for the risk matrix technique to provide a complete view of multiple aspects. Hence, an advance systematic technique that introduces more than two variables such as the FMEA technique can be employed to fill in the gap.

The application of FMEA follows a series of successive steps. First, it analyses the process, then identifies potential failures or hazards. The next step will be risk evaluation; unlike the risk matrix, the FMEA methodology advances more into considering ratings for detectability along with ratings for severity of failure and ratings for the occurrence of a failure (Cicek and Celik, 2013). Although FMEA has been popularly used in the risk assessment process to identify high-risk events in situations where objective failure data is available, it has also suffered a major drawback in its use of Risk Priority Number (RPN) (Liu, 2016).

The drawbacks of the traditional RPN methodology have been widely analysed (Xu et al., 2002, Zhang and Chu, 2011). Recently, a careful literature survey reveals that though the FMEA method can take different aspects of risk into consideration, it does lack a high level of data certainty, hence, is not capable of addressing such uncertainty that exists in AMSSO risk management.

Consequently, novel risk approaches are needed to overcome such key drawbacks. Several new methods based on uncertainty treatment theories such as FL, Dempster-Shafer (D-S) theory, Grey System Theory, Monte Carlo simulation, BN, Markov models, and Artificial Neural Networks (ANNs) have been proposed in the literature to enhance the performance of FMEA, especially when criticality analysis is concerned (Yang et al., 2008b, Li and Chen, 2019). However, such new methods add to the development of more precise risk analysis and likewise render themselves susceptible by losing visibility and easiness, which are improvements of the conventional FMEA method.

Yang et al. (2008b) suggested a new hybrid methodology to elucidate in a complementary way the role of BN in FRB risk inference. In this case, the BN rule is employed to aggregate all relevant IF-THEN rules with belief structures and yields failure priority values given by posterior probabilities of linguistic risk expressions. While the FRB is employed as an effective tool to bring about expert judgments for rationalising the configuration of subjective probabilities.

This chapter aims to apply the novel FMEA approach (also called FRBN) by incorporating FRB and BN to rationalise the Degrees of Belief (*DoBs*) distribution in order to address the problem of uncertainty in risk estimation of AMSSOs. The novel FMEA approach with the ability to incorporate different weights of risk parameters into FRB is described in the subsequent sections.

A particular test case regarding AMSSO safety evaluation is investigated to demonstrate the feasibility of the new methodology. Thereafter, a discussion based on the results obtained is shown in the latter part of this section. Next to the discussion is the conclusion section (section 3.7). Subsequently, this study will contribute to facilitating the FMEA applications in risk theoretical research, and to improving practical safety management for AMSSO and other complex engineering systems.

3.2 Background Analysis

3.2.1 Fundamental aspects of the notion of uncertainty in AMSSO risk analysis

There are two fundamentally different forms of uncertainty in AMSSO risk analysis. The first type (aleatory uncertainty) refers to the uncertainty of input arising from randomness due to inherent variability in the system while the second type (epistemic uncertainty) refers to the uncertainty of input arising from lack of knowledge/information, such as event data from expert judgement (Sun et al., 2018). While epistemic uncertainty can be reduced, aleatory uncertainty cannot, and for this reason, it is sometimes called irreducible uncertainty (Çağnan and Akkar, 2018). Consequently, this research is concerned mainly with the second source of uncertainty.

In standard risk analysis, model parameters are assumed constant values, nevertheless, on many occasions, these parameters are difficult to assess or estimate. Thus, their initial deterministic character is considered insufficient and parameters are assumed random variables. When this occurs, the aim of the risk analysis is to monitor the effect of this randomness on a given target variable. In the context of risk analysis bounded by a lack of knowledge of subjective input data, the focus is on the treatment of uncertainty (Çağnan and Akkar, 2018).

Quantitative maritime risk studies hardly discuss the uncertainty of their developed risk model or the sensitivity of their results in relation to changes in the specific parameters of the risk model (Sormunen et al., 2015). However, this research will address the uncertainties in the developed risk analysis model by carrying out the sensitivity of the risk analysis technique and the obtained results.

3.2.2 Fundamental aspects of the notion of Fuzziness and Probability

Fuzziness and probability are related but they both have different concepts. Fuzziness is a type of deterministic uncertainty that defines the event class ambiguity (Eleye-Datubo et al., 2008). As with probability, the concept of fuzziness can be assessed by attaching numeric values between 0 to 1 or 0 to 100 to each preposition in order to represent uncertainty. Fuzziness measures the degree to which the preposition is correct whereas, probability measures how likely the proposition is to be correct.

However, it seems more appropriate to investigate the fuzzy probability of any system risk analysis limited by a shortage of objective data (Dubois and Prade, 1997), than to completely dismiss probability as a special case of fuzziness. Subsequent sections in this research combine both concepts (and methods) of probability and fuzzy logic to tackle inexactness in risk analysis.

3.3 A review of FMEA/fuzzy FMEA

FMEA methodology offers a systematic procedure for the analysis of a system to identify the possible failure modes, the causes of such failure, and the effects on the system's performance. It is very important to be aware that a failure mode is not the cause of a failure, but it reveals the way in which failure has occurred (Arabian-Hoseynabadi et al., 2010). In addition, an FMEA is not restricted to a specific event, but rather it can analyse the safety level of a process or system (Davis et al., 2008). Hence, the inclusion of FMEA, to analyse the safety level in an AMSSO, is suitable and practicable.

The traditional FMEA method has three key components, namely failure occurrence likelihood (L), consequence severity (C), and the probability of failures being undetected (P). These three components can be used to analyse the safety level of a risky operation and to calculate their RPN (Lipol and Haq, 2011).

In evaluation and prioritisation of risks, the traditional FMEA is seen to suffer some critical drawbacks (Yang and Bai, 2009) such as rank reversal etc., for other drawbacks see (Lipol and Haq, 2011). To counter the weaknesses of the application of FMEA, some researchers have identified four key viewpoints (Bowles and Peláez, 1995). These four viewpoints include 1) fuzzy logic for prioritising failures, 2) fuzzy risk priority number, 3) fuzzy assessment of FMEA, and 4) cost estimation using FMEA. In the review of these viewpoints, the integration of fuzzy logic in prioritising failures was most suitable in overcoming the major problems of calculating RPN in FMEA Vinodh et al. (2012).

Xu et al. (2002) presented an approach for carrying out a fuzzy FMEA assessment to overcome FMEA drawbacks. Guimarães and Lapa (2004) used the Fuzzy Inference System (IF-THEN rules). The RPN was calculated and compared with fuzzy RPN, which was compared from experts' view and drew inferences. Dong (2007) published an article connected to FMEA based on fuzzy cost estimation. Fuzzy utility theory combined with fuzzy membership functions were utilised for calculating the RPN, and the presentation of team opinion was done through the application of the fuzzy membership concept. The author used a risk priority index to prioritise the failures. This process enhanced the performance of FMEA in product design and manufacturing.

Wang et al. (2009) used fuzzy weighted geometric mean to carry out a study on FMEA application; the authors proposed an approach in which severity, occurrence, and detection were utilised as fuzzy variables. By means of those variables, fuzzy RPN was simplified.

From these literature surveys, it is observed that fuzzy sets in all their variations proved to be more realistic in dealing with the setbacks of the traditional FMEA RPN calculation (Aven, 2016). The fuzzy sets have interval distribution probabilities with qualitative characteristics to express the strength of an expert's knowledge to inform the risk analyst or decision-makers. The fuzzy set is compatible with the conventional risk analysis techniques and popularly used today in several industries, including the nuclear industry. (Guimarães and Lapa, 2007).

It is well known that risk analysis techniques are not an exact science (Sandle, 2015), and in some cases they do suffer some drawbacks. Hence, it is worthy to mention that the application of Fuzzy Logic (FL) in FRBN suffers some drawbacks in its inability to give generalised results and the difficulty in developing the fuzzy rules. However, it offers an advanced risk-based approach to handle problems with imprecise and incomplete data.

3.4 Methodology for modelling AMSSO Risk Analysis

Nowadays, we see elements of integrative thinking to arrive at a more realistic results in the risk analysis of a complex system. Not long ago, researchers combined the Bayesian subjective probability technique with FL to solve the problem of subjective data uncertainty and the scarcity of statistical accident data. As a result, Yang et al. (2008a) developed a hybrid Fuzzy Rule-based Bayesian Reasoning (FRBR) to overcome the key weaknesses of the traditional FMEA.

The novel FRBR (also termed FRBN) methodology uses the Bayesian marginalisation rule to take in all relevant IF-THEN rules with belief structures then calculates failure priority values in posterior probabilities. The BN mechanism in FRBR offers a simple mathematical principle for calculating conditional and marginal probabilities of a random and dynamic event. Conditional probability is the probability of an event given the occurrence of an influencing event whereas marginal probability is the unconditional probability of an event.

The BN mechanism is employed as a tool to perform FRB risk inference to model uncertainty in a system and deals with the subjective probability that may represent the *DoB* from an expert data and applies it in a precise and relevant way (Jones et al., 2010).

An FRB can be used as an effective way to prompt expert judgments for rationalising the configuration of subjective probabilities. This methodology is gaining popularity in recent years and has successfully been applied in container supply chain risk management (Yang et al., 2010) and in the offshore industry (Yang and Wang, 2015), etc.

The development of the FRBR defines the role of BN mechanism in Fuzzy Rule-based risk inference in a complementary manner and achieves sensitive failure priority values without compromising the simplification of the traditional RPN approach.

The rule-based approach in FRBN consists of IF-THEN rules and a translator that controls the application of the rules, which in FMEA risk analysis, is described as the connection between risk parameters in the IF portion and risk levels in the THEN portion (Alyami et al., 2019).

The IF-THEN fuzzy rule-based approach offers a variable scale to represent expert (subjective) data to moderate the effect of disagreement in expert data and the effect from the variable sizes of expert participants. The values of the antecedent portion determine the values of the consequent portion. The IF part is called antecedent while the THEN part is called consequent (Krzyżanowska et al., 2017). These IF-THEN rule statements can be utilised to formulate the conditional statements that include the complete knowledge base.

The novel FRBN method justifies the *DoB* distribution and creates a new risk-based decision support tool for AMSSO risk evaluation. An FRB with belief structures is more enlightening and realistic than the traditional IF-THEN rule because of its high success in functional mapping between antecedents and the consequent output, principally in view of vague knowledge representation (Yang et al., 2008a).

Therefore, the novel FRBN is a preferred option in AMSSO risk analysis because of its ability to solve the problem of the scarcity of primary observations and consequent shortage of statistical data.

The steps for developing the novel FMEA analysis for modelling AMSSO risk analysis, based on the proposed FRBN approach, are drawn as follows:

- Definition of problems (preparatory phase)
- Establish an FRB with a belief structure in FMEA
- Identification of all potential and significant hazard events
- Developing a BN Model with a rational distribution of *DoB* in FRB
- Prioritising the hazard events and comparing the result with benchmark risk
- Validate the model by using sensitivity analysis techniques

3.4.1 Formation of an FRB with belief structure in FMEA of AMSSO risk analysis

3.4.1.1 Definition of the problem– Preparatory phase

The whole system of AMSSO including the seismic survey vessel, the Arctic sea and additional systems such as navigation and monitoring systems, all represent a complex and expensive system. Seismic survey operation in locations covered by ice, debris, large swells or other obstacles can make surveying difficult, expensive or even impossible (Gagliardi et al., 2018).

Gathering information on the prioritization of AMSSO risk factors for investigation can be tricky as one risk factor can be as perilous as the other in terms of accident consequences and their impact on operation. Risk factors herein refer to any risk element with an attribute or characteristic with the potential to cause an accident. Reports from Lloyd's Marine Intelligence Unit Sea Searcher Database, Transportation Safety Board of

Canada, Canadian Hydraulics Centre, MAIB and Allianz Global (from section 2.5.2) revealed several accident categories within the Arctic Circle from early 2000s to 2018.

These can be summarised into seven (7) major accident categories. These seven accident categories include:

i. Machinery damage
ii. Wrecked/ stranded
iii. Miscellaneous (e.g. near-miss)
iv. Fire/ Explosion
v. Contact (e.g. harbour wall)
vi. Hull damage
vii. Foundered.

Although these accidents are common to AMSSO, it is pertinent to note that the above accident category and thus the types of problems, or risks, associated with different categories of ships and activities vary tremendously (Engler and Pelot, 2013). Hence, further investigation revealed that about 6 (six) risk factors are common to each of the 7 accident category. These 6 risk factors which are present in AMSSO are presented as a subcategory and listed below:

1) Human error
2) Ship Navigational System States
3) Ship Operational System States
4) Weather States
5) Ice states
6) Ship Class States.

These risk factors combine largely to constitute No.7) Ship-Ice Collision risk factor, in which the above six risk factors merge into issues related to Ship-Ice Collision. Ship-Ice Collision model represents the goal of the FRBN risk investigation.

3.4.1.2 Establish an FRB with belief structure in FMEA

In the traditional FMEA, three risk parameters, Likelihood (*L*), Consequences (*C*), and Probability of failure being undetected (*P*), are utilised to evaluate the safety level of each failure mode. The impact (*I*) of a failure or hazard event which is capable of triggering a cascade effect that could slow down or completely stall seismic acquisition (Pemberton et al., 2015) is noteworthy in AMSSO risk investigation. In addition, the impact (*I*) of a hazard event has the potentiality to cause delays in operation, thus affecting the compliance with the consent or licence conditions (JNCC, 2017), hence, resulting in financial impact and consequent payment – except not stated in the acquisition contract (IAGC, 2014). Therefore, the inclusion of impact (*I*) of a hazard event is crucial in AMSSO risk analysis.

The four new risk parameters (*L*, *C*, *P*, and *I*) are fashioned to form the IF portion while the risk analysis of hazard events is presented in the THEN portion in an FRB. To simplify subjective data collection, a set of linguistic grades of High, Medium, and Low and Very Low is used to describe *L*, *C*, *P* and *I*. The description of the linguistic grades of *L*, *C*, *P*, and *I* assignment is similar to the work done by Alyami et al. (2019) and Yang et al. (2008a) and described here in the Tables 3, 4, 5, and 6.

Table 3: Likelihood assignment definition

Assigned rating	If the likelihood is:
Extremely Remote	Very Low: Might occur every 6 to 10 years and beyond
Remote	Low: Might occur once every 7 months to once every 1 to 5 years
Reasonably Probable	Medium: Might occur once in 2 months to twice a year
Frequent	High: Might occur monthly or weekly or daily

Table 4: Consequent assignment definition

Assigned rating	If the consequence is:
Insignificant	Very Low: Injury requiring little or no first aid, no significant harm to people, vessel and environment
Minor	Low: Minor damage (dents and scratches) degradation of the vessel strength (local damage to the structure), or causing between 1 and 9 major injuries or causing injury requiring more than first aid
Major	Medium: Major damage/ degradation of the vessel strength, or causing between 10 and 100 major injuries
Catastrophic	High: Total loss of life, vessel or severe damage to the environment

Table 5: Probability of a hazard being undetected definition

Assigned rating	If the probability to detect a hazard is:
Very Low	Possible to be detected through regular checks or easily observed with less attention
Low	Possible to be detected through mere diagnosis or observed with proper attention
Medium	Difficult to be detected through mere diagnosis or proper attention
High	Impossible to be detected through mere diagnosis or regular checks or proper attention

Table 6: Impact of hazard to operation definition

Assigned rating	If the impact of hazard to an operation is:
Very Low	Negligible impact on operations capability of the vessel
Low	Little impact on the operations capability of the vessel
Medium	Degraded operations capability or readiness to halt operation
High	Loss of ability to accomplish the operations or operation failure in the vessel

As a result of the lack of properly documented accident data, the belief degrees of the parameters expected for each hazard event will be centred on knowledge gained from past and similar events. However, the belief structure is introduced to model the incompleteness in the THEN portion. The theoretical development of the belief structure is as follows (Wan et al., 2019, Yang et al., 2008a).

$$R_h: IF\ A_1^h\ and\ A_2^h and\ A_3^h\ and\ \ldots and\ A_m^h\ ,$$

$$\text{THEN}\ \{(D_1, \beta_{1'}^h), (D_2, \beta_{2'}^h), \ldots, (D_N, \beta_{N'}^h)\} \qquad 3.1$$

$$(\Sigma_{j=1}^N \beta_j^k \leq 1)$$

Where $\beta_j^h (j = 1,2, \ldots, N)$ is the DoB to which D_j is understood to be the consequent in the hth multiple-inputs and single-output rule, when the input satisfies the antecedents A^h = $\{A_1^h , A_2^h , \ldots, A_m^h$. N is the number of all possible consequents. And if $\Sigma_{j=1}^N \beta_j^h = 1$, then the hth is considered complete, if not, otherwise.

In establishing the FRB with belief structure in FMEA, experts with first-hand experience in AMSSO use the linguistic assessment of Very Low (*VL*), Low (*L*), Medium (*M*) and

High (*H*) with the *DoB*. The linguistic variables for describing each risk parameter can vary depending on the situation, with reference to the relevant studies in the literature. Following the formation of the FRB with belief structure in FMEA, certain set of rules are followed. For example:

Rule 1: If L is Very Low, C is Very Low, P is Very Low and I is Very Low,

Then R is Very Low with a 100% DoB, Low with a 0% DoB, Medium with a 0% DoB and High with a 0% DoB

Rule 2: If L is Very Low, C is Very Low, P is Very Low and I is Low,

Then R is Very Low with a 75% DoB, Low with a 25% DoB, Medium with a 0% DoB and High with a 0% DoB.

Rule 3: If L is Very Low, C is Very Low, P is Very Low and I is Medium,

Then R is Very Low with a 75% DoB, Low with a 0% DoB, Medium with a 25% DoB and High with a 0% DoB.

Rule 3: If L is Very Low, C is Very Low, P is Very Low and I is High,

Then R is Very Low with a 75% DoB, Low with a 0% DoB, Medium with a 0% DoB and High with a 25% DoB.

From the above *DoB* rationing, it suggests that a proportion method is employed to rationalise the *DoB* distribution. This further explains that the *DoB* belonging to a particular grade in the THEN portion is calculated by dividing the number of the risk parameters, that receive the same grade in the IF portion by Four (4).

For example, in Rule 1, the number of the risk parameters receiving the Very Low grade in the IF portion is four. The DoB belonging to Very Low in the THEN portion is therefore computed as 100% (4/4 = 100%). In Rule 2, the numbers of the risk parameters receiving the Very Low and Low grades in the IF portion are three (3) and one (1), respectively. The *DoBs* belonging to Very Low and Low in the THEN portion are therefore 75% (3/4 = 75%) and 25% (1/4 = 25%). It can be formed as follows, see Equation 3.2:

$$DoB_h = \frac{\sum_{j=1}^{r} DoB_{hx}}{r} \tag{3.2}$$

where, h^{th} represents the linguistic terms number $(h = 1, \dots, 4)$

r represents the total number of the inputs' attributes, and

x represents an individual input's attribute.

For the benefit of this model application, Equation 3.2 can be expressed further as:

$$DoB_h = \frac{\sum_1^4 DoB_{h1} + DoB_{h2} + DoB_{h3} + DoB_{h4}}{4} \tag{3.3}$$

Likewise, the FRB used in AMSSO containing 256 rules (4×4×4×4) with a rational *DoB* distribution can be achieved and shown in Appendix 1 and partly represented in Table 7.

Table 7: The developed FRB with a belief structure for AMSSO

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
No	(L)	(C)	(P)	(I)	V.Low (R1)	Low (R2)	Medium (R3)	High (R4)
1	V.Low (L1)	V.Low (C1)	V.Low (P1)	V.Low (I1)	1	0	0	0
2	V.Low (L1)	V.Low (C1)	V.Low(P1)	Low (12)	0.75	0.25	0	0
3	V.Low (L1)	V.Low (C1)	V.Low (P1)	Medium (I3)	0.75	0	0.25	0
4	V.Low (L1)	V.Low (C1)	V.Low (P1)	High (14)	0.75	0	0	0.25
5	V.Low (L1)	Low (C2)	V.Low (P1)	V.Low (I1)	0.75	0.25	0	0
.	…	…	…	…	…	…	…	…
253	High (L4)	Medium (C3)	High (P4)	High (I4)	0	0	0.25	0.75
254	High (L4)	Medium (C3)	Medium (P3)	V.Low (I1)	0.25	0	0.5	0.25
255	High (L4)	High (C4)	Medium (P3)	Low (I2)	0	0.25	0.25	0.5
256	High (L4)	High (C4)	High (P4)	High (I4)	0	0	0	1

3.4.1.3 Identifying all potential and significant hazard events in AMSSO

The knowledge for identifying all significant hazards was drawn from the literature review and Experts' judgement. The literature review reveals that the Arctic oil and gas development and transportation involve significant risks caused by the unique features of this region, such as ice, severe operating conditions, unpredictable climatic changes, and remoteness (Khan et al., 2018). In addition, the performance of vessel systems worsens in harsh environments, which as a result increases the risk of collision (Khan et al., 2018). Khan et al. (2014) identified multiyear sea ice, extremely low temperatures, ice-ridges, and pack ice as the chief cause of the growing rate of ship accidents in the Arctic region.

Other literature, points out that a huge portion of Arctic waters are uncharted and according to Rear Admiral Gerd Glang, Director of the NOAA Office of Coast Survey, estimates it would take over 100 years to chart Alaska's Arctic coastline (Clark and Ford, 2017, Mollitor, 2018) due to insufficiently available navigation technologies (Mollitor, 2018). Human error is not left off the list of the significant risk factors in AMSSO (Rothblum, 2000). Li et al. (2012) reviewed 87 project reports and academic research papers to analyse consequences and frequency-based risk estimation models independently. They claim that human error is one of the highest significant risk factors in offshore ship operation and recommend more research in this field.

In the search for expert knowledge input, a pre-elicitation meeting was organised in September 2016 with the research Directors of Studies (DoS) and two-supervision team. The goals of the meeting were 1) selection of experts mainly from Arctic countries to contribute their knowledge both in hazard identification and in the quantitative risk analysis phase, and 2) setting out the important questions that would be used to seek their subjective opinion. The experts selected, based on their experience in Table 8, have primary experience in Arctic voyages and/or AMSSOs for over 10 years.

After a series of contacts with concerned experts and a careful literature review, a list of 48 hazard events was identified in the AMSSO Ship-Ice collision accident model. Further investigation was carried out to screen the hazard events based on their likelihood, consequences severity, hazard detection probability, and the impact of hazard to the operation. This further screening resulted in 21 hazard events in AMSSO. Consequently, a clustering technique mentioned in section 2.11.2 is introduced to show the hierarchical clustering of the 21 significant hazard events and their dependencies. The graphical view of the events' dependency is shown in Figure 20, and the risks' grouping is represented in Table 9.

Table 8: Expert's knowledge and experience

Experts	Company	Experience	Arctic region
A	A leading marine geophysical services company in Norway	6-10 years as an Arctic shipping stakeholder	The Norwegian Arctic
B	A leading marine geophysical services company in Norway	11-20 years as an Arctic seismic survey crew	Canadian, Greenland, Norwegian Arctic
C	A leading University in China	6-10 years as an Arctic risk management researcher	Canadian, Greenland, Norwegian Arctic
D	A leading marine geophysical services company in Norway	21 years and above as an Arctic seismic survey crew	Greenland, others including the Antarctic
E	A leading University in Norway	6-10 years as an Arctic risk management researcher	The Norwegian Arctic

Table 9: Risk factors and associated hazard events in AMSSO risk model

Risk group 1	S/N	Risk group 2 (Risk Factor)	S/N	Risk group 3	Source	Result
Ship-Ice Collision	A1	Risk related to the Vessel navigation system	B1	Limited radio communication	(Khan et al., 2018), (Kum and Sahin, 2015)	Loss
			B2	Limited sophisticated electronic navigation equipment (such as radar, sonar, infrared, and microwave radiation sensors onboard satellite)	(Kum and Sahin, 2015), (Kujala et al., 2009)	Loss
			B3	Failure in establishment and maintenance of external aids to navigation	(Sahin and Kum, 2015)	Loss
			B4	Poor ice chart (Not updated)	(Mollitor, 2018)	Grounding Sinking

Risk group 1	S/N	Risk group 2 (Risk Factor)	S/N	Risk group 3	Source	Result
	A2	Risk related to vessel operational system	B5	Faults in winch/ cable		Halt operation,
			B6	Insufficient manoeuvring characteristics of the vessel not specifically built for ice breaking or quick manoeuvring for rapid change of ice conditions.	(Serdar and Bekir, 2015)	Collision, Grounding
			B7	Insufficient hull strength	Expert	Flooding, Sinking
			B8	Operational incapacitation of other vessels (such as icebreaker, tugs)	Expert	Collision
Ship-Ice Collision	A3	Risk related to Weather	B9	Snow accumulation on the seismic equipment and superstructures	(Serdar and Bekir, 2015)	Sinking, Halt operation
			B10	Poor visibility as a result of fog, prolonged Polar night	(Kujala et al., 2009), Expert	Collision
			B11	Machinery seize up with low temperatures	(ABS Advisory, 2014b), (Marchenko et al., 2015)	Collision, Halt operation
			B12	Seasickness caused by erratic motion of the vessel	(Serdar and Bekir, 2015)	Injury, Halt operation
	A4	Risk related to ice	B13	Ice restrictions which affect the vessel's movement and force to change direction and speed	(Canadian Coast Guard, 2013)	Collision

Risk group 1	S/N	Risk group 2 (Risk Factor)	S/N	Risk group 3	Source	Result
			B14	Pieces of floating multiyear ice/icebergs causing machinery damage	(Canadian Coast Guard, 2013)	Collision
			B15	Streamer, air hose entangled in ice	Expert	Halt operation
	A5	Risk related to human factor	B16	Practical incompetency for duty such as experience, skills, local knowledge of waters, usage of devices	(Li et al., 2012)	Grounding, Sinking, Loss, Sinking
Ship-Ice Collision	A5	Risk related to human factor	B17	Inappropriate design of task or operation such as night navigation, route planning, anchoring etc	Expert	Collision
			B18	Available warning mechanism is insufficiently developed and used	(Serdar and Bekir, 2015)	Collision
			B19	Workload-causing stress, fatigue, bad mood as a result of very short daylight	Expert	Collision, injury
			B20	Lack of situation awareness	Expert, {Lawrence P Hildebrand, 2018 #304}	Grounding, Sinking, Collision

Risk group 1	S/N	Risk group 2 (Risk Factor)	S/N	Risk group 3	Source	Result
			B21	Inadequate communication	Expert, (Kum and Sahin, 2015)	Collision, Halt operation

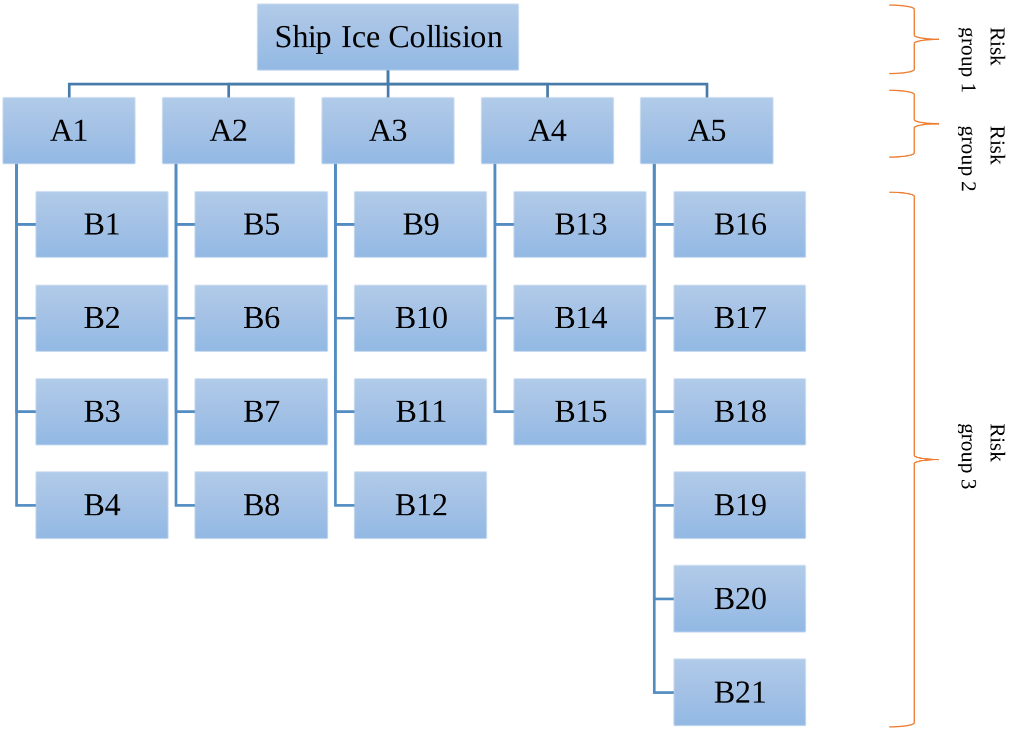

Figure 20: A Dendrogram of the dependable relationship of the 21 hazard events in AMSSO Ship-Ice Collision Risk Model

A1-A5, B1-B21 in Figure 20 are described in Table 9.

It can be observed that the interdependencies of the 21 hazard events are not considered. The main difficulty with the interdependencies of events is the definition of group-wise events. The problem is that some hazard events may not occur until the end of a stage. Each risk group is restricted to event time and only considered at a time point between groups. This approach also provides information suppose the 21 hazard events occurred sequentially. The risk group interval can easily be implemented in computer software that supports the random risk analysis style.

3.4.1.4 Develop a BN Model with a rational distribution of DoB in FRB

3.4.1.4.1 Rule aggregation for prior probability of Hazard events

Since there is a possibility of uncertainty in hazard event data, some event data may be inputted into the FMEA modelling using the described linguistic grades with *DoB*. This invariably means that several rules will be used in the risk analysis of a singular hazard event. These rules are capable of synthesising the connected *DoB* in the THEN portions of the several rules involved in the risk analysis. Alyami et al. (2019) and Yang et al. (2008a) buttressed the ability of BN to collate cluster or non-linear causal relationships, and model the *DoB* in the THEN portion of an FRB. In order to incorporate BN, the FRB established earlier will need to be represented first in the form of conditional probability. See, for instance, Rule 2 in Table 7, this can be represented thus:

Rule2: IF $Very\ Low\ (L1), Very\ Low\ (C1), Very\ Low\ (P1)\ and\ Low\ (I2),$

THEN $[(0.75, Very\ Low\ (R1)), (0.25, Low\ (R2)), (0, Medium\ (R3)), (0, High\ (R4))].$

This can be further expressed in the form of conditional probability as thus:

Given L_1, and C_1, P_1 and I_2, the probability of the risk evaluation for each linguistic term (Rh) where Rh (R_1 = Very Low, $R_2 = Low$, R_3 = Medium, R_4 = High) is (0.75, 0.25, 0, 0) or

$$p(Rh|L_1, C_1, P_1, I_2) = (0.75, 0.25, 0, 0) \qquad 3.4$$

Where "|" depicts conditional probability.

Concerned experts in AMSSO risk analysis can analyse a hazard event using their subjective judgements centred on primary observations with respect to the four risk parameters and their linked linguistic grades. Taking the mean of the *DoBs* assigned by multiple experts to the linguistic grades of each parameter supports the calculation of the prior probabilities: $p(L_i)$, $p(C_j)$, $p(P_k)$ and $p(I_l)$ of the four parent nodes, N_L, N_C, N_P, and N_I.

3.4.1.4.2 Bayesian Network mechanism

By means of a BN technique, the FRB constructed in FMEA of AMSSO Risk Analysis can be modelled and transformed into a five-node converging connection that contains the four parent nodes, that is, *L*, *C*, *P*, and *I* (parent nodes N_L, N_C, N_P, and N_I) and the child node R (child node N_R). Once the rule base has been transferred into a BN framework, then the rule-based risk inference for the failure (risk) criticality analysis will be simplified as the calculation of the marginal probability of the child node N_R from the four parent nodes, N_L, N_C, N_P, and N_I.

To marginalise R, the required conditional probability table of N_R, $p(R|L, C, P, I)$), can be found using Table 7. It represents a 4 × 4 × 4 × 4 table containing values of $p(R_h|L_i, C_j, P_k, I_l)$ (*h*, *i*, *j*, *k*, *l* = 1,…, 4). Whereas, the marginal probability of N_R can be calculated as:

$$p(R_h) = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{4}\sum_{l=1}^{4} p(R_h|\, L_i, C_j, P_k, I_l)p(L_i)p(C_j)p(P_k)p(I_l) \qquad 3.5$$

Where: R_h *(R_1= Very Low, R_2= Low, R_3= Medium, R_4=High)*

3.4.1.4.3 Utility functions for hazard events prioritization

The overall belief structure provides a wide-ranging view that displays the ratings and intervals for each hazard event evaluation with their assessed *DoBs*. In a practical sense, however, the risk ranking of hazards events cannot be easily solved by analysing their overall belief structures. Hence, all the belief structures need to be converted into expected risk scores of either 0 to1,or 0 to 10 or 0 to100, with 1 or 10 or 100 in the range being the highest critical score. The main aim of using a utility function is to prioritise the hazard events. A new risk (evaluated hazard event) prioritization index (also known as Risk Index (RI)) can be found using the Equation 3.6 (Chen et al., 2018):

$$\mathrm{RI} = \sum_{n=1}^{N} \beta_n \times u(H_n) \quad (3.6)$$

Where β_n= consequent belief degree, N denotes the number of linguistic terms, and utility $u(H_n)$ is taken as "0" for Very Low, "0.33" for Low, "0.66" for Medium, and "1" for High in RI calculation. The calculation of the RI using the utility functions can be simplified and represented in Table 10.

Table 10: Risk Index calculation

Hn	Very Low	Low	Medium	High
Vn	1	2	3	4
$u(H_n)$	$\frac{1-1}{4-1} = 0$	$\frac{2-1}{4-1} = 0.33$	$\frac{3-1}{4-1} = 0.66$	$\frac{4-1}{4-1} = 1$
β_n	27.39	26.23	25.83	20.55
$\sum_{n-1}^{n} \beta_n = 100$	27.39 + 26.23 + 25.83 + 20.55 = 100			
$\beta_n \times u(H_n)$	27.39 × 0	26.23 × 0.33	25.83 × 0.66	20.55 × 1
DoB	$\sum_{n=1}^{n} \beta_n \times u(H_n)$= 27.39 ×0 + 26.23 ×0.33 + 25.83 ×0.66 + 1 ×20.55 = 46.25			

3.4.1.4.4 Prioritisation of the HEs using the new FRBN benchmark risk

No industrial or engineering activity is entirely free from risk. Several stakeholders and regulatory bodies around the world require that risk levels be reduced to levels that are As Low As Reasonably Practicable, or "ALARP". The "ALARP region" lies herein between 0 and 8% as represented in Figure 21. The expressed-preference approach in Figure 21 utilised experts' opinions with the FRBN mechanism to obtain information about risk levels warranting mitigation action. The higher the value of RI for a hazard event, the higher the risk on an AMSSO.

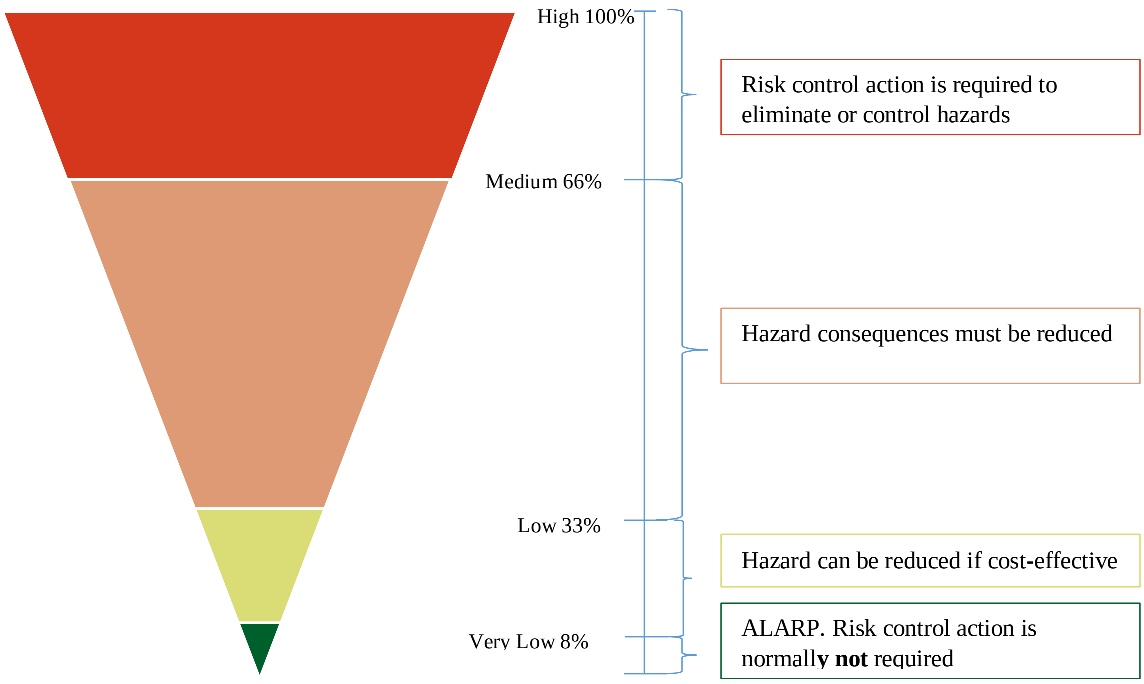

Figure 21: Tolerability of personal risk using FRBN benchmark risk

The 8% Very Low is obtained by adjusting this linguistic grade of "Very Low" to 100% (that is, the worst case of Very Low) in the FRBN risk model while keeping other linguistic grades to zero. The 33% Low is obtained by adjusting this linguistic grade "Low" to 100% (that is, the worst case of Low) in the FRBN risk model. This process is repeated for other risk levels to obtain 66% Medium and 100% High as shown in Figure 21.

Risk levels ≤ 8% in the developed benchmark risk would normally not require risk control action. Risk levels ≤ 33% would require risk control action if the cost/benefit ratio is < 1. Risk levels ≤ 66% and ≥ 100 must be reduced and prevented from occurring, as these fall within the intolerable regions of the benchmark risk.

3.4.1.4.5 Model Validation using sensitivity analysis techniques

Model validation involves processes and testing intended to verify that new models are performing as expected, in line with their design objectives (Clayton, 2016). Since this is the first time of applying FRBN in the subject area, it is important to validate the risk analysis model. Moreover, testing the newly developed risk model (FRBN-AMSSO) is important, especially in the involvement of subjective elements in the generated methodology (Yang et al., 2008a).

A more reliable validation method that is gradually gaining popularity in engineering risk management is sensitivity analysis. This method will be conducted to check the authenticity of the belief structures based on expert judgements. Checking the sensitivity in the FRBN method offers an analytical value judgment for the conclusions of risk evaluation (or RI). Checking the sensitivity of parameters is usually performed as a sequence of tests in which the modeller sets different parameter values to measure the changes caused by a change in the risk parameters (Alyami et al., 2019).

There are three possible axioms that can be used as a mechanism for validating the proposed FRBN model. These axioms can vary depending on the area of interest and are generally accepted as a rule of statements or as a principle that is accepted to be true with the system of "logic" defined and self-evident truth that needs no proof (Asuelimen et al., 2019, Yang et al., 2008a). The mechanism of the three axioms are stated below (Wan et al., 2019):

Axiom 1. A slight increase or decrease in the prior subjective probabilities of each input node should certainly result in the effect of a relative increase or decrease of the posterior probability values of the output node.

Axiom 2. Given the same variation of subjective probability distributions of each risk parameter in the antecedents, its magnitude of influence on the RI will remain consistent with their weight distributions.

Axiom 3. The total influence magnitudes of the combination of the probability variations from *x* attributes (evidence) on the values should always be greater than the one from the set of x - y ($y \in x$) attributes (sub evidence).

3.5 Trial application of the proposed FRBN Model

In order to carry out a trial application of the proposed model and to analyse the Ship-Ice Collision accident scenario in AMSSO, the five-step methodology presented in Section 3.4 is utilised.

3.5.1 Preparatory phase

This phase includes the selection of an oil field for investigation and the selection of appropriate experts that will contribute their knowledge and judgement in the real-world application of the FRBN model. The Greenland, Iceland and Norwegian Seas (GINS) is selected in this study to demonstrate the applicability of FRBN. The GINS or otherwise referred to as "Arctic Odden" is selected in this study because of its fair presence of ice throughout most periods of the year, vast amount of fisheries, oil & gas, and other hydrocarbon resources. (Seidov et al., 2013). This prospect project is perceived as a rather busy region of the Arctic Circle.

The characteristic of the GINS can be defined as a semi-enclosed sea of the Arctic Ocean, to which it is mainly connected at oceanic depths through the Fram Strait (see Figure 22). The large-scale circulation of the GIN Sea is ruled by the East Greenland Current flowing southward to the west, the Norwegian Atlantic Current flowing northward to the east, and the Icelandic Current flowing southeastwardly alongside the frontal boundary with the Atlantic Ocean. Apart from the landfast ice of the Greenland Shelf, the ice cover consists of multiyear ice exported from the Polar Sea and seasonal ice formed within the GINS (Hopkins, 1990). Arrows in the Figure 22 show current flow in and out of the GIN Sea.

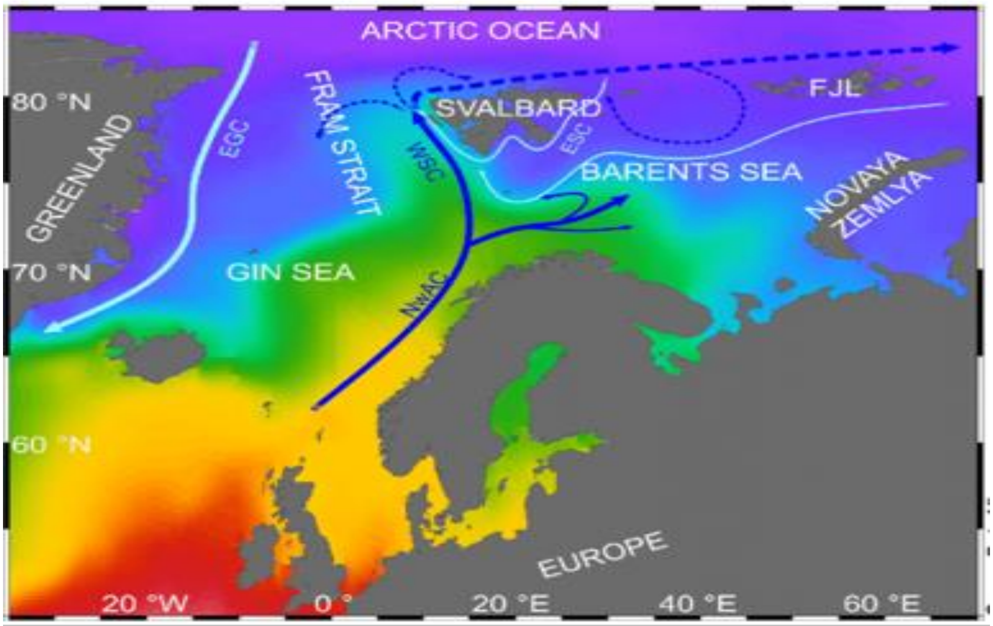

Figure 22: Main ocean currents around the GIN Sea from 1955 to 2012 (Locarnini et al., 2013)

It is important to note that a vast amount of ice in the GINS persists from a few days to several months. The earliest appearance can be found in December, the latest in April, almost equally distributed within these months (Niederdrenk and Mikolajewicz, 2016).

The goal of the investigation has been presented in section 3.4.1. For the trial application of FRBN, a questionnaire was developed from the pre-elicitation meeting that was held in September 2016. Experts that were contacted with the questionnaire were selected based on their experience in Arctic Shipping, with more emphasis on the AMSSO in the selected prospect region. Table 8 shows the background and experience of the selected experts.

3.5.2 Establish an FRB with belief structure in FMEA

The FRB developed in Section 3.4.1 is used in this study. The FRB offers a rational distribution of the *DoB* as well as transparency and simplicity in the risk parameters. Its strength lies in its ability to increase flexibility in the definition of the *DoB* distributions in individual rules. In addition, to allow an easy validation by experts and the option of inserting additional rules based on the experts' memories and experience, especially in areas that have not been covered in analysis.

3.5.3 Identifying all potential and significant hazard events in the Ship-Ice Collision risk model in AMSSO

Literature review (see 2.10.2 and 3.4.1.3), and experts' knowledge and experience (see Table 8 for experts' background and experience) constituted the basis for identifying all significant hazard events in the Ship-Ice Collision risk model in AMSSO. Some of the existing hazard events identified in this study were reviewed specifically for the GINS prospect project characteristics, and listed as follows:

B1: Limited radio communication;

B2: Limited sophisticated navigation;

B3: Failure in the establishment of external aid;

B4: Poor ice chart;

B5: Faults in winch/ cable;

B6: Insufficient manoeuvring characteristic;

B7: Insufficient hull strength;

B8: Operational incapacitation of other vessels;

B9: Snow accumulation on seismic equipment;

B10: Poor visibility as a result of fog;

B11: Machinery seize up with low temperatures;

B12: Seasickness caused by erratic motion of the vessel;

B13: Ice restrictions, which affects the vessel's movement;

B14: Pieces of floating multi-year ice/icebergs causing machinery damage;

B15: Streamer entangled in ice;

B16: Practical incompetency of duty;

B17: Inappropriate design of task;

B18: Available warning insufficiently used;

B19: Workload causing stress;

B20: Lack of situational awareness;

B21: Inadequate communication.

In the developed questionnaire from the series of pre-elicitation meetings, the experts are requested to evaluate each of the 21 significant hazard events identified with respect to the four risk parameters using their matched linguistic grades and *DoBs*.

3.5.4 Develop a BN Model with a rational distribution of *DoB* in FRB

3.5.4.1 Rule aggregation for HEs prior probability

The feedback received from the five experts is initially combined (by conducting an average calculation) to yield hazard events' input values in terms of the four risk parameters. The averaged hazard events' input is then used in the new FRBN in Section 3.4 based on the new FRB with rational *DoBs* in Section 3.4.1 to prioritise the 21 hazard events.

Given Equation 3.4, the prior probabilities of the four nodes in BN based FMEA can be attained. For example, to analyse B1, limited radio communication, the hazard event's input values in terms of the four risk parameters are gleaned from the expert's knowledge, then the prior probabilities of the four nodes can be calculated, as shown in Table 11.

Table 11: Prior Probabilities of NL, NC, NP, and NI when analysing Ship-Ice Collision in GNIS AMSSO

Hazards	Experts	Likelihood				Consequence severity				Probability of failure undetected				Impact of failure to operation			
Limited radio communication		VL	L	M	H	VL	L	M	H	VL	L	M	H	VL	L	M	H
	A	30	30	20	20	10	30	50	10	40	50	10	0	10	20	50	20
	B	0	20	50	30	80	20	0	0	80	20	0	0	0	30	70	0
	C	20	30	30	20	30	40	30	10	10	10	50	30	50	30	20	0
	D	60	20	20	0	40	30	20	10	50	50	0	0	10	40	40	10
	E	50	30	0	20	0	30	70	0	70	30	0	0	0	0	20	80
	GM probability	**28**	**26**	**23**	**19**	**25**	**29**	**29**	**10**	**41**	**27**	**14**	**12**	**14**	**24**	**35**	**17**
	Av Prior probability	**32**	**26**	**24**	**18**	**32**	**30**	**34**	**6**	**50**	**32**	**12**	**6**	**14**	**24**	**40**	**22**

Here, "geometric mean (GM)" values were compared with "mean (Av)" values to account for zero value input, but there was not much difference between the "geometric mean" and the calculated "mean" values, so, the "mean" values are preferred for consistency throughout the prior probabilities calculations.

3.5.4.2 Bayesian reasoning mechanism

Once the earlier identified probabilities of the four nodes in BN based FMEA are obtained in Table 11, it can be converted to obtain $p(Rh|L_i, C_j, P_k, I_l)$ and the risk analysis of the Ship-Ice Collision from the data set in Table 11 can be calculated by the Equation 3.5 as *Rh* (*R_1= 31.36% Very Low, R_2= 28.11% Low, R_3= 27.00% Medium, R_4= 13.53% High*).

The calculation can also be computerised using the Hugin software (Hugin Lite 8.6 Version) (Andersen et al., 1989) as represented in Figure 23.

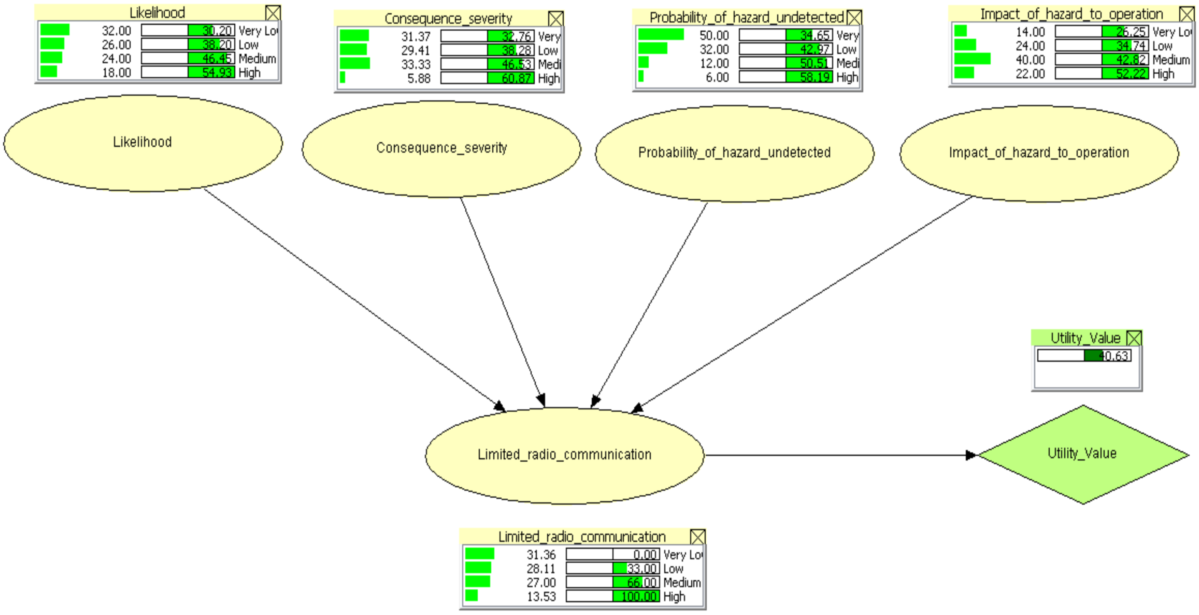

Figure 23: Risk evaluation of B1 in the Ship-Ice Collision risk model using Hugin software

3.5.4.3 Utility functions for hazard events prioritization in the Ship-Ice Collision model in AMSSO

The result of the computerised calculation represented in Figure 23 can be explained as the risk analysis of "Limited radio communication" in Ship-Ice Collision model in AMSSO being *31.36% DoB Very Low, 28.11% DoB Low, 27.00% DoB Medium, and 13.53% DoB High*. Next, Equation 3.6, and Table 10 is used to calculate the utility value or risk index value for B1 in the Ship-Ice Collision model as 40.63%.

Similarly, the risk-ranking index of all the 21 hazard events can be obtained from the Hugin computer application, and the results herein presented in Table 12.

Table 12: The risk-ranking index evaluation of the 21 hazard events

S/N	Accident categories	Risk evaluation				Equivalent Rank total
		Very Low	Low	Medium	High	
1	Limited radio communication	31.36	28.11	27.00	13.53	40.63
2	Limited sophisticated electronic navigation equipment	26.41	24.18	25.19	24.21	48.82
3	Failure in establishment and maintenance of external aids to navigation	19.10	29.97	32.63	18.31	49.73
4	Poor ice chart (Not updated)	18.61	34.06	29.51	17.82	48.54
5	Faults in winch, cable	20.39	30.09	27.60	21.92	50.07
6	Insufficient manoeuvring characteristics of vessel ….	26.74	24.52	23.31	25.44	48.91
7	Insufficient hull strength	28.17	28.30	19.73	23.80	46.16
8	Operational incapacitation of other vessels	29.06	27.25	22.38	21.31	45.08
9	Snow accumulation on the seismic equipment and superstructures	28.79	27.15	23.82	20.25	44.93
10	Poor visibility as a result of fog, prolonged polar night	13.37	24.46	31.61	30.56	59.49
11	Machinery seize up with low temperatures	24.24	26.33	24.48	24.95	49.80
12	Seasickness caused by erratic motion of the vessel	36.12	30.20	25.76	07.92	34.89

S/N	Accident categories	Risk evaluation				Equivalent Rank total
		Very Low	Low	Medium	High	
13	Ice restrictions that affect the vessel's movement..	23.41	26.25	26.03	24.31	50.15
14	Pieces of floating multi-year ice/icebergs causing machinery damage	22.53	29.11	25.65	22.72	49.25
15	Streamer, Air hose entangled in ice	25.88	29.33	28.59	16.21	44.75
16	Practical incompetency for duty such as experience	16.80	34.63	35.68	12.89	47.86
17	Inappropriate design of task or operation such as night navigation etc	19.38	30.35	31.45	18.82	49.59
18	Available warning mechanism insufficiently developed and used	20.15	34.35	28.43	17.07	47.17
19	Workload causing stress, fatigue	16.07	27.45	32.72	23.76	54.41
20	Situation awareness and bad decision-making	14.78	23.75	27.85	33.62	59.84
21	Inadequate communication	16.24	27.12	31.83	24.80	54.76

3.5.4.4 Prioritising the hazard events and comparing the result with benchmark risk.

Upon the application of FRBN in AMSSO risk analysis, the significant hazards can be prioritised in the following manner (top-down) in Table 13. Following this, is a comparison between the FRBN results with the newly developed benchmark risk. Such comparison invariably suggests a very important risk-analytical technique for risk decision-making (Piegorsch, 2010). The concept of risk prioritisation and the new FRBN benchmark risk evolved partly from the awareness that absolute safety is generally an unachievable goal (Piegorsch, 2010), and hence, certain risk levels can be deemed tolerable.

From the comparison, it is revealed that the analysed risks of the 21 hazard events are well above the tolerable region of the developed benchmark risk in Figure 21, hence further risk decision making is required.

Table 13: Prioritisation of AMSSO risks in GIN Sea

Hazard Event	Equivalent Rank total	Risk Ranking Number (RRN)
Situation awareness and bad decision-making	59.84	1
Poor visibility as a result of fog, prolonged polar night	59.49	2
Inadequate communication	54.76	3
Workload causing stress, fatigue	54.41	4
Ice restrictions that affect the vessel's movement..	50.15	5
Faults in winch, cable	50.07	6
Machinery seize up with low temperatures	49.80	7
Failure in establishment and maintenance of external aids to navigation	49.73	8
Inappropriate design of task or operation such as night navigation etc	49.59	9

Hazard Event	Equivalent Rank total	Risk Ranking Number (RRN)
Pieces of floating multi-year ice/icebergs causing machinery damage	49.25	10
Insufficient manoeuvring characteristics of the vessel	48.91	11
Limited sophisticated electronic navigation equipment	48.82	12
Poor ice chart (Not updated)	48.54	13
Practical incompetency for duty such as experience	47.86	14
Available warning mechanism insufficiently developed and used	47.17	15
Insufficient hull strength	46.16	16
Operational incapacitation of other vessels	45.08	17
Snow accumulation on the seismic equipment and superstructures	44.93	18
Streamer, Air hose entangled in ice	44.75	19
Limited radio communication	40.63	20
Seasickness caused by erratic motion of the vessel	34.89	21

3.5.4.5 Model Validation using sensitivity analysis techniques

The outcome of this new model having four variables (Very Low, Low, Medium and High) needs to be verified against its effective application. In addition, the reliance and verification of the outcome of the FRBN can be carried out using validation techniques such as sensitivity analysis.

3.5.4.5.1 Sensitivity Analysis (SA)

SA is the study of the relative importance of different input factors on the model output (Saltelli et al., 2000). SA validates the sensitivity of the parameter in the model in order to confer confidence in the use of the new methodology in a real-world application. In this section, the model with its simulation as illustrated in Figure 23 would be verified with the aim of satisfying the three axioms involved in the process described in Section 3.4.1.4.5. The examination of the model is conducted for "B1" in the Ship-Ice Collision risk model as follows:

- Axiom 1: An increase in a risk parameter node (for example "likelihood") prior probability value of an event's linguistic variable (for example "high"), will result in an increase in the B1 utility value. For example, an increase of B1's likelihood node prior probability from 18 to 100% resulted in an increase of its utility value from 40.63 to 54.93% as represented in Figure 24. Utility value is referred to as the final risk estimation of an event.

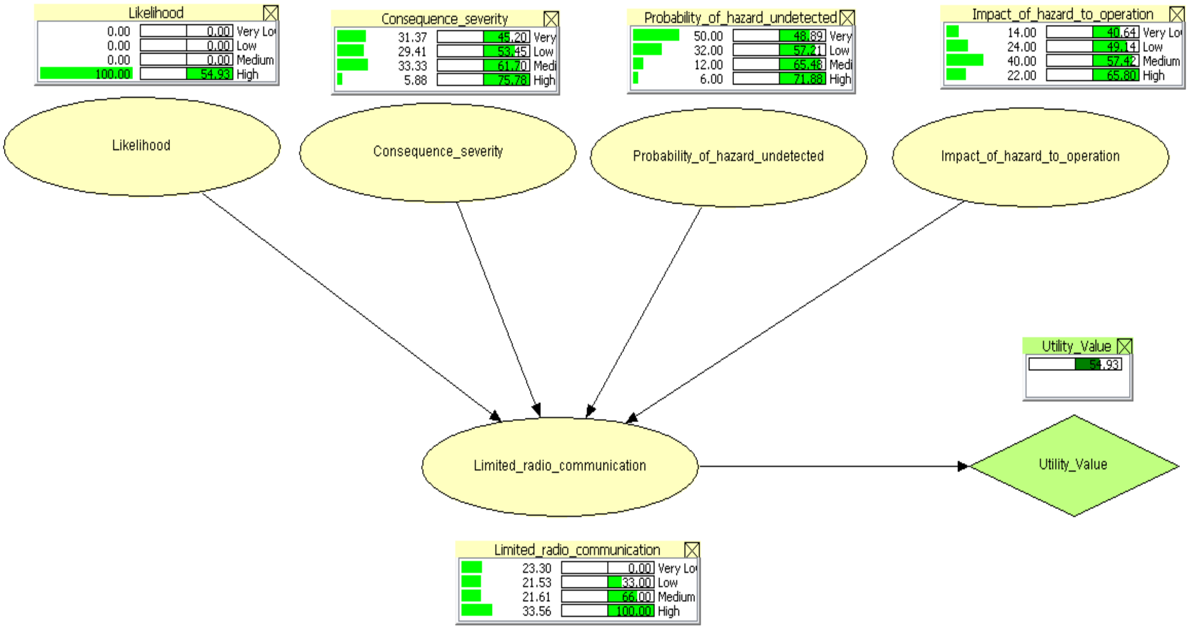

Figure 24: Model validation by adjusting B1's likelihood to 100% "High"

- Axiom 2: A further increase in the risk parameter nodes (for example a combination of “likelihood” and “consequence severity”) prior probabilities of an event’s linguistic variables (for example “high”), will result in a much higher utility value compared to the utility value from a singular increase in risk parameter node prior probability of an event’s linguistic variable. For example, an increase of B1’s likelihood and consequence severity nodes from 18 to 100% “High” and 6 to 100% “High” respectively resulted in a much higher utility value of 75.78% as shown in Figure 25 compared to the utility value obtained from a singular increase in the prior probability of likelihood node in Figure 24.

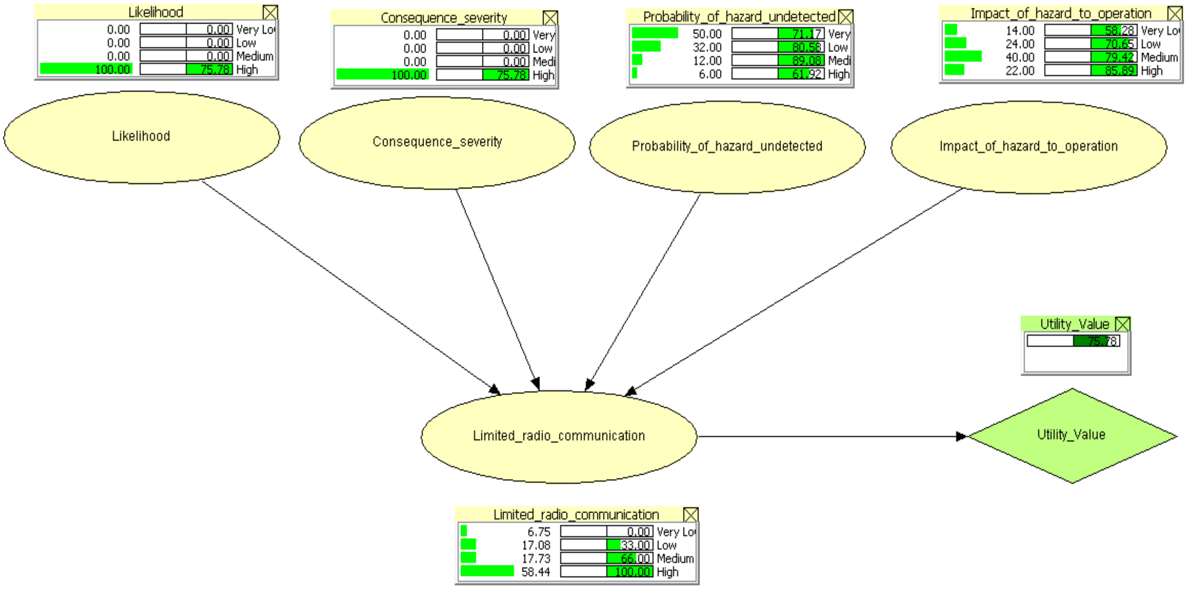

Figure 25: Model validation by adjusting B1's "likelihood" and "consequence severity" to 100% "High"

- Axiom 3: Further to Figure 25, an additional increase in the risk parameter nodes' prior probabilities of an event's linguistic variable, (for example "high") will result in yet, a further increase in the utility value greater than the utility value obtained from the increase in the combination of two risk parameter nodes' prior probabilities. For example, an increase of B1's likelihood, consequence severity and impact and operation nodes from 18 to 100% "High", 6 to 100% "High" and 22 to 100% "High" respectively, resulted in a much higher utility value of 85.89% shown in Figure 26 compared to the utility value attained from the two-combination increase in the prior probabilities shown in Figure 25.

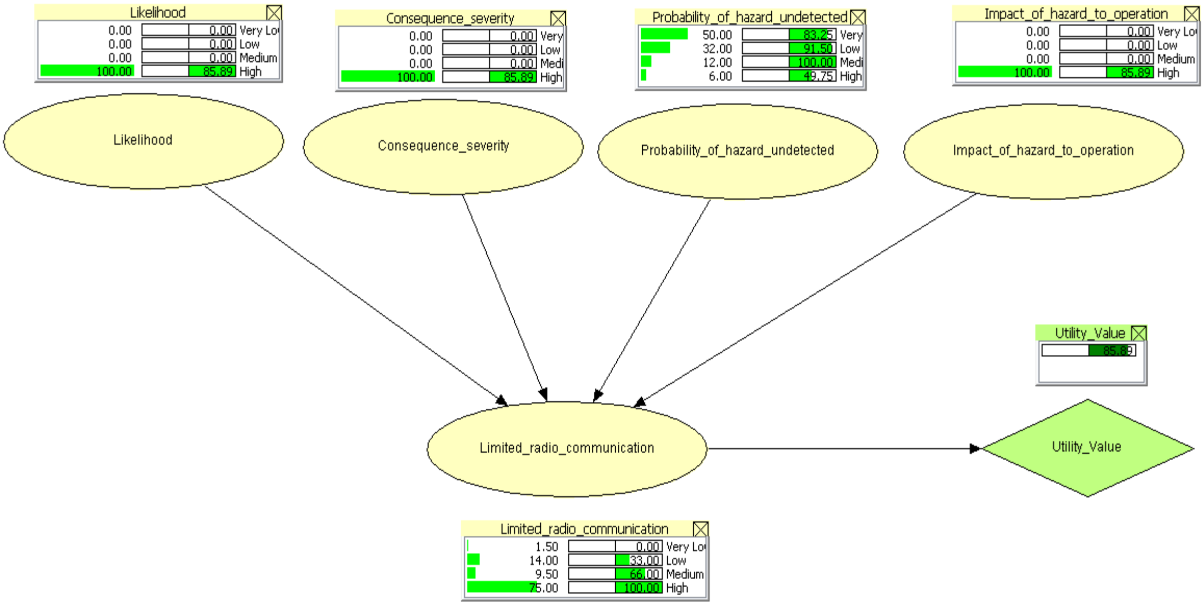

Figure 26: Model validation by adjusting B1's "likelihood", "consequence severity" and "impact to operation" to 100% "High"

From the SA, it is revealed that, as risk criticality increases in an event (for example an event with 100% "high"), the utility value also increases as demonstrated in Figures 24 to 26, and as the risk criticality is low in an event, the utility value is also observed to be relatively low. These observations are shown in a couple of tests represented in Figures 27 and 28.

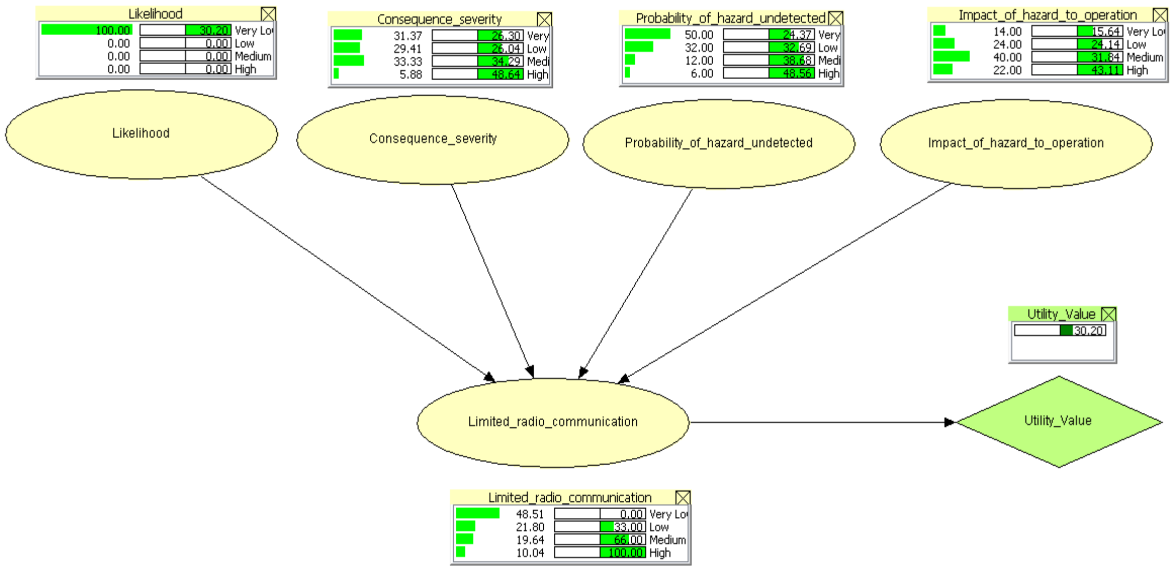

Figure 27: Model validation by adjusting B1's likelihood to 100% "Very Low"

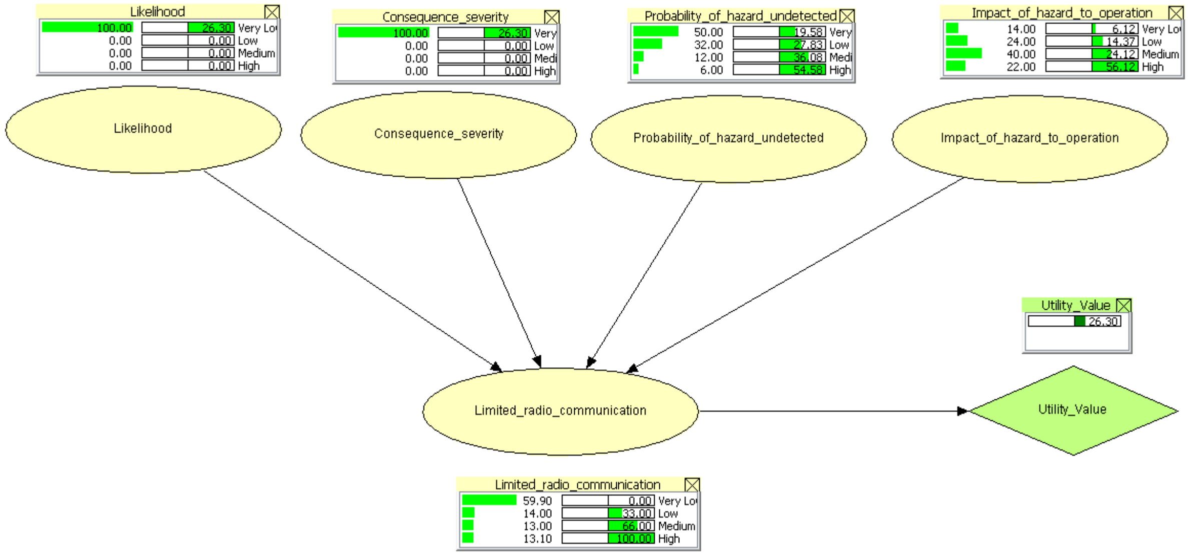

Figure 28: Model validation by adjusting B1's "likelihood" and "consequence severity" to 100% "Very Low"

These revelations go further to buttress the fact that the output node is sensitive to any change in the prior probability values of the input nodes. Consequently, this series of test validates the results and the application of FRBN in a real-world application, hence the FRBN risk-based methodology can be relied on in complex risk analysis.

3.6 Results and Discussion

From the result of the FRBN risk analysis in Table 13, the ranking of the AMSSO hazard event in GINS indicated that B20 (lack of situation awareness) has the highest contribution (59.84%) to cause major disruption to Arctic marine seismic survey activity and endanger the safety of the crew, assets and the environment.

AMSSO in the GNIS and within the Arctic Circle is a challenging task (Björn Heyn et al., 2018) and several major oil giants such as Statoil recognise this fact (Henderson and Loe, 2016). This statement is valid as it is evidenced that none of the hazard events identified in section 3.5.3 fell within the ALARP region of the newly developed FRBN "benchmark risk" in Figure 21. This implies that more attention needs to be focussed on preventing a "lack of situational awareness" from occurring to prevent Ship-Ice Collison and financial loss in AMSSOs.

B10 (Poor visibility as a result of fog, prolonged polar night) has the second highest contribution of 59.49% to cause major disruption to Arctic marine seismic survey activity and thus cause harm to people, environment and the seismic survey assets. Down the risk ranking hierarchy in Table 13 is B12 (Seasickness caused by erratic motion of the vessel) having the lowest contributing factor of 34.89%. Although this falls slightly over the ALARP region of the FRBN benchmark risk, less effort compared to B20 can be made to curtail this risk as recent studies show that seasickness decreases between the ages of 21 and 40 years (McIntosh, 1998). Meaning if younger crewmembers are involved in AMSSO, the risk of seasickness can be reduced to some extent.

Human factor remains a major concern in AMSSO and in general shipping operation. From the result of Table 13, it is observed that the human factor appeared in the first five-hazard event risk ranking. Therefore, it is worth mentioning that to reduce or prevent Ship-Ice Collision, the L, C, P and I risk parameters of all hazard events must be reduced, and special attention must be paid to B20 and human factors in general.

3.7 Conclusion

The benefits of the use of the clustering dendrogram in this chapter to depict the interactions among the hazard events, and the introduction of expert knowledge cannot be overemphasized, especially when sufficient accident record data is lacking or incomplete. The dovetailing of the FMEA and Bayesian Network approach with fuzzy logic, otherwise termed FRBN, gives an effective tool to process subjective judgement for characterising 21 critical hazards, and prioritising these hazard events in FMEA under high uncertainty.

The distribution of the four linguistic terms (Very Low, Low, Medium and High) over the four risk parameters (L, C, P and I) dilutes the risk of biased judgement. The validation of the FRBN model reveals its reliability in real life scenario. It also reveals that the highest and lowest cases of linguistic grades (Very Low and High) have a dominating effect on the resultant risk score, as seen in Figures 24 to 28. This new model is simple to compute and allows new hazard events to be introduced without collapsing the ongoing analysis.

Moreover, this new model provides a powerful risk evaluation tool for Arctic shipping risk management. This new model also highlights its advantages in facilitating risk analysis from the design stage of a system to its operation when being suitably tailored for use.

The work herein also recognises that other major concerns in AMSSO, such as legal, managerial, and natural and political factors can be investigated in a similar way in order to provide a panoramic view on Arctic oil and gas E&P lifecycle. It is, therefore, necessary to determine which of the 21 hazard events has more risk influence on the global safety performance of AMSSO. The risk influence of the 21 hazard events and the measurement of the global safety performance of the Ship-Ice Collision accident scenario will be determined in the next Chapter.

Chapter 4– An investigation into the global safety performance and risk influence of hazard events on the ship-ice collision model in AMSSO

Overview

This chapter examines the risk influence of the 21 hazard events earlier analysed locally in Chapter 3. To ascertain the risk influence of each hazard event on the Ship-Ice Collision model, a global RI of Ship-Ice Collision model in AMSSO is investigated.

A novel method is adopted to achieve this investigation – by incorporating an FRBN developed in chapter 3 with AHP and ER in a complementary manner. The former with the AHP provides a realistic and flexible method to define input hazard data and to determine the relative weights of individual hazard event at the third and second level respectively on the risk dendrogram developed in Chapter 3. The latter is used to aggregate both the hazard events at the bottom level and the corresponding risk factors in the upper levels of the risk dendrogram, thereby producing the global RI of Ship-Ice Collision. This novel method has the benefit of accounting for uncertainties existing in the measurement of the global RI of the Ship-Ice Collision model.

Thus, allowing dynamic risk-based decision support in AMSSO from a systematic perspective. The novel feature of the proposed method provides a new sensitivity analysis method to rank the hazard events by taking into account their specific RIF. The empirical results reveal that the qualitative and quantitative hybrid approach is capable of dealing with uncertainties in risk and hazard data; hence, its application to a real-world scenario can be reliable.

4.1 Introduction

The risk analysis carried out in Chapter 3 has revealed the need to measure the RIF of each hazard event of AMSSO in the studied GINS region. It is worth noting that the commercial extraction of hydrocarbon resources in the prospect project – GIN Sea–, is somewhat in this stage at an infancy level (Sydnes et al., 2017). Therefore, the operability and safety of the seismic survey operation in the prospect project and the Arctic region need to be investigated and measured. The global safety measurement of Ship-Ice Collision accident case in AMSSO generally plays an important role in improving seismic data and safeguarding lives, assets and the environment.

Given the task of assessing the RIF of each hazard event and the measurement of the RI of Ship-Ice Collision in AMSSO, certain questions, such as "what to measure" and "how to measure" can be tricky since these questions have not been attempted in AMSSO risk analysis. Although the Polar Code through the IMO has made efforts in mitigating risks in the Arctic marine and offshore domain, experts argue that activities in the Polar region are still very risky and hence, the Polar Code has not done enough to ensure safety in Arctic operations (CBC News, 2015).

The Polar Code entered into force on January 1, 2017 and was amended on July 1, 2018. With the recent rules and amendments, there is not even a guarantee that the recent changes in the Polar Code rules will be adhered to (The Guardian Newspaper, 2014). It becomes even more important to develop an RI value for AMSSO in the prospect GNI Sea – if the RI value falls in the intolerable region of the FRBN benchmark risk –, to allocate resources for risk control, and for a continued safe and efficient AMSSO. The RI measurement carried out in this chapter will also support the Polar Code and other private regulatory bodies to curb the envisaged high risks in AMSSO.

This chapter develops a conceptual AMSSO safety measurement model that represents a stout performance measurement tool and provides a diagnostic instrument to Arctic oil and gas explorations flexibly and economically. It is worth mentioning that the need and importance of measuring a system's safety lie in the fact that decision-makers are generally concerned in estimating the riskiness of a system for resource planning, inventory management, development of realistic policies for age replacement, and logistics support (Alyami, 2017).

Estimating the RI or safety level in AMSSO involves a thorough assessment of both the complexities and the uncertainties in the Arctic system. The arctic system herein represents the environment, assets and the operation. Arriving at a specific RI is usually dependent on multiple attributes. Moreover, the estimation will take into account inherent data uncertainties that are unavoidable in AMSSO contexts.

Data (hazard information) uncertainty mainly arise from the lack of primary observation and the poor accident statistics record. Data uncertainty is a key issue in estimating risk or safety level in any engineering system. Other key issues that are considered in this study are 1) the probability of an incorrect assessment technique; 2) various risk parameters and stochastic values that exist in measurement; 3) the various hazard events and risk factors in estimation and 4) shortage of experts due to the insufficient primary observation of events.

However, previous risk researches have scantily dealt with uncertainties and complexities in a multifaceted system, albeit, knowledge from past studies such as port system (Alyami et al., 2019), supply chain system (Yang et al., 2010), hydrometeorological ensemble forecasting (Kavetski, 2019), and et cetera, will be incorporated herein to deal with uncertainties in risk and safety measurement.

Knowledge from past and complex risk researches reveal that to arrive at a more reliable RI measurement in a system, it is important to identify and synthesise the different alternatives with several criteria involved in the system (Gaonkar et al., 2010). The synthesising of the different alternatives and their corresponding criteria can be problematic in the practical sense. However, the difficulty in comparing different alternatives with several criteria in the practical sense has led to the development of MCDM under fuzziness. Fuzziness, which is a type of imprecision that is associated with fuzzy sets, has been mentioned and described in sections 2.10.3 and 3.2.2.

A more realistic approach to analyse the global RI of the Ship-Ice Collision model, to arrive at a value of the highest degree of desirability will be the integration of knowledge from MCDM techniques under fuzziness (Gaonkar et al., 2010). An early review of MCDM problems was carried out by Hwang and Yoon (Tzeng and Huang, 2011) and since then, several MCDM problems have been tackled by various academic researchers working in the area of decision-making in a fuzzy environment (Verma et al., 2007, Gaonkar et al., 2008). Cases of MCDM techniques being used with FL include MAUT, AHP, VIKOR and ER.

In contrast, the fuzzy MCDM methods do not solve missing or incomplete information as much as ER does (Gaonkar et al., 2010). The ER approach which is based on the logic of the Dempster-Shafer theory (capable of tackling missing or incomplete information) has proved to be more useful and practical when a decision problem under consideration includes multiple criteria, which are of both a quantitative and qualitative nature (Sönmez et al., 2002). The ER approach is also suitable for handling uncertain subjective judgments when considering multiple attributes.

Sönmez et al. (2001) and Xu and Yang (2003) utilised ER in their studies to arrive at a decision in the presence of multiple attributes and subjective judgements. Also, see Liu et al. (2005) and Xie et al. (2008). More recent papers such as Ahmadzadeh and Bengtsson (2017) and Asuquo et al. (2019) have utilized ER in solving multiple attribute problems involving subjective judgements.

ER has also been formulated, advanced, and finally implemented into a Windows-based software called Intelligent Decision Systems (IDS) (Xu and Yang, 2001). Literature has revealed that the ER approach supported by IDS, has significant advantages over conventional methods in helping to improve consistency, transparency, and objectivity in assessments (Xu and Yang, 2006). The ER approach supported by IDS also has the advantage of eliminating manual calculation errors in assessments.

Consequently, this Chapter proposes to develop an FMEA approach integrated with the ER technique capable of measuring the global RI of AMSSO. The ER can also be utilised with other MCDM techniques such as AHP. AHP is preferred in this study because of its suitability. The benefit of the use of ER with AHP is described in subsequent sections. Also, a proposed methodology for modelling the RI of AMSSO is elaborated in section 4.3.

The hybrid integration of FRBN with AHP and ER is then used in a practical case to measure the RI of AMSSO in a complementary way in section 4.4. The ER is utilised here to synthesise the evaluations of the various risk factors and the associated hazard events from the bottom to the top level in the hierarchy decision tree.

The novelty of this hybrid integration (FRBN-AHP-ER) approach lies in the fact that:

1. It for the very first time incorporates the risk impact of components to the whole system into the safety measurement of the ship-ice collision model;
2. It combines various uncertainty models, such as FRBN for hazards' risk estimation and ER-AHP for risk synthesis from components to system levels, systematically and;
3. It newly uses a "zero score" approach to quantify the RIF of each hazard event in a Ship-Ice Collision accident model. This is carried out to test both the sensitivity of the model and its compatibility with the FRBN risk-based model, as well as to prioritise the hazard events. The "zero score approach" is achieved by assigning a zero score or excluding each hazard event at a time from the analysis, and re-running the analysis. This approach reveals each hazard event's influence on the system's safety. From a theoretical viewpoint, the proposed hybrid method can be tailored for risk ranking of any large engineering system of comparable features (i.e. a hierarchical risk structure).

4.2 Research Background

4.2.1 A brief review of research on AHP

As mentioned earlier in section 4.1, MCDM techniques offer a proactive approach to measure the overall RI of AMSSO. To obtain a more reliable RI score or value using the ER approach, it is important to assign weights of risk criteria hierarchically (Song and Kang, 2016). In particular, there are more than a few techniques for deriving criteria weights in this approach. However, this could be a cognitively challenging task, subject to diverse biases, with the elicited values deeply dependent on the method of assessment.

In a bid to find the paramount technique for deriving criteria weights in the determination of the RI of the Ship-Ice Collision model, a literature review was carried out. To identify those journals/academic papers that gave the most valuable information, a search was carried out using the MCDM as a keyword in the search title and the abstract bar using the following databases: ScienceDirect, Elsevier, Springer, and IEEE Xplore. Results gathered included journal articles and conference proceedings pinpointing mainly on marine operations and management science.

The result was further screened to papers that focussed on the application of popular techniques. Consequently, eleven popular methods were identified, and among them is the AHP technique. AHP as a type of MADM analysis has been extensively used in research because of its suitability to compare and weigh attributes via a hierarchy structure and ability to verify the consistency of subjective data through a consistency ratio method (Song and Kang, 2016).

AHP is similar in popularity to both Multi-Attribute Value Theory (MAVT) and Multi-Attribute Utility Theory (MAUT) (Saaty, 1980). MAUT is only an extension of MAVT (Fishburn and Keeney, 1974) and the two methods – AHP and MAUT –, rest on the different assumptions on value measurements, whereas AHP is developed independently of other decision theories (Velasquez and Hester, 2013).

The major feature of the AHP method is its use of pairwise comparisons, which are employed both to compare the alternatives concerning the various criteria and its use to estimate criteria weights (Løken, 2007, Lade et al., 2012). Analytical Network Process (ANP) is essentially the general form of AHP and it is non-linear, as contrary to AHP, which is "hierarchical and linear with the goal at the top and the alternatives at the lower levels" (Wang, 2012). Despite the inability of AHP to prioritise groups or clusters of elements in a network. Several researchers have compared the use of AHP with other MCDM techniques and compared the results. For example, Leung et al. (1998) analysed decision-making within Hawaii's pelagic fisheries using AHP. Even with the variation among the questionnaire used to create the AHP input data, the AHP approach was able to weigh criteria importance for sustainable fisheries and this led to alternative rankings similar to successful rankings in the past.

Bentes et al. (2012) examined a telecommunications company in Brazil and assessed its organizational performance using AHP to prioritize performance perspectives and indicators. In the study, AHP was integrated with the Balanced Scorecard (BSC), a framework for performance assessment, to appropriately rank alternatives. The BSC explicitly assesses organisational performance from multiple dissimilar perspectives. This framework put to bear, the related necessary criteria and alternatives, while the AHP was utilised for comparisons, weighting, and rankings. With three alternatives and four criteria, the AHP was able to take into account several measures and perspectives.

Albeit, limitations such as, self-assessment bias affecting internal validity present in the AHP-BSC hybrid application, the study concluded that the combination of the AHP-BSC hybrid methods led to a ranking of organisational performance that was far superior to previous methods.

One of the biggest criticisms in the application of AHP is its susceptibility to rank reversal. Due to the nature of comparisons for AHP rankings, the addition of alternatives at the end of the process could cause the final rankings to flip or reverse (Velasquez and Hester, 2013). Although AHP is very functional and popular in both academia and in the real world, there are also various biases and misuse of the method which are heavily based on the lack of theoretical basis (Bulut and Duru, 2018).

AHP has seen much use in performance-type problems, political strategy, public policy, resource management, corporate policy, and planning strategy (Hati et al., 2017). Resource management problems make up the disadvantage of rank reversal by having a definite number of alternatives in the assessment. AHP's ability to handle larger problems makes it ideal to handle problems that compare performance among alternatives. Nevertheless, problems, where alternatives are commonly added, would do well to avoid this method (Velasquez and Hester, 2013).

In recent years, because of integrating thinking and advancing technologies, integrating several methods has become a commonplace in MCDA. Consequently, a careful selection of multiple methods can take account of the deficiencies that may be present in certain methods. A summary of MCDM methods is presented in Table 14. It is observed from the literature review that most of the MCDM methods have seen a common pattern of improvement and progression, such as the transition from MAVT to MAUT and, to an extent, AHP to ANP. Outranking methods, like PROMETHEE and ELECTRE, which were predominant earlier on in the development of the MCDA field, have been overtaken by the application of value measurement approaches such as AHP, ANP, and MAUT (Velasquez and Hester, 2013).

Table 14: Description of notable MCDM methods (Velasquez and Hester, 2013, Vinodh et al., 2014)

Methods	Advantages	Disadvantages	Areas of application
Multi-Attribute Utility Theory (MAUT)	Takes uncertainty into account; can incorporate preferences	Needs a lot of input; preferences need to be precise	Economics, finance, actuarial, water management, energy

Methods	Advantages	Disadvantages	Areas of application
			management, agriculture
AHP	Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data-intensive.	Problems due to the interdependence between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria; rank reversal.	Performance-type problems, resource management, corporate policy and strategy, public policy, political strategy, and planning.
Case-Based Reasoning (CBR)	Not data-intensive; requires little maintenance; can improve over time; can adapt to changes in the environment.	Sensitive to inconsistent data; requires many cases.	Businesses, vehicle insurance, medicine, and engineering design.
PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation)	Easy to use; does not require an assumption that criteria are proportionate	Does not provide a clear method by which to assign weights	Environmental, hydrology, water management, business and finance, chemistry, logistics and transportation, manufacturing and assembly, energy, agriculture
Fuzzy Set Theory	Allows for imprecise input; takes into account insufficient information	Difficult to develop; can require numerous simulations before use.	Engineering, economics, environmental, social, medical, and management.
Simple Multi-Attribute Rating Technique (SMART)	Simple; allows for any type of weight assignment technique;	The procedure may not be convenient considering the framework.	Environmental, construction, transportation and logistics, military, manufacturing and assembly problems.

Methods	Advantages	Disadvantages	Areas of application
	less effort by decision-makers		
Simple Additive Weighting (SAW)	Ability to compensate among criteria; intuitive to decision-makers; the calculation is simple does not require complex computer programs.	Only estimates; does not always reflect the real situation; result obtained may not be logical.	Water management, business, and financial management.
TOPSIS	Has a simple process; easy to use and program; the number of steps remains the same regardless of the number of attributes.	Its use of Euclidean Distance does not consider the correlation of attributes; difficult to weight and keep a consistency of judgment.	Supply chain management and logistics, engineering, manufacturing systems, business and marketing, environmental, human resources, and water resources management.
ELECTRE (ELimination and Choice Expressing Reality)	Takes uncertainty and vagueness into account.	Its process and outcome can be difficult to explain in layman's terms; outranking causes the strengths and weaknesses of the alternatives to not be directly identified	Energy, economics, environmental, water management, and transportation problems.
VIKOR	Easy to use	Does not easily estimates the compromise solution	Sustainability, renewable energy, management, risk, and financial management, water resource planning, tourism, health, supplier

Methods	Advantages	Disadvantages	Areas of application
			selection, human resource management

4.2.2 Analytic Hierarchical Process (AHP) Methodology

AHP is a decision-making technique originally developed by Thomas Saaty (Saaty, 1977). The technique is one of the mathematical methods for analysing complex decision problems with multiple criteria and can handle qualitative and quantitative attributes (Arslan and Turan, 2009). AHP is a methodical approach that implies structuring criteria of multiple options into a system hierarchy. This includes relative values of all criteria, and comparing alternatives for each particular criterion and defining the average importance of alternatives (Lavasani et al., 2011).

Among the significant strengths of the AHP method is its ability to integrate either objective or subjective perceptions, or tangible and intangible assessments based on simple pairwise comparison matrices (Da Cruz et al., 2013). The main goal of an AHP is to choose an alternative that suitably satisfies a given set of criteria out of a set of choices or to determine the weight of the criteria in any application using the decision-maker's or expert's experience/knowledge in a matrix of a pairwise comparison of attributes (Saaty, 2008).

The execution of the pairwise comparison is to arrange n criteria in row and column of $n \times n$ matrix. Essentially, the AHP mechanism works by developing priorities for alternatives (or criteria) used in judging the alternatives (or criteria). The goal of the AHP mechanism is to develop priorities for the criteria in terms of their importance. The developed priorities display the performance of the alternatives on each criterion. The description of the assessment grades of the criteria is presented in Table 15 and Table 16.

The judgement of each expert can be aggregated using Equation 4.1, and the assumed quantified judgement on the pairs of criteria can be mathematically represented as A_i and A_j then simplified by an $n \times n$ single value comparison matrix A (Pillay & Wang, 2003). Therefore, Equations 4.1 and 4.2 can be used and described below.

$$\text{Average Numerical Value Rating} = \frac{\sum_{i=1}^{n} a_i}{N} \quad i = 1,2,3,\dots,n \qquad (4.1)$$

Where a_i is an input value by an expert for the same criterion and N is the total number of experts that participated in the pairwise comparison questionnaire.

Table 15: Scale for assessment grades of the criteria for the important pairwise comparison

Assessment Grade	Description of assessment grade	Numerical value rating
Equally important	Two criteria contribute equally to the objective	1
Between moderately more and equally important	There is a compromise between two criteria being considered within the grades.	2
Moderately more important	Experience and judgment slightly favour a criterion over another	3
Between moderately more and strongly more important	There is a compromise between two criteria being considered within the grades	4
Strongly more important	Experience and judgment strongly favour a criterion over another	5
Between strongly more and very strong important	There is a compromise between two criteria being considered within the grades	6
Very strongly important	A criterion is strongly favoured over another and its importance is demonstrated in practice	7

Assessment Grade	Description of assessment grade	Numerical value rating
Between very strong and extreme important	There is a compromise between two criteria being considered within the grades	8
Extreme important	The evidence favouring a criterion over another is of the highest order of affirmation	9

$$A= (a_{ij}) = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ . & . & \dots & . \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \tag{4.2}$$

where each a_{ij} is the relative importance of the criteria a_{ij} and i, j =1,2,3,…,n. The weighting vector of a specific element k in the pairwise comparison matrix is defined as w_k. The weighting vector represents the priority of each element in the pairwise comparison matrix in terms of its whole contribution to decision-making (Uyan, 2013). Given this, w_k can be represented mathematically as follows:

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}\right) \qquad (k= 1,2,3,\ldots\ldots,n) \tag{4.3}$$

Where a_{ij} represents the entry of row i and column j in a comparison matrix of order n. For the sake of simplicity, Equation 4.3 can be described as follows (Uyan, 2013) to arrive at a normalized pairwise comparison:

- Summation of the values in each column of the pairwise comparison matrix.
- Divide each entry in the matrix by its column sum.

- Establishment of the average of the elements in each row.

Table 16: Scale for assessment grades of the criteria for the unimportant pairwise comparison

Assessment Grade	Description of assessment grade	Numerical value rating
Equally important	Two criteria contribute equally to the objective	1
Between moderately more and equally unimportant	There is a compromise between two criteria being considered within the grades.	1/2
Moderately more unimportant	Experience and judgment slightly favour a criterion over another	1/3
Between moderately more and strongly more unimportant	There is a compromise between two criteria being considered within the grades	1/4
Strongly more unimportant	Experience and judgment strongly favour a criterion over another	1/5
Between strongly more and very strong unimportant	There is a compromise between two criteria being considered within the grades	1/6
Very strongly unimportant	A criterion is strongly favoured over another and its importance is demonstrated in practice	1/7
Between very strong and extreme unimportant	There is a compromise between two criteria being considered within the grades	1/8
Extreme unimportant	The evidence favouring a criterion over another is of the highest order of affirmation	1/9

The values of weights (i.e. w_k) obtained in the pairwise comparison questionnaire and the subjective input, need to be validated using Consistency Ratio (CR). The key determinants of the CR value are the Consistency Index (CI) and Random Index values. Saaty (1980) acknowledged that, whenever a CR value of 0.10 or less is obtained, it implies that the pairwise comparison questionnaire and experts' judgement are rational and can be acceptable. However, in any pairwise comparison evaluation, where CR value is greater than 0.10, this means that the w_k is not valid (Dantsoho, 2015, Saaty, 1980). Hence, the pairwise comparison calculation must be reviewed or rejected at once. Given this, CI can be mathematically described as follows:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad 4.4$$

Where n stands for the number of alternatives (or criteria) being compared and $\lambda_{\max}$ stands for the maximum eigenvalue of an n x n comparison matrix. To identify $\lambda_{\max}$ value in any pairwise comparison evaluation, $\lambda_{\max}$ can be mathematically described as follows:

$$\lambda_{\max} = \sum_{j=1}^{n} \frac{\frac{\sum_{k=1}^{n} w_k a_{ij}}{w_j}}{n} \qquad 4.5$$

Where w_j is the weight regarding the column (j) in the $n \times n$ matrix.

Since the values of CI and $\lambda_{\max}$ can be known using Equations 4.4 and 4.5, CR value can be solved using its mathematical relation as follows (Saaty, 1990):

$$\text{CR} = \frac{CI}{RI} \qquad 4.6$$

Where RI, is the random index, this random index depends on the n in a pairwise comparison evaluation. The random index value can be selected from Table 17.

Table 17: Average RI values (Saaty, 1980)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

4.2.2.1 Ranking of the intermediate hazard

Ranking of the intermediate hazard events is used to estimate the risk level of each hazard event in the intermediary level of the ER decision tree. The intermediate hazards are ranked according to the values of their scores revealed from the application of AHP model on AMSSO. An intermediate hazard associated with highest score value is assigned a rank of 1. The intermediate hazard with the second-highest score value is assigned a rank of 2. Other rankings of alternatives will follow the same procedure.

4.2.3 A brief review of research on Evidential Reasoning (ER)

Dempster originally presented the theory of evidence (Dempster, 1967) and since then, it has gone through several modifications and improvements by Shafer (1976). Consequently, the evidence theory is often referred to as the Dempster-Shafer theory or D-S theory (Yang, 2001). Formerly, ER was employed for information aggregation in expert systems as an approximate reasoning tool (Buchanan and Shortliffe, 1984, Lee and Yang, 2017) and then used in decision- making under uncertainty and risk in contrast to Bayes decision theory (Yager, 1992, Yager, 1995, Lee and Yang, 2017).

The ER approach is one of the latest developments in the MCDM subjects and has been widely used by a large conglomeration of researchers (Yang and Singh, 1994). Based on the D-S theory, an ER approach (Yang, 2001, Xu and Yang, 2001) has been developed to describe and handle uncertainties by employing subjective assessment using the combination of FL.

ER is different from some conventional MCDM methods that use a decision matrix to describe an MCDM problem. Instead, it uses an extended decision matrix, in which each attribute of an alternative is defined by a distributed assessment employing a belief structure often referred to as *DoB*. The distributed assessment concept was proposed by Zhang in 1989 to synthesise distributed assessment information (Zhang et al., 1989).

The combination of FL and the distributed assessment with ER is suitable to model incompleteness and ignorance in subjective judgement explicitly. For example, the distributed assessment result of the quality of a ship engine using fuzzy grades could be {(Excellent, 70%), (Good, 30%), (Average, 0%), (Poor, 0%), (Worst, 0%)}, which means the quality of the ship engine is assessed to be "Excellent" with 70% *DoB* and "Good" with 30% *DoB*.

One of the benefits of employing distributed assessment is that it can model precise data and account for various types of uncertainties such as probabilities and vagueness in subjective judgements (Xu and Yang, 2005, Zhang et al., 2016). ER is a more precise model when dealing with a complex system with various types of uncertainties, this is evident from its application in recent times (Zhao et al., 2018, Chen et al., 2018, Jiang et al., 2018) and (Fu et al., 2019).

The ER approach is the only method so far with the ability to handle MCDM problems with uncertainties and hybrid nature (Xu and Yang, 2001, Bazargan-Lari, 2014, Derbel and Boujelbene, 2016). Hybrid nature here is referred to as a mixture of qualitative (e.g. risk level "low") and quantitative (e.g. risk level "90%") attributes, mixture of deterministic (e.g. price of a car "£") and probabilistic attributes (e.g. fuel economy of a car "random") or incommensurable units. It describes and handles uncertainties by using the concept of *DoB*.

Uncertainties in this context could be in the form of 1) absence of data, 2) incomplete description of an attribute and 3) random nature of an attribute. For the absence of data, the total sum of *DoB*s in the distributed assessment for that attribute will be scored zero. For an incomplete description of an attribute, the total sum of *DoB*s in the distributed assessment for that attribute will be somewhere between 0% and 100%. For the random nature of an attribute, the probability will be utilised here (Xu and Yang, 2001), and the probability distribution will be converted into the *DoB*s in the distributed assessment for the attribute.

The rationality behind the mentioned ER approach is that, if a system has a good or bad sub-attribute, then the system must be good or bad to a certain magnitude. The magnitude is measured by both the degree to which that sub-attribute is vital to the system and the degree to which the sub-attribute belongs to the good or bad category.

The integration of the ER algorithm into a Windows-based software referred to as the Intelligent Decision System (IDS) was achieved in the late 1990s. Moreover, the ER approach and the IDS software have become the main tool for many research projects in Liverpool Logistics Offshore and Marine Research Institute, LOOM (Riahi, 2010). The principle (theory) of ER is discussed in section 4.2.3 while the major benefits of using the ER approach are listed as follows:

- It is capable of handling incompleteness, uncertainty, and vagueness data, as well as complete and precise data in MADA problems.
- It can provide the users with unlimited flexibility by allowing them to express their judgements both subjectively and quantitatively. IDS can handle a large scale MADM easily with a 128MB RAM PC (Xu and Yang, 2001).

- It is capable of accommodating or representing the uncertainty and risk inherent in decision analysis for multiple-factor analysis (Riahi, 2010).
- It can offer a rational and reformulated methodology to aggregate the data assessed based on its hierarchical evaluation process.
- It transforms mature computing software and uses the IDS to obtain the assessment output, which relieves the users from the lengthy and tedious model building and result from analysis process using Windows-based click and design activity.
- The ER approach and the information conversion techniques used in IDS have all-encompassing theoretical foundations (Yang and Singh, 1994).

4.2.4 ER Principle

As stated in subsection 4.2.3, the ER approach is different from other conventional MCDM methods, because it uses *DoB* structure to symbolise an assessment in a distributional form. For example, in risk analysis, an assessor may have the following four evaluation grades: $H= \{H_1, H_2, H_3, H_4\} = \{Very\ low, Low, Medium, High\}$

Solving an MCDM problem with M attributes A_i $(i = 1, \ldots, M)$, K alternatives O_j $(j = 1, \ldots, K)$, and N evaluation grades H_n $(n = 1, \ldots, N)$ for each attribute is represented using an extended decision matrix with $S(A_i(O_j))$ as its element at the i^{-th} row and j^{-th} column where $S(A_i(O_j))$ is given as follows:

$$S(A_i(O_j)) = \{(H_n, \beta_{n,i}(O_j)), n = 1, \ldots, N\} \qquad i=1,\ldots,M \quad j=1,\ldots,K \qquad 4.7$$

Where $1 \geq \beta_{n,1} \geq 0$ (n=1,…,4) denotes the degree of belief that the attribute A_1 is assessed to the evaluation grade H_n. $S(A_1(O_1))$, this also implies that the attribute A_1 is assessed to the grade H_n to a degree of $\beta_{n,1}\times100\%$ (n=1,…,4) for the alternative O_1.

There cannot be $\sum_{n=1}^{4}\beta_n > 1$. The assessment $S(A_1(O_1))$ of an attribute A_1 on an alternative O_1 is considered to be a complete distribution if $\sum_{n=1}^{4}\beta_n = 1$ and an incomplete assessment mean $\sum_{n=1}^{4}\beta_n < 1$ (Lee and Yang, 2017). In ER framework, both the complete and incomplete assessment can be considered (Yang, 2001, Xu and Yang, 2001, Wang et al., 2006).

It is worth noting that an attribute could have its own set of evaluation grades that may be different from those of other attributes (Yang, 2001).

Assume ω_i is the relative weight of the attribute A_i and ω_i is normalised so that $1 \geq \omega_i \geq 0$ and $\Sigma_{i=1}^{L}\omega_i = 1$ where L is the total number of attributes in the same group sharing the same upper-level attribute in the attribute hierarchy. To simplify the assessment, only the combination of complete assessments is investigated. The definition of the recursive ER algorithm, capable of aggregating both complete and incomplete assessments is detailed in Yang (2001). Without loss of generality and for illustration, the ER algorithm presented below is for combining two attribute assessments only.

Assuming the first assessment is given in Equation 4.8 as:

$$S(A_1(O_1)) = \{(\beta_{1,1}, H_1), (\beta_{2,1}, H_2), (\beta_{3,1}, H_3), (\beta_{4,1}, H_4)\} \quad 4.8$$

Then, the second assessment is given by:

$$S(A_2(O_2)) = \{(\beta_{1,2}, H_1), (\beta_{2,2}, H_2), (\beta_{3,2}, H_3), (\beta_{4,2}, H_4)\} \quad 4.9$$

Combining the two assessments $S(A_1(O_1))$ and $S(A_2(O_2))$, it then can be represented thus: $S(A_1(O_1)) \oplus S(A_2(O_2))$. Assume that $S(A_1(O_1))$ and $S(A_2(O_2))$ are both complete, then

$m_{n,1} = \omega_1\beta_{n,1}$ (n=1,…,4) and $m_{H,1} = 1 - \omega_i \sum_{n=1}^{4}\beta_{n,1} = 1 - \omega_1$

$m_{n,2}$ = $\omega_2 \beta_{n,2}$ (n=1,…,4) and $m_{H,2}$ = $1 - \omega_i \; \sum_{n=1}^{4} \beta_{n,2} = 1 - \omega_2$

Where each $m_{n,j}$ (j=1, 2) is referred to as basic probability mass each $m_{H,j}$ (j=1, 2) is the remaining belief for attribute j unassigned to any of the H_n (n=1, 2, 3, 4).

The ER algorithm is used to aggregate the basic probability masses to generate combined probability masses, denoted by m_n (n=1, …, 4) and m_H using the following equations:

$m_n = k(m_{n,1}m_{n,2} + m_{H,1}m_{n,2} + m_{n,1}m_{H,2})$, (n=1,…,4)

$m_H = k(m_{H,1}m_{H,2})$

Where

$$k = \left[1 - \Sigma_{t=1}^{4} \Sigma_{\substack{n=1 \\ n \neq t}}^{4} m_{t,1} m_{n,2}\right]^{-1} \qquad 4.10$$

The integration of the combined probability masses can then be carried out with the third assessment in the same manner. The process is recursive until all assessments are aggregated. The final combined probability masses are independent of the order in which individual assessments are aggregated.

If there are only two assessments, the combined degrees of belief β_n (n=1,…,4) are generated by:

$$\beta_n = \frac{m_n}{1 - m_H} \text{ (n=1,…,4)}$$

The combined assessment for the alternative O_1 can at this point be represented as follows:

$S(O_1)$= {(β_1, H_1), (β_2, H_2), (β_3, H_3), (β_4, H_4)}

An average score for O_1, denoted by u(O_1), can also be provided as the weighted average of the scores (utilities) of the evaluation grades with the belief degrees as weights, or

$$u(O_1) = \sum_{i=1}^{4} u\,(H_i)\beta_i \qquad 4.11$$

Where $u(H_i)$ is the utility of the i-th evaluation grade H_i. If evaluation grades are assumed to be equidistantly distributed in the utility space, for example, the utilities of the evaluation grades can be given as follows (refer to Table 10):

$u\,(\mathrm{H}_1) = u\,(very\ low) = 0.00$

$u\,(\mathrm{H}_1) = u\,(low) = 0.33$

$u\,(\mathrm{H}_1) = u(medium) = 0.66$

$u\,(\mathrm{H}_1) = u(High) = 1.00$

Instead of aggregating average scores, the ER approach utilises an evidential reasoning algorithm established based on decision theory and evidence integration rule of the D-S theory to aggregate *DoB*s (Lee and Yang, 2017). Average scores are not necessary for aggregating attributes in the ER approach, and this makes the ER approach distinct from other MCDM techniques.

4.2.5 The selection of ER and AHP

The integration of AHP and ER approaches have been seen in many MADM studies such as project screening, bridge condition assessment, and risk management. Ng and Chuah (2014) applied AHP-ER in the evaluation of design alternatives' environmental performance. Recently, AHP-ER was utilised to assess the operational uncertainties of a particular piece of equipment in a marine and offshore system based on an oil analysis technique (Asuquo et al., 2019).

The integration of AHP-ER remains effective and popular because it has been proven that based on the theory of AHP and ER, the model is flexible and practical to cope with qualitative, quantitative and/or uncertain data (Zhang et al., 2012). Dehe and Bamford (2015) made a comparison of the results of an MCDA model through a case of healthcare infrastructure location. It is demonstrated that the solution by the combination of AHP and ER, provided a traceable and robust framework.

It is for the first time that AHP and ER will be used to measure safety level in AMSSO, this integrated technique will need to be investigated and validated. Since this integrated method has been observed to solve large scale real-life problems, confidence can be bestowed on this combined technique as it has been effective and transparent in dealing with fuzzy situations.

4.3 Methodology for measuring the global RI value in AMSSO

In Chapter 3, the risk analysis that was carried out was restricted to hazard events located at the bottom level of the Ship-Ice Collision risk dendogram. However, this risk analysis has not wholly addressed the risks in AMSSO from a systematic view. There is a knowledge gap in the overall RI measurement in AMSSO.

The ER approach in this chapter is utilised for aggregating risk estimations of the entire spectrum of hazard events centred on a *DoB* decision matrix and the evidence combination rule of D-S theory. Here, the ER utilises a distributed modelling framework, in which the risk analysis of each hazard event is carried out using a set of collectively thorough and mutually exclusive assessment grades obtained from an FRBN method in Chapter 3.

For the ER approach to aggregate criteria at the top-level criterion, AHP and/or any other methods can be used for generating relative weights of criteria from the bottom level of criteria in a decision tree (Xu and Yang, 2001).

The new proposed methodology for measuring the global RI of a Ship-Ice Collision scenario in AMSSO, using the integrated FRBN, AHP and ER approaches, can not only model the diversity and uncertainty of subjective information in complex FMEA, but also incorporate the relative local risk level of hazard events into the determination of the RI of the system. This whole process is done in a precise and logical manner and allows the investigation into how sensitive the result is to changes in weights and belief degrees to certain attributes.

More significantly, by incorporating ER and AHP with the FRBN analysis, the risk measurement of each hazard event can be investigated from both local (i.e., its individual risk level) and global (i.e., it's RI to the system safety) viewpoints.

The steps for measuring the global RI value in AMSSO utilising the novel ER approach can be drawn as follows:

a. Preparatory phase (goal setting).
b. Develop a hierarchical structure to describe Ship-Ice Collision safety performance.
c. Assign weights to attributes using AHP or any other suitable method.
d. Use the ER algorithm to synthesise the risk and weight result of each hazard event both at the bottom and intermediary level in the ER decision tree respectively, for safety measurement of the Ship-Ice Collision risk model.
e. Compare the results with a benchmark risk
f. Evaluate the risk impact of each hazard event on the system by using sensitivity analysis to validate the developed model.

4.3.1 Preparatory phase

The prospect project described in Chapter 3, subsection 3.5.1 will serve as a case study for the application of ER in the global risk analysis of Ship-Ice Collision in AMSSO. The purpose of this preparatory phase is to access the risk analysis task carefully concerning the Arctic shipping regulations; this in return will assist in determining the extent and depth of the ER application. An up-to-date description of IMO's contribution to safe Arctic shipping operations and the strict regulations concerning Ship Class in Arctic operations have been presented in Chapter 2, section 2.9.

Information regarding Arctic accident and linked hazard information will be provided by reputable Arctic accident investigation organisations such as MAIB, Allianz Global, and first-hand observations. The experts consulted in Chapter 3, will also be contacted in this chapter to provide a first-hand judgement in this chapter. Experts' background and experience have been presented in Chapter 3, Table 8 (Experts' knowledge and experience).

4.3.2 Develop a hierarchical structure to describe the Ship-Ice Collision safety performance

The hazard events and associated intermediary events investigated in this study are those identified through the combination of the literature survey, experts' memories and field investigation. The hierarchical structure of events in the Ship-Ice Collision safety performance showing the interactions among the hazard events has been presented in Figure 20. Wherein the clustering dendrogram mentioned in Chapter 2, section 2.11.2 and Chapter 3, section 3.4.1.3 was utilised. The top-level (risk group 1) of the dendrogram risk tree represents the goal of the investigation, the intermediary and bottom levels represent risk groups 2 and 3 respectively.

4.3.3 Assign weights to attributes using AHP

Since attributes are rarely of equal importance, it is necessary to assign attribute weights in the ER approach to determine the most suitable path to measure the global RI of AMSSO. One of the most popular methods of assigning attribute weights in risk analysis is through the utilisation of the AHP technique (Chen et al., 2018). The AHP technique can handle both qualitative and quantitative multi-attribute factors. The theory and foundation of the AHP method has been presented in section 4.2.2.

4.3.4 Using the ER algorithm to synthesise the risk and weight result of each hazard event and each intermediate event for safety measurement of the Ship-Ice Collision risk model.

The risk analysis of each hazard event in the Ship-Ice Collision model in Chapter 3 with the corresponding linguistic grading and *DoB* and of course, their corresponding crisp values from the utility assessment can be utilised as the input value in the ER approach for measuring the global RI of AMSSO. The dovetailing of the D-S theory and the FRBN is an effective way to solve MCDM problems that include fuzzy and random information from several sources. One possible way of achieving this is to extend the D-S theory to include the feature of fuzzy set theory so that its capability can be enriched to process both crisp and fuzzy information. The D-S's rule of combination has been described explicitly in section 4.2.3.

4.3.5 Result analyses compared with the developed FRB benchmark risk

The developed FRBN benchmark risk allows the stakeholders to compare the RI of the whole system to an ALARP level, or an intolerable risk level. The results of the ER will be compared to the developed FRB benchmark risk, presented in Figure 21.

4.3.6 Methodology to evaluate the Risk Influences of each hazard event on the system

There are different techniques for validating the knowledge-based system, nevertheless the most commonly used techniques are 1) data validation; 2) validation by testing; 3) field tests; 4) subsystem validation and 5) sensitivity validation (Mokhtari et al., 2012). Among these techniques, sensitivity analysis is a preferred technique in systems relying on uncertainty management (Gonzalez and Dankel, 1993, Hoops et al., 2016). Sensitivity analysis in this study tries to examine the sensitivity of a risk-based model to individual hazard event or risk factors.

Sensitivity analysis is necessary to evaluate the hazard event's risk impact by finding the risk magnitude of each hazard event on the entire system through sensitivity tests. The sensitivity tests demonstrated in this study have been developed on the analysis process of the ER methodology validation to quantify the risk impact of each hazard event on the system (Alyami et al., 2019).

The new method of sensitivity analysis allows stakeholder or risk assessor to evaluate the risk impact of each hazard event on the system safety and rank them accordingly by taking into account both the local and global risk estimate.

At this point, to verify the methodology used in developing the model in section 4.3, the sensitivity analysis must at least, agree with the following three axioms if the methodology is reasonable and its inference reasoning assumed to be logical (Mokhtari et al., 2012, Chen et al., 2018):

Axiom 1: A minor decline in a hazard event input data i.e. belief degrees of a hazard event, should result in a decrease of the output data i.e. RI of the Ship-Ice Collision model (i.e. top-level) correspondingly.

Axiom 2: A minor increment in a hazard event input data i.e. belief degrees of a hazard event, should result in an increase of the output data i.e. RI of the Ship-Ice Collision model (i.e. top-level) correspondingly.

Axiom 3: A minor decline or increment of the relative weights for the intermediary hazard events should result in a decrease or an increase of the output data i.e. RI of the Ship-Ice Collision model (i.e. top-level) correspondingly.

In order to transform the ER tedious and lengthy model construction and outcome analysis, an IDS developed in 2001 (Xu and Yang, 2001) will be employed. The IDS software is intended to transform the tedious and lengthy model construction and outcome analysis process into an easy Windows-based "click" and design activity. The following sections are devoted to the modelling of a real-world application of ER integrating AHP and FRBN in AMSSO RI measurement.

4.4 Trial application of the proposed FRBN-AHP-ER Model in AMSSO.

In order to carry out a trial application of the proposed FRBN-AHP-ER model in determining the hazard events' RIF and measuring the Ship-Ice Collision risk in AMSSO, the five-step methodology presented in Section 4.3 is utilised.

4.4.1 Preparatory phase

This trial application includes the selection of a prospect project in order to investigate the application of the proposed ER in the subject area. The GINS is selected in this study to demonstrate the applicability of ER in determining the hazard events' RIF and measuring of the Ship-Ice Collision risk in AMSSO.

The GINS is a high prospect area for hydrocarbon resources such as crude oil and natural gas. The Arctic nature and the characteristic of the GINS have been described in Chapter 3, section 3.5.1.

For the trial application of FRBN-AHP-ER in the GINS AMSSO, a questionnaire was developed from the elicitation meeting that was held in November 2017. Experts that were contacted with the questionnaire were selected based on their experience in Arctic shipping, with more emphasis on the GINS AMSSO. Table 8 from Chapter 3, shows the background and experience of the selected experts.

4.4.2 Develop a hierarchical structure to describe the Ship-Ice Collision RI in the GINS

The hierarchical structure to describe the Ship-Ice Collision RI in the GINS AMSSO has been presented in Figure 20 and described in section 4.3.2.

4.4.3 Assign weights to attributes using the AHP method

AHP methodology is utilised to estimate the weights of the intermediary criteria in the intermediary level of the structured event hierarchy of the Ship-Ice Collision risk model in the GINS. Response was received from five of the questionnaires that were sent to nine concerned experts. An Excel spreadsheet is utilised in the pairwise comparison of the intermediary events in order to simplify Equation 4.2 and to represent the subjective judgement of each expert. The result from the Excel spreadsheet is represented in tabular form. Thereafter, a geometric mean is taken for the five responses to converge the subjective judgement of the five valid responses as shown in Table 18.

Table 18: Geometric Mean of subjective judgement of expert 1 to #5

	A1	A2	A3	A4	A5
A1	1	0.60	0.28	0.44	0.25
A2	1	1	0.29	0.35	0.20
A3	3.6	3.4	1	0.63	0.33
A4	2.3	2.9	1.6	1	0.42
A5	4.0	5.0	3.0	2.4	1
Sum=$\sum_1^5 A$	11.9	12.9	6.17	4.82	2.2

A1 to A5 have been defined in Chapter 3, sub-sub section 3.4.1.3.

The weighting of each element in the pairwise comparison matrix can be obtained using Equation 4.3, and simplified in Table 19:

Table 19: Prioritization of criteria

	A1	A2	A3	A4	A5	w_k
A1	0.08	0.05	0.05	0.09	0.11	7.6
A2	0.08	0.08	0.05	0.07	0.09	7.4
A3	0.30	0.26	0.16	0.13	0.15	20.2

A4	0.19	0.22	0.26	0.21	0.19	21.4
A5	0.34	0.39	0.49	0.50	0.45	43.4

The Excel spreadsheet calculation reveals that:

A1= 7.60% (risk related to vessel navigation system).

A2= 7.40% (risk related to vessel operation system).

A3= 20.2% (risk related to weather).

A4= 21.40% (risk related to Ice).

A5= 43.40% (risk related to human factor).

The values of weights (i.e. w_k) obtained in the pairwise comparison questionnaire and the subjective input, need to be checked for consistency. This is checked using Equations 4.4, 4.5 and 4.6. The values of CI and λ_{max} is also revealed from the consistency check. The Random Index number which depends on the number of criteria being compared in a pairwise comparison evaluation is obtained from Saaty Table (Saaty, 1980). CR value is obtained from the maximum Eigenvalue of the comparison matrix in Table 20. See Table 21 for the CI and CR values.

Table 20: Maximum Eigenvalue of the comparison matrix

	A1	A2	A3	A4	A5	Sum	Sum/weight
A1	0.08	0.04	0.06	0.09	0.11	0.38	5.0
A2	0.08	0.07	0.06	0.07	0.09	0.37	5.0
A3	0.27	0.25	0.20	0.13	0.14	0.99	4.9
A4	0.17	0.21	0.32	0.21	0.18	1.09	5.09
A5	0.30	0.37	0.60	0.51	0.43	2.21	5.09
λ_{max}							5.016

Table 21: Consistency Index and Ratio of the comparison matrix

λ_{max} (Lambda Max)	5.016
CI	0.0035
CR	0.003125

From the consistency check, it is revealed that there is great consistency in the subjective judgements of all experts; hence, the CR value equals zero (less than 0.1)

4.4.4 Using the ER algorithm to synthesise the risk and weight result of each hazard event and each intermediate event for safety measurement of the Ship-Ice Collision risk model

The main computer platform of IDS for solving an MCDM problem is a model display window, which has a toolbar, menu bar, and a model display window. The hierarchy of events in the Ship-Ice Collision model can be readily constructed using the modelling menu or the connected short cuts in the toolbar. The hierarchy of events in the Ship-Ice Collision case study is represented in Figure 29. The IDS also provides an assistant model constructor for constructing large-scale models that may have hundreds of attributes and options.

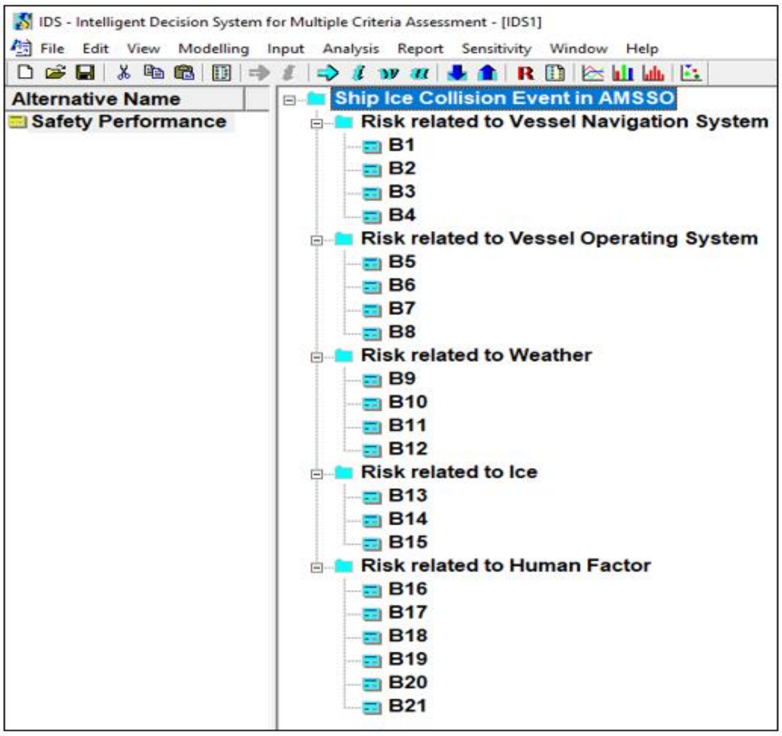

Figure 29: Hierarchy of Ship-Ice Collision risk analysis using the IDS model display

Once, the hierarchy of events is developed, the individual hazard event data from the FRBN results are inputted into the IDS model at the bottom level.

Once the local risk input for individual hazard event has been inputted, the second part is the assigning of weights from the AHP results to the intermediary hazard events at the intermediary level in the IDS model display window. IDS software uses the ER algorithm to synthesise collective information to arrive at the global goal or global RI of the Ship-Ice Collision risk in the GINS AMSSO.

Consequently, the RI of the AMSSO in GINS can be described in a form of linguistic grades with *DoB* values of 26.05% High, 24.19% Medium, 24.10% Low and 25.67% Very Low, as represented in Figure 30, and the utility value is calculated using Equation 4.10 in section 4.2.4 as 49.97%.

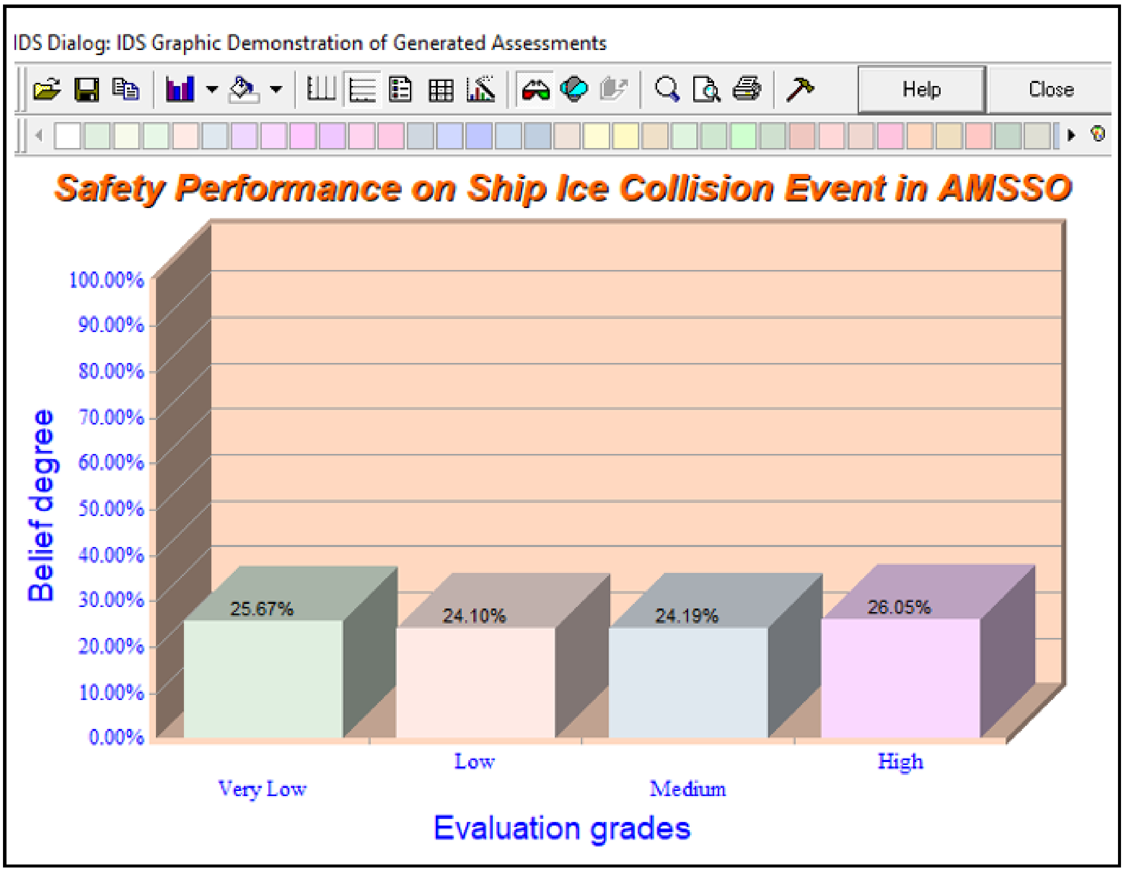

Figure 30: Risk Index of AMSSO in GNIS using IDS model result display

4.4.5 Result Analyses compared to the developed FRB benchmark risk

When the results of the ER are compared to the developed FRB benchmark risk, it is observed that the risk level of Ship-Ice Collision in the studied prospect project, being at 49.97%, is at an intolerable region. The 49.97% risk level is far above the ALARP region on the developed benchmark risk hence, hazard consequences must be reduced, and a design action is required to eliminate or control hazard events.

4.4.6 Sensitivity analysis to validate the developed model.

The sensitivity analysis used in this section is achieved through the three Axioms described in section 4.3.6.

Axiom 1: The result of the application of Axiom 1 on GINS prospect project is depicted in Table 22. It is revealed that a minor decrease in B1's consequent grade resulted to a decline of the original Risk Index value of Ship-Ice Collision from 49.97 to 49.1771 as represented in Table 22.

Axiom 2: The result of the application of Axiom 2 on GINS prospect project is depicted in Table 22. It is revealed that a minor increase in B1's consequent grade resulted in an increment of the original Risk Index value of Ship-Ice Collision from 49.97 to 51.0971 as represented in Table 22.

Table 22: Recalculated RI value for Ship-Ice Collision model based on Sensitivity Analysis

Original RI (Output)	Increasing consequent grade e.g “H” to 100% in the bottom level hazard event:	Hazard event	Decreasing consequent grade e.g “H” to 0% in the bottom level hazard event:
49.97	New RI		New RI
	↑51.0971	B1	↓49.1771
	↑50.9298	B2	↓49.0267
	↑50.9278	B3	↓48.908
	↑50.948	B4	↓49.008
	↑50.933	B5	↓48.903
	↑50.939	B6	↓49.029
	↑50.985	B7	↓49.075
	↑51.019	B8	↓49.099
	↑53.130	B9	↓47.374
	↑52.272	B10	↓46.512
	↑52.833	B11	↓47.077
	↑53.745	B12	↓47.965
	↑54.019	B13	↓45.879
	↑54.103	B14	↓49.483
	↑54.508	B15	↓46.308
	↑55.362	B16	↓45.058
	↑55.148	B17	↓44.904
	↑55.395	B18	↓45.154
	↑54.644	B19	↓44.411
	↑54.034	B20	↓43.864
	↑54.584	B21	↓44.354

Axiom 3: The result of the application of Axiom 3 on GINS prospect project is depicted in Figure 31. It is revealed that a minor change in the weight of an intermediary event

from 1.0 to 0.5 for example resulted in a decline of the original RI value of Ship-Ice Collision from 49.97 to 50.29 RI level.

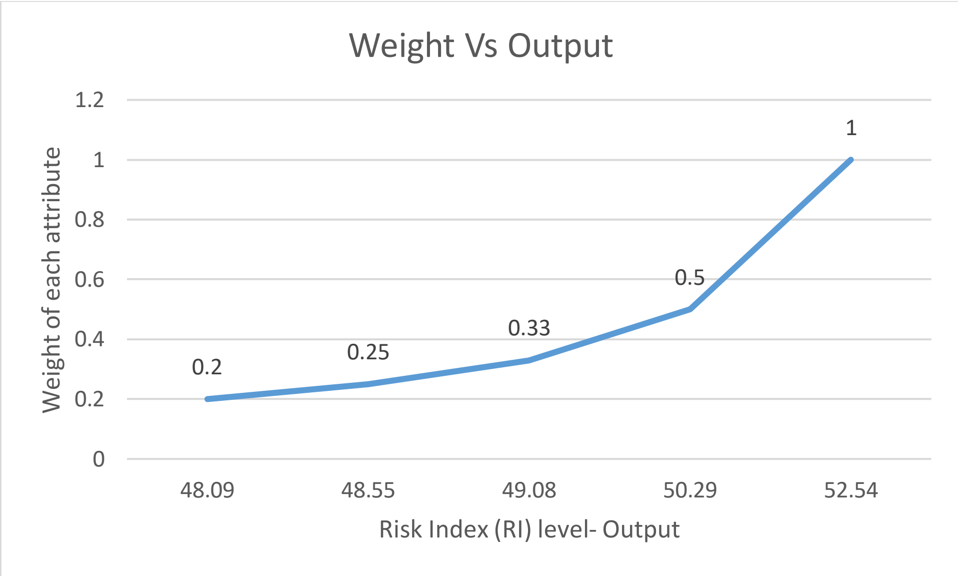

Figure 31: Behaviour of change in intermediary-hazard event weights to the output value

What follows next is the ranking and prioritisation of the most hazardous events at the bottom level having the most influence on the Ship-Ice Collision model globally. This is done to verify which hazard event has more risk influence on the studied system from a perspective view, using the sensitivity analysis method.

To evaluate the RIF of each hazard event, for instance, B1, the utility value of B1 is assigned a "zero" score and the whole system re-analysed. To arrive at B1's RIF, the resultant global RI value from the re-analysis is subtracted from the original global RI of the Ship-Ice Collision model. For the sake of illustration, subsection 4.4.4 gives a utility of 49.97% as the global RI for Ship-Ice Collision, after excluding B1 from the global Ship-Ice Collision risk analysis, Table 23 gives a utility score of 48.624%. Subtracting 48.624% from 49.97% gives, a RIF's value of B1 equals 1.346. This analysis is done repeatedly by excluding one hazard event each time for every analysis to arrive at an event with the highest RIF. The result and the ranking of the event's RIF's value are represented in Table 23.

Table 23: RIF of hazard event on Ship-Ice Collision model

Utility Score		RIF value	Novel Ranking
Original RI	49.97%		
Exclude only B1	48.624	1.346	20
Exclude only B2	47.965	2.005	9
Exclude only B3	47.861	2.109	4
Exclude only B4	47.961	2.009	8
Exclude only B5	47.904	2.066	6
Exclude only B6	47.991	1.979	11
Exclude only B7	48.224	1.746	13
Exclude only B8	48.322	1.648	17
Exclude only B9	48.301	1.669	15
Exclude only B10	47.064	2.906	1
Exclude only B11	47.884	2.086	5
Exclude only B12	49.163	0.807	21
Exclude only B13	47.844	2.126	3
Exclude only B14	47.942	2.028	7
Exclude only B15	48.517	1.453	19
Exclude only B16	48.317	1.653	16
Exclude only B17	48.235	1.735	14
Exclude only B18	48.355	1.615	18
Exclude only B19	47.995	1.975	12
Exclude only B20	47.730	2.24	2
Exclude only B21	47.965	2.005	9

Accordingly, based on the results obtained in Table 23, the hazard events can be prioritised in order of the importance, in terms of risk impact on GINS AMSSO and from the obtained new risk rank order, the most significant hazard events can be listed as follows:

1. B10 - Poor visibility as a result of fog, prolonged polar night;
2. B20 - Lack of situational awareness.
3. B13 - Ice restrictions, which affects the vessel's movement;
4. B3 - Failure in establishment and maintenance of external aids to navigation and;
5. B11 - Machinery seize up with low temperatures.

This prioritization satisfies the third novelty of the hybrid integration of ER with AHP and FRBN models.

4.5 Results and Discussion

The risks to lives, assets, and environment and the huge financial investment in AMSSO is determined by various elements with various risk parameters and several probability distribution grades. It is observed from the sensitivity analysis carried out in Chapter 3 that if the *DoB* of "H" in occurrence likelihood (*L*) of a hazard event, e.g. if B1 is reduced, the RI of B1 is reduced correspondingly. Moreover, if the "H" of B1 is reduced as shown in Table 22, then the outcome of ER is reduced correspondingly. It is evident from the sensitivity analysis carried out in this chapter that a minor change in the FRBN model, results in a corresponding change of the Ship-Ice Collision (top-level event) model output.

The benchmark risk, which was constructed from the syntheses of experts' opinions and the developed FRBN in Chapter 3, is utilised to provide a comparison with the RI measurement obtained in this chapter. As presented in Figure 30, the obtained RI (goal) measurement of GINS AMSSO shows a 25.67% "Very Low", 24.10% "Low", 24.19% "Medium" and 26.05% "High" with a utility score of 49.97%. From the obtained goal measurement, it can be seen that the risk level in the GINS AMSSO is above the ALARP region of the developed benchmark risk requiring further action for risk management.

It is worth mentioning that the utility score of 49.97% for the RI measurement of GNIS AMSSO may fluctuate depending on the dynamic conditions and the operational uncertainty to which the AMSSO is subjected over a specific period.

In line with the sensitivity analysis carried out in section 4.4.6, it is revealed that the model is more sensitive to Hazard events B10 and B20 than to the other hazard elements in the risk cluster. The model sensitivity reveals the RIF of all hazard events from B1 to B21, and this coincides largely with the local FRBN risk analysis results and hazard event prioritization in Chapter 3. The result of the sensitivity test has further proved the importance of human risk factors in the Arctic marine and offshore industry, with B20 – from the human risk factor – having the highest risk score in the FRBN model and 2nd place in the ER global risk analysis.

The case study results confirm that the proposed ER method is capable of offering sensitive and flexible risk results in genuine situations by simplifying the description of failure information, enhancing both the precision and the visibility of FMEA. Consequently, the ER method provides a powerful risk evaluation tool and provides a reliable RI measurement for AMSSO.

4.6 Conclusion

This chapter proposes a novel ER methodology incorporating an FRBN and an AHP approach to handle limited failure data in AMSSO for determining the RI level of an AMSSO. The FRB accounts for the *DoB* distribution of FRBN by utilising the same set of linguistic grades in both IF and THEN parts and applying that set to evaluate the hazard events of a Ship-Ice Collision scenario. The risk in this research is not only defined by the occurrence likelihood (*L*) and consequence severity (*C*) but by other risk parameters such as the probability of failure, being undetected (*P*) and impact of a hazard to operation (*I*). The FRBN simplifies the calculation between risk parameters' input and output based on *DoB*s at the bottom level in the hierarchical clustering of events in the Ship-Ice Collision scenario. The AHP provides a justifiable means to rank the intermediary hazard events at the intermediary level of the hierarchical clustering of events in the Ship-Ice Collision scenario to facilitate the RI measurement at the top level.

Although the risk analysis of this chapter heavily depends on expert evidence, it is noteworthy that the risk statement derived from this research is subject to change in deadlock situations. In the absence of a deadlock or conflicting risk data, the hybrid FRBN-AHP-ER approach offers a more suitable way to characterise and address uncertainties and vagueness from the subjective estimates of multiple decision-makers. This novel integration in assessing risk level in AMSSO offers a powerful tool to synthesise all hazard events from the bottom to the top level of investigation (goal), and provide the RIF of all hazard events in the investigated system.

This novel methodology has revealed the following merits compared to other risk analysis techniques currently applied in the maritime domain:

- The ER approach provides a procedure for aggregation which can represent the new risk parameters under high and imprecise situations.
- The methodology offers managerial insights to analysts in a rational, reliable, traceable and transparent manner for joint modelling of complex systems with a group of experts under situations of high operational boundaries.

- The methodology offers researchers an effective technique to make full use of the information generated at the lowest level in a risk dendrogram to evaluate the safety of the whole system for safety improvement of its operations.
- The methodology uses a user-friendly computer aid in the risk evaluation process that helps to predict the risk magnitude and describes the real RI of a system. The user-friendly computer aid means that the computer aid can be used and by a large number of safety engineers and decision-makers all over the world thus reducing the manual (human) ER calculation errors.

Hence, the novel methodology in measuring the global RI of Ship-Ice Collision and the RIF of each hazard event on the Ship-Ice Collision in AMSSO has proved to tackle some of the key issues in AMSSO risk analysis. The key issues earlier mentioned can be summarised as 1) data uncertainties; 2) the probability of an incorrect assessment technique; 3) various risk parameters and stochastic values that exist in measurement; and 4) the various hazard events and risk factors in estimation.

This study mainly focused on the operational aspects including natural and environmental factors, leaving the other risk aspects– such as including managerial, political, climate, economic, SAR infrastructures, and operational, technical, natural and environmental issues–, to be addressed in future work. The high-risk level in the operational aspect of AMSSO needs to be reduced to the ALARP region. Several risk-reducing measures are needed to formulate effective risk reduction process. The implementation of several risk-reducing measures comes at a cost (Pamuntjak, 2016). The strategy for a proactive and cost-effective measure to tackle the high risk in AMSSO will be discussed and analysed in Chapter 5.

Chapter 5– Optimal Risk Control Measure for AMSSO using an AHP-TOPSIS hybrid technique

Overview

The chapter presents an advanced risk-based decision strategy to tackle the revealed high risk of AMSSO from previous chapters. The practice of accounting for various Risk Control Options (RCOs) or alternatives with their associated criteria to ensure a safe and efficient AMSSO can be seen as an MCDM process. A capable hybrid-MCDM technique that can efficiently account for hybrid subjective data, as well as diverse risk reduction measures and their corresponding criteria to prevent and control risk, is the AHP-TOPSIS.

AHP and the TOPSIS methodology have been merged to formulate a hybrid approach to assess the costs and benefits from risk reduction associated with the diverse RCOs in reducing risks in AMSSO. In order to evaluate the benefits of risk reduction, this chapter introduces an economic benefit calculation adopted by the offshore industry to avert a fatality.

The novelty of the application of the AHP-TOPSIS approach in the newly studied area is twofold. Firstly, the newly proposed approach can provide results comparable to the ones obtained using existing risk management decision-making methods when the input data is finalised. Secondly, the newly proposed approach can also provide solutions where the traditional approaches cannot, especially when the decision input data are uncertain and of hybrid nature. This chapter presents the most preferred risk control measures in AMSSO that are capable of addressing risk reduction and operational efficiency in an easy, cost-effective and timely manner.

5.1 Introduction

Despite the presence of hazards and the high cost of investing in Arctic oil and gas exploration, mariners, safety engineers, and stakeholders must develop effective measures to ensure safe and efficient operation in order to ensure Return on Investment (ROI), the protection of lives, assets and the environment. Arriving at an effective measure to ensure safe and efficient operation centred on several alternatives can be a complex task. It becomes even more complex when all the identified alternatives have shared criteria that obviously lead to more familiar and better decisions, in order to get the most appropriate solution. Hence, it is important to find a suitable MCDM technique to work satisfactorily in risk prevention and control.

To ensure safe and efficient operation, three main key elements are considered, namely; 1) technical safety standard and built-in margins against failures or accidents; 2) additional safety barriers (technical or operational) put in place by stakeholders against failures and; 3) measures taken to maintain the integrity of these barriers against failure over time (Helge, 2012). The first key element is mostly covered through class and statutory rules dovetailed with other international standards like the IMO and Polar Code, the second and the third key elements involves the human component (Helge, 2012).

The human component is believed to contribute nearly 85% of most of the marine and offshore accidents (Alkhaldi et al., 2017, Chan et al., 2016) and this is further revealed from the risk analysis carried out in chapters 3 and 4 of this research. Hence, it is logical to invest hugely in human elements to manage accidents. Other factors that are worth investing in, are the organisation, technological facilities, and the environment. To ensure that risk is adequately controlled, the designed technology, organisation, and the environment will work with the human element (people) and enhance their performance (Rothblum, 2000, Coles, 2017).

Several techniques exist for MCDM (Velasquez and Hester, 2013), albeit, there are no better or worse techniques, but some techniques previously discussed in Chapter 4 are better suited to some particular decision problems than others.

There are a few studies emphasising on reducing the future risk pattern in the Arctic and the subsequent need for emergency capacities in the case of an accident in the Arctic. Although some researchers have focussed on the aftermath of an accident by suggesting an increase in the emergency resource capacity (Ehlers et al., 2014). A few others have focused on transferring the consequences of risk to marine insurers (Sawhill, 2017). While others have focussed on ice management (Mollitor, 2018, Haimelin et al., 2017), and safe route planning to lessen Arctic risks (Huntington et al., 2015, Zhang et al., 2017). Hardly any research/studies focus on developing a combined technical and operational solution to prevent and control the dynamic risk of AMSSO or at least Arctic shipping risks in general.

Hence, this chapter presents a new combined technical and operational solution for mitigating risks in AMSSO using AHP-TOPSIS. This modern hybrid MCDM approach to select the most suitable RCO will ensure an economically and technically possible risk control strategy to guarantee a safe and efficient AMSSO. The risk control strategy carried out in this chapter considers all suitable technical and operational solutions with respect to distinct decision criteria and measures taken to maintain the integrity of these barriers against failure over time. The consideration of all suitable and effective RCOs with respect to the distinct decision criteria delivers a systematic and proactive risk prevention and control strategy.

With the aid of literature review and expert elicitation, fifteen (15) effective RCOs, and four distinct decision criteria are established. The introduction of AHP provides a thorough assessment of the four distinct criteria by considering the weight of each criterion, while the TOPSIS approach provides a means of finding the most suitable alternative or RCO from several other alternatives. The AHP-TOPSIS hybrid technique involves the design of an easy to comprehend questionnaire to resolve the hybrid nature of the RCOs selection problem and the ambiguity of concepts that are linked with experts' opinion.

The main aim of the application of the AHP-TOPSIS hybrid technique is to offer solutions for systematic and proactive risk control and management strategy in real-world AMSSO. In addition, this hybrid AHP-TOPSIS can provide solutions to a sensible selection of RCOs in a situation where relevant data is scarce.

5.2 Research Background

5.2.1 A review of Decision-Making Support (DMS) methods

One of the most commonly used DMS methods in the marine and offshore sector is the MCDA (Shafiee et al., 2019). It is worth noting that MCDM, multiple-criteria decision analysis (MCDA) and multiple-attribute decision analysis (MADA) mean the same thing, and they represent a sub-discipline of operations research that explicitly evaluates multiple conflicting criteria in decision-making. This method is increasingly becoming popular for decision-making in the Arctic marine seismic surveying sector because the orthodox single-criterion Decision-Making methods cannot deliver efficient results considering the complexity of Arctic marine seismic exploration and development activities. The MCDA method provides a flexible approach to solve complex problems with multiple criteria (e.g., economic, technical, social, legal and environmental) by aiding decision-makers to make clear and consistent decisions.

In the study of the Decision-Making, a decision is usually reached among the various choices of alternatives centred on a set of criteria/attributes (Hwang and Yoon, 2012, Tzeng and Huang, 2011). For instance, the selection of a day-to-day travel method may include alternatives such as the use of a bicycle, public transportation, or a private motor vehicle. Several criteria may include cost, travel time, convenience, health factor, traffic, and several other factors. Various criteria might conflict with each other (Yoon and Hwang, 1995). Criteria may be quantitative such as travel time, or qualitative such as convenience. In some cases, the criteria may not be well defined. In the day-to-day travel example, the criteria-convenience may not be quantified in a simple way.

Consequently, various MCDA methods have been developed for solving complex problems such as the travel example described above and the complex Decision-Making problems in the marine and offshore industry (Shafiee et al., 2019) not excluding the Arctic industry. However, some of the most popular MADM methods include VIKOR, AHP, and TOPSIS (Castro and Parreiras, 2018). These and more have been described in the previous chapters.

With the knowledge of the application of the various MCDM techniques, this chapter proposes an integrated approach, synthesising AHP with the TOPSIS techniques to determine the most suitable risk prevention strategy for AMSSO risks. The advantage of this integrated method is that it enables the consideration of both tangible (qualitative) and intangible (quantitative) criteria as well as benefit and cost criteria in the selection of risk prevention and control strategy of AMSSO risks.

Cost and benefit which also provide support for making a decision to arrive at the most suitable risk prevention and control strategy in engineering systems are also considered in the strategic decision-making process of this chapter. The Cost-Benefit Assessment (CBA) concept offers decision-makers the opportunity to evaluate the economic viability of different RCOs. The main strength of this approach is that it offers results that are compatible with market mechanisms (Shafiee et al., 2019).

The CBA process involves summing up the equivalent money value of present costs of an RCO and compares the result with the present value of benefits from the implementation of the RCO in order to ascertain if the RCO is worth investing in. An RCO is considered useful if the totality of its benefits becomes greater than the sum of its costs or when the benefit to cost ratio is greater than "one". The TOPSIS method is preferable in this research as it is able to maximise benefit, whilst minimising cost to offer support with the cost, and benefit viewpoint.

In summary, the AHP provides an advanced, yet effective means to tackle multiple criteria decision problems. The importance of an AHP methodology has been scrutinised and proved in several applications (Saaty, 1980, Gupta, 2015, Dey, 2006, Singh and Singh, 2019). The AHP can be used alone or synthesised with other methods such as Grey Theory, VIKOR, and TOPSIS (Improta et al., 2018, Darko et al., 2018). While AHP is utilised to convert subjective assessments of relative importance to weights of alternatives, the TOPSIS method can be used to synthesise all the criteria in the system, to find the most suitable alternative, which is the closest to the ideal solution, furthest away from the negative ideal solution with a description of precise Euclidean distance.

The TOPSIS methodology has also been scrutinised and proved effective in several applications (Behzadian et al., 2012, Kolios et al., 2016, Huang and Li, 2012, Tanriverdi et al., 2018, Khalif et al., 2019). The TOPSIS method is a favourable MCDM method that addresses the problem as a group in its decision matrix (Kaliszewski and Podkopaev, 2016, Shih et al., 2007).

Most MCDM methods have their advantages and drawbacks. Most of their drawbacks arise from rank reversal such as with AHP, but the TOPSIS method has been proven to have one of the lowest numbers of rank reversals in analysis (Shih et al., 2007).

Also, the TOPSIS method is preferred to other MCDMs as it offers a non-monotonic utility output, with maximum utility located somewhere in the middle of the attribute range (Kalbar et al., 2012), meaning, it finds the most suitable alternative in decision-making that minimises costs (for instance) and maximises benefits (for instance). That is, the greater the attribute value, the more it is preferred. An example is fuel efficiency: the greater the attribute value, the less it is preferred.

The following benefits of the application of the TOPSIS method in the selection of the most suitable RCO in addressing risks according to Kalbar et al. (2012) are listed as thus:

- It provides a sound logic that represents the rationale of human preference,
- It provides a unique visualisation of the alternatives on a polyhedron,
- It provides a scaler value that takes into consideration the best and worst alternative choices simultaneously and

- It provides a simple computation process that can be simply programmed into a spreadsheet.

Despite TOPSIS' simplicity and popularity in concept, it is frequently criticised because of its incapability to tackle sufficiently the uncertainty of the weights/importance of criteria and imprecision inherent in the process of representing the perceptions of decision makers (Tseng et al., 2018). In order to overcome this drawback, AHP is synthesised with TOPSIS. The AHP-TOPSIS hybrid methodology allows decreasing the uncertainty and the data loss in group decision making and hence, certifies a robust solution to a decision-making problem (Efe, 2016).

Therefore, the combination of AHP and TOPSIS methodology offers results that are more informative in the RCO selection and decision-making to ensure the most suitable RCO is selected. In ranking of all the RCOs in order of preference concerning the distinct criteria, AHP-TOPSIS will be adopted in tacking the decision-making problems in preventing and controlling risks in AMSSO. However, in order to apply the selected MCDM techniques to solve real-world decision problems, it is important to develop a mathematical framework to abstract information into the selected techniques and to demonstrate the validity of the model.

The AHP mathematical modelling has been presented in the previous chapter; hence, a description of the TOPSIS and the mathematical formulation of the combined AHP-TOPSIS is presented in subsequent sections.

5.3 Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) Methodology

With the difficulty of arriving at a decision in the presence of complex situations such as those that address operational and financial risks, methods to support decision-makers are being extensively investigated. One of the most widely used methods to address complex decision-making problems is the TOPSIS methodology. The TOPSIS developed by Hwang and Yoon in 1981 (Chen, 2015), has been receiving more and more attention.

Aruldoss et al. (2013) carried out a survey on various MCDM methods and applications, the result from the survey indicated that the TOPSIS technique had the most applications when compared to other MCDM methods such as ELECTRE, Grey Theory, AHP, and VIKOR.

Behzadian et al. (2012) also carried out a literature survey on TOPSIS applications; the result from the survey revealed that 269 papers were published in 103 scholarly journals from 2000 to 2012. The survey results also showed a trend in the application of TOPSIS with other MCDM methods rather than the stand-alone TOPSIS. These combinations have made the traditional TOPSIS method more workable and relevant when handling theoretical and practical problems.

Other recent surveys of the TOPSIS approach include the review of 105 papers from 2000 to 2015, and the result also showed that TOPSIS is still relevant in addressing complex decision-making problems (Zavadskas et al., 2016).

The TOPSIS method assumes that each criterion has a propensity of monotonically increasing or decreasing in utility, which leads to the definition of the positive and the negative ideal solutions. In order to evaluate the relative closeness of the alternatives to the ideal solution, the Euclidean distance approach is incorporated in the TOPSIS technique. A series of comparisons of these relative distances will provide the preference order of the alternatives (Aruldoss et al., 2013).

The TOPSIS method first converts the various criteria dimensions into non-dimensional criteria similar to the ELECTRE method (Triantaphyllou, 2013). The way the TOPSIS methodology works, is that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS). This method is utilised for prioritising alternatives, which gives the most appropriate performance in multi-criteria decision-making.

5.4 Overview of AHP-TOPSIS

As mentioned earlier regarding TOPSIS methodology's inability to tackle sufficiently the uncertainty of the weights/importance of criteria in subsection 5.2.1, the need to combine TOPSIS with a more suitable technique is inevitable. AHP methodology can tackle the main drawbacks of TOPSIS as earlier mentioned in subsection 5.2.1. The AHP-TOPSIS methodology allows lowering the uncertainty and the information loss in a group Decision-Making session and hence, certifies a robust solution to a decision-making problem (Efe, 2016).

From a literature survey, there are several examples of synthesising TOPSIS with AHP to advance the consistency of the subjective weights (Yang et al., 2011, Vipul et al., 2018). This modern hybrid approach takes the benefits of two different methods in order to account for the uncertainties linked with the problem under study (Ghosh, 2011, WANG and LIU, 2007, Sadi-Nezhad and Khalili Damghani, 2010).

The basic principle of the TOPSIS method is centred on the idea that the selected alternative should have the closest distance to the positive ideal solution and furthest distance to the negative ideal solution (Ghosh et al., 2019, Aruldoss et al., 2013). In order to match the alternatives and update the final ranking, the Euclidean distances between separate alternatives and together with the ideal and negative ideal solutions are solved first; thereafter, the closeness coefficient is calculated to evaluate the two distances respectively (Taylan et al., 2015).

The AHP-TOPSIS process starts from the construction of a decision matrix as represented in Equation 5.1, given *m* alternatives, *n* criteria or attributes and *k* decision analysts (Wang and Chang, 2007, Dantsoho, 2015).

$$R_k = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ \vdots \\ A_m \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \dots & C_n \end{matrix} \\ \begin{bmatrix} r_{11} & r_{11} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \dots & \vdots \\ \vdots & \vdots & \dots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \end{matrix} \quad i = 1, 2, \dots, n; j = 1, 2, \dots, n \qquad 5.1$$

In the decision matrix in Equation 5.1, $A_1, A_2, \dots, A_m$ stands for the alternatives or RCOs, and $C_1, C_2, \dots, C_n$ stand for criteria or attributes, while r_{ij} represents a crisp number that expresses the ranking of the alternative A_i concerning criterion C_j. In circumstances where the decision- makers are more than one, then the average of their evaluations or ratings is taken as r_{ij}. In addition, the decision matrix can be normalised using X_{ij} (Yue, 2011) as described in Equation 5.2. X_{ij} is used to transform several criteria/attributes dimensions into non-dimensional criteria/attributes in order to enable the selection of any alternatives with regards to all the criteria/attributes.

$$X_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} {r_{ij}}^2}}, \qquad i = 1,2,\dots,n; j = 1,2,\dots,n \qquad 5.2$$

It is essential to weigh the normalised decision matrix. Weighting is assessed using Equation 5.3 in order to enable the determination of both the distance separation measure for the PIS (represented as ${D_i}^+$) and the distance separation measure for the NIS (${D_i}^-$). Where PIS and NIS can be described as the Positive Ideal Solution and Negative Ideal Solution respectively.

$$V_{ij} = w_j \text{ x } X_{ij}, i = 1,2,\dots,n; j = 1,2,\dots,n \qquad 5.3$$

From Equation 5.3, w_j stands for the weight of jth criterion, while V_{ij} is the crisp value that represents the rating of the alternative A_i concerning the criterion C_j in the weighted normalised decision matrix.

The PIS and NIS can be denoted as V^+ and V^- respectively. The V^+ and V^- are mathematically defined in Equations 5.4 and 5.5, to enable the calculation of the ${D_i}^+$ and ${D_i}^-$.

$$V^+ = \{ {V_1}^+, {V_2}^+, {V_3}^+, \dots, {V_n}^+\}, = \{(max_j V_{ij} \mid j \in J)\}, \{(min_j V_{ij} \mid j \in J')\} \qquad 5.4$$

$$V^- = \{ {V_1}^-, {V_2}^-, {V_3}^-, \dots, {V_n}^-\}, = \{(min_j V_{ij} \mid j \in J)\}, \{(max_j V_{ij} \mid j \in J')\} \qquad 5.5$$

J and J' define the benefit and cost criteria respectively as used in this research and according to Mahmoodzadeh et al. (2007). ${D_i}^+$ and ${D_i}^-$ will be developed so as to facilitate the measurement of all the alternatives with their PIS and NIS. ${D_i}^+$ and ${D_i}^-$ can be described mathematically as presented in Equations 5.6 and 5.7 respectively.

$$ {D_i}^+ = \sqrt{\sum_{j=1}^{n} (V_{ij} - {V_j}^+)^2} \ , i = 1,2, \dots , n; j = 1,2, \dots , n \qquad 5.6 $$

$$ {D_i}^- = \sqrt{\sum_{j=1}^{n} (V_{ij} - {V_j}^-)^2} \ i = 1,2, \dots , n; j = 1,2, \dots , n \qquad 5.7 $$

The ranking of the several alternatives such as $A_1, A_2, \dots , A_n$ can be carried out employing the relative closeness to Ideal Solution, symbolised as ${RC_i}^+$. Consequently, ${D_i}^+$ and ${D_i}^-$ are employed to describe ${RC_i}^+$ using the mathematical relation in Equation 5.8.

$$ {RC_i}^+ = \ = \frac{{D_i}^-}{{D_i}^+ + {D_i}^-} \ , i = 1,2, \dots , n; j = 1,2, \dots , n \qquad 5.8 $$

The most suitable alternative will be the value of ${RC_i}^+$ closest to (1) one.

5.4.1 Ranking of Alternatives

Ranking of the RCOs is employed to aid the Decision-Making process. The ranking reveals which alternative can be selected to achieve optimum safety and efficiency. The RCOs are ranked with respect to their ${RC_i}^+$ values. An RCO linked with the highest ${RC_i}^+$ value is of utmost importance, followed by the second highest ${RC_i}^+$ value, then third, fourth and so on.

5.4.2 Decision-making on the most suitable RCO

Strategic decision-making in AMSSO requires a search for alternatives and structuring of alternatives in the context of the risk prevention and control objectives. These alternatives must include definable criteria. In order for decision-making to be effective, all measurable parameters including the goal must be within the realm of available information (Frankel, 1982, Corcoran, 2013). Available information from the application of the AHP-TOPSIS can be selected to improve the safety and lower or prevent risk in AMSSO. Results from AHP-TOPSIS have been used and relied on in different industries (Behzadian et al., 2012) and stakeholders can rely on the RC_i^+ values to take a strategic decision in AMSSO and other dynamic operations.

5.4.3 A systematic structure of AMSSO risk control and prevention utilising a hybrid AHP-TOPSIS methodology

To reduce and manage hazard events in AMSSO, a risk-based decision strategy AHP-TOPSIS model is used to select the most suitable RCO from a list of RCOs that can prevent accidents and improve the safety and efficiency in AMSSO. The framework of the AHP-TOPSIS hybrid technique is presented in Figure 33.

The organisation of steps in Figure 33 to tackle the risk of "lack of situational awareness" in AMSSO starts from the preparatory stage, that is, the assessment of the risk level of "lack of situational awareness" in an AMSSO. The next step is to check if the risk level of "lack of situational awareness" is acceptable or not. If the risk level were low, there would be no necessity to carry out further investigation as shown in Figure 33. However, if otherwise, further investigation will need to be carried out to identify RCOs (alternatives) and associated attributes (criteria) for a safe and efficient AMSSO.

Once all the RCOs and associated criteria have been identified through expert opinion and literature review, an evaluation is carried out to ascertain how logical, the identified criteria are. Following this, an evaluation is carried out to assess the weights of the criteria through an AHP methodology. The overall evaluation is again checked for errors and consistency. In situations of erroneous evaluations, the opinions of experts are re-investigated before the application of TOPSIS methodology is commenced.

The mechanism of the TOPSIS is employed to rank all RCOs against the associated criteria to arrive at an economically viable RCO. Finally, the most suitable RCO, which is ranked number “one” in the AHP-TOPSIS hybrid method, can be employed to tackle the risk of “lack of situational awareness” in AMSSO.

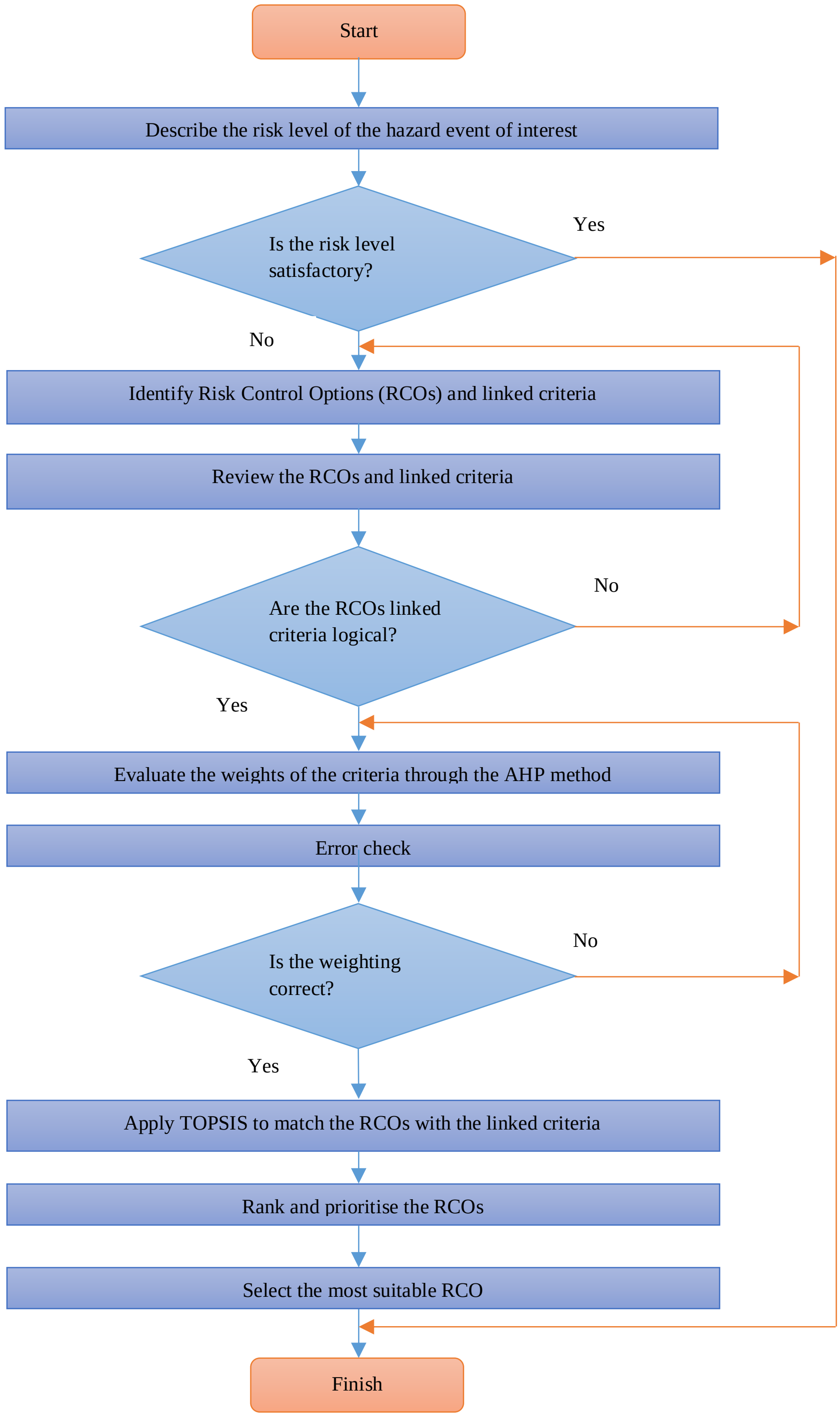

Figure 32: A systematic structure of AMSSO risk control, employing a hybrid AHP-TOPSIS Methodology

The reliability of the model is validated through a sensitivity analysis check to ensure its applicability and reliability in preventing risks in AMSSO. Sensitivity analysis involves checking and validating results from an investigation. It can be done by checking how sensitive minor changes to input data can affect the overall result. In this chapter, sensitivity analysis will be conducted by increasing the weight of each criterion individually with respect to the results obtained from AHP application, then TOPSIS steps are re-activated, and the new results are monitored for the decision-making process (Hanine et al., 2016, Fox et al., 2016).

Another new sensitivity analysis will be carried out by increasing and decreasing the value of the distance separation measure for the PIS and monitoring the results. It is worth mentioning that increasing the criterion weight by "*i*" value simultaneously, the weights linked with other criteria are decreased by "*i*" value to make up for the increment percentage on the increased criterion. Nevertheless, if the weight is approaching less than "*i*" value, then the outstanding weight will be split on the outstanding criteria and this process continues until "*i*" value is used up.

5.6 Development of integrated risk management in AMSSO

Engineering risk management in either the nuclear, marine or offshore sector is an important concept related to the safety and financial integrity of an organisation, and risk prevention is a vital part of its strategic development. The strategy of an organisation on risk management ought to be that all the risks it is exposed to must be identified (see Chapters 2 and 3), assessed (see Chapters 3 and 4), reduced to a tolerable limit, and if possible prevented for safe and efficient operation.

The cost of implementing an RCO or a combination of RCOs depends on the methods used to manage unexpected events (Vasile and Croitoru, 2012), and in most cases, they do come with a hefty cost penalty (Mansouri et al., 2009).

Integrating risk control and management into the day-to-day affairs of any engineering operation and AMSSO, in particular, will depend on the following:

a) Goal of investigation
b) Having complete data or information about all the RCOs
c) Being able to differentiate and comprehend all the pertinent differences between the RCOs,
d) Employing comprehensive criteria that will be useful throughout the lifecycle of the decision's consequences, and lastly,
e) Time available to carry out all of the above in a sensible time window.

In practice, most risk prevention and control strategies depend largely on profit or safety. If safety is paramount to an organisation, then diligence regardless of cost will tend to be favoured in risk management decision-making. If profits and production targets are paramount to an organisation then care, diligence and quick delivery of operation will be favoured. However, the fact that timely execution of Arctic marine seismic survey projects and diligence are trade-offs means that it is difficult to maximise both at the same time. This strain is the source of a big organisational problem, which is, finding a suitable balance between cost and benefit.

The assessment of cost-effectiveness in this regard necessitates a systematic and efficient cost-benefit analysis (CBA). An efficient CBA is centred on the utilisation of a risk management algorithm, which takes into consideration the complex and operational uncertainty of the system (Wang and Trbojevic, 2007) and the amount of information of the various RCOs and criteria. Therefore, the main aim of any joint Decision-Making process is to achieve the most suitable combination of criteria for logical decision-making. In addition, effort needs to be geared towards identifying, developing, and structuring those criteria that affect alternatives selection in an appropriate way. The choice of the most suitable RCO(s) will enable the most suitable risk control and prevention of AMSSO risks.

5.7 A description of the risk of "Lack of Situational Awareness" in AMSSO

In previous chapters, the risk associated with AMSSO is found not to be in the acceptable regions of the developed FRBN benchmark risk. The risk of each hazard was first analysed locally and later analysed globally with respect to the goal (Ship-Ice Collision). Upon the local and global risk analysis, some of the hazard events that contributed mostly to compromise the safety and efficiency of AMSSO were found to be "lack of situational awareness", "ice restrictions which affects vessel's movement", "practical incompetency of duty", "workload causing stress" and "pieces of floating multi-year ice/icebergs causing machinery damage".

5.7.1 A comparison study

For the sake of comparison study, twenty-three (23) accident reports were examined between attendant vessels and offshore facilities on the Northern part of the Norwegian sea (part of GIN sea), where lack of situation awareness was found as one of the most critical hazard events leading to collisions in the studied Arctic region (Sandhåland et al., 2015). Baker and McCafferty (2005) published their three-year long-term analysis of maritime accidents from Arctic seas in Norway, United States, Canada to open seas in the United Kingdom and Australia, and according to their findings, lack of situation awareness was revealed as a major causal factor in the majority of Arctic accidents investigated.

Barnett (2005) used two surveys of accident data and three case studies to highlight the main concerns in the sources of shipping failure. Among the main causal factors found in the research, lack of onboard situational awareness was revealed as a critical risk factor.

Also, in the review of 150 accident reports from 2002 to 2005 from the website of the Australian Transportation Safety Bureau (ATSB) in Barnett (2005), causal factors were categorised into root cause groupings. The 'Lack of situational awareness' group had the highest contribution to accidents with a total of the score of 27.5%, while management, a non-human error, and a risk group scored 24.5%, 15%, and 30% respectively. Although the authors recognised that these root cause groupings are subject to different interpretation, the results agree largely with the UK Marine Accident Investigation Branch (MAIB) database. Nevertheless, the management group refers to nearly entirely on-board management factors, with only 4.5% of these factors credited to organisational impacts, such as the business management and the level of staffing.

Therefore, the lack of situation awareness that is a subset of the human management risk factor will form the focus of study in this chapter, this is so because full-scale risk prevention and control of other 20 hazard events will be too voluminous to investigate.

5.8 Data collection method

Having the correct information about the integrated risk control and being able to differentiate between all the RCOs and their matched criteria begins with the understanding of the scope and goal of the investigation. Vital information on integrated risk control and prevention of "lack of situational awareness" can be sourced through an in-depth literature review and brainstorming session with several experts having a first-hand experience of managing both Arctic and AMSSO risks. Different information is required to identify, analyse and to unify such an integrated risk prevention and control information into one strategic risk control and prevention model.

The data collection method used in this research used both qualitative and quantitative data sets, namely the experts' judgement and mathematical models. The mathematical models used with experts' knowledge in the development of integrated risk control and prevention strategy in this research include AHP-TOPSIS. The expert judgement methodology, as used in this study, is categorised into three chronological stages:

1. Choosing experts refers to expert selection. The process of choosing the concerned experts in this present study is described in subsequent sections.
2. Elicitation refers to the process of proposing opinions or expert judgements through different means. In this study, this was supplied through questionnaires.
3. Aggregation refers to the means of taking the average or converging of the different expert opinions offered in the study (Endrina et al., 2018).

5.8.1 A review on the selection of criteria considered in preventing and controlling a lack of situation awareness risk

The criteria for risk prevention enables the stakeholders (decision-makers) to determine whether is it reasonably practicable to reduce or prevent the risk of a hazard event. Aminbakhsh et al. (2013), Alyami (2017), Giunipero and Eltantawy (2004), and Armer et al. (2013) jointly highlighted four main criteria in preventing the operational risks in the workplace. The four criteria can be revised as:

1) Cost of implementation,
2) Technical difficulty,
3) Risk reduction and

4) Benefit of risk reduction.

Although there is a paucity of literature on AMSSO risk management, however, the literature reviewed from similar operations to AMSSO combined with Vanem et al. (2008) represents the following main criteria used in preventing and controlling the risk of lack of situation awareness:

1) Cost: the cost of reducing or managing risk in monetary value. It is a metric that can be calculated per year or forecast for a future financial period. This chapter focuses on risk control cost, i.e. the cost of installing a safety barrier or the operational processes designed to reduce risk such as investing in human, hardware elements, etc.
2) Technical difficulty: this refers to the ease or difficulty of applying the required safety barrier accurately and dependably.
3) Risk reduction: measures taken to reduce the risk parameters L, C, I, P–, of AMSSO. Risk reduction may include engineering, safety barriers, safety inspections, or claims management. The acronyms L, C, I, and P have been described in previous chapters. Although risk reduction will contribute to less human loss, damage to the environment and property, it is also important to ascertain the benefit of this reduction in monetary terms.
4) Financial benefit of risk reduction: this refers to the financial benefit achieved in preventing the loss of lives, assets and damage to the Arctic environment. Technical as this may sound, what underlies the issue of fixing a price to the loss of life, assets and the environment is far from just technical. It is, in fact, an overwhelmingly ethical issue. However, it might be reasonable to consider the high risk of working in the Arctic offshore environment and the average salary an

individual earns throughout their active 35 service years. That is, if the risk of working offshore is 70% greater than working onshore (Tseng and Cullinane, 2018), then a conversion factor of 1.7 is utilised to calculate the value of human life. The conversion factor multiplied by an average annual salary of £100,000 for an individual oil worker in the Nordic countries (The Offshore Post, 2014), then multiplied by an individual service life of 35 years, puts the value of human life at approximately £6,000,000. This estimate sum will be assumed as the benefit derived from preventing the loss of life, assets, and damage to the Arctic environment. The above calculation is a mere generalisation, however, more details on the above calculation and other logical generalisations on the value of human life in a monetary unit can be seen in Partnoy (2012).

5) <u>Duration of implementation</u>: this refers to the time taken to carry out or install a risk control measure. Long terms risk control measures such as training are only considered on a yearly basis.

5.8.2 A review on the selection of RCOs targeted to prevent and control "the lack of situation awareness" risk in AMSSO

The alternatives (RCOs) in preventing and controlling the risks in AMSSO should include actions targeted to prevent the situation from manifesting in the first place, or actions targeted to reduce both the likelihood and the consequences of risk as well as the impact of the hazard to operation. There are a few published papers on AMSSO risk management. Nevertheless, a thorough literature review and knowledge from experts can be tailored towards achieving a safe and efficient AMSSO. See Table 24 for the list of RCOs targeted towards preventing and reducing the risk of situation awareness in AMSSO.

Table 24: RCOs tailored for lack of situation awareness risk in AMSSO

S/N	Alternative or RCO	Literature source
1	Training to improve knowledge and competence	Sandhåland et al. (2015), Zhang et al. (2019), Dalaklis and Baxevani (2018)
2	Teaching English language to improve communication	Expert, Berg et al. (2013), Wang and Zhang (2000)
3	Providing quality foods and exercise facilities to improve the crew's health and wellbeing	Carter et al. (2019), Expert
4	Use of durable and readable material for on-board information display	Nippon (2010), Expert
5	Automating the operation of the vessel	Ottesen (2014), Pazouki et al. (2018)
6	Provide physical barriers to restrict unintended access to important controllers	Nippon (2010), Expert
7	The design and installation of equipment should consider the user body size to avoid awkward posture	Nippon (2010), Expert
8	Improved navigation and communication equipment	Wright and Baldauf (2018), Aziz et al. (2019)
9	Improved recruitment procedure	Wang and Zhang (2000)
10	Providing education in cultural awareness and cultural sensitivity training	Horck (2008), Håvold et al. (2018)
11	Assigning personnel to monitor the roles and responsibilities of each crew member	Meyer (2016), Expert
12	Allocate resources for strategic planning	Wang and Zhang (2000), Expert
13	Assign personnel to monitor the workload distribution	Espevik and Olsen (2013), Ellis (2014), Expert
14	Non-operational use of cell phone/ entertainment device	SFS (2017), Towns (2007)
15	Training crew on how to react to rough weather situations	Expert, Wróbel et al. (2017)

The hierarchical structure of RCOs targeted to prevent the lack of situation awareness in AMSSO as used in this study is presented in Figure 34.

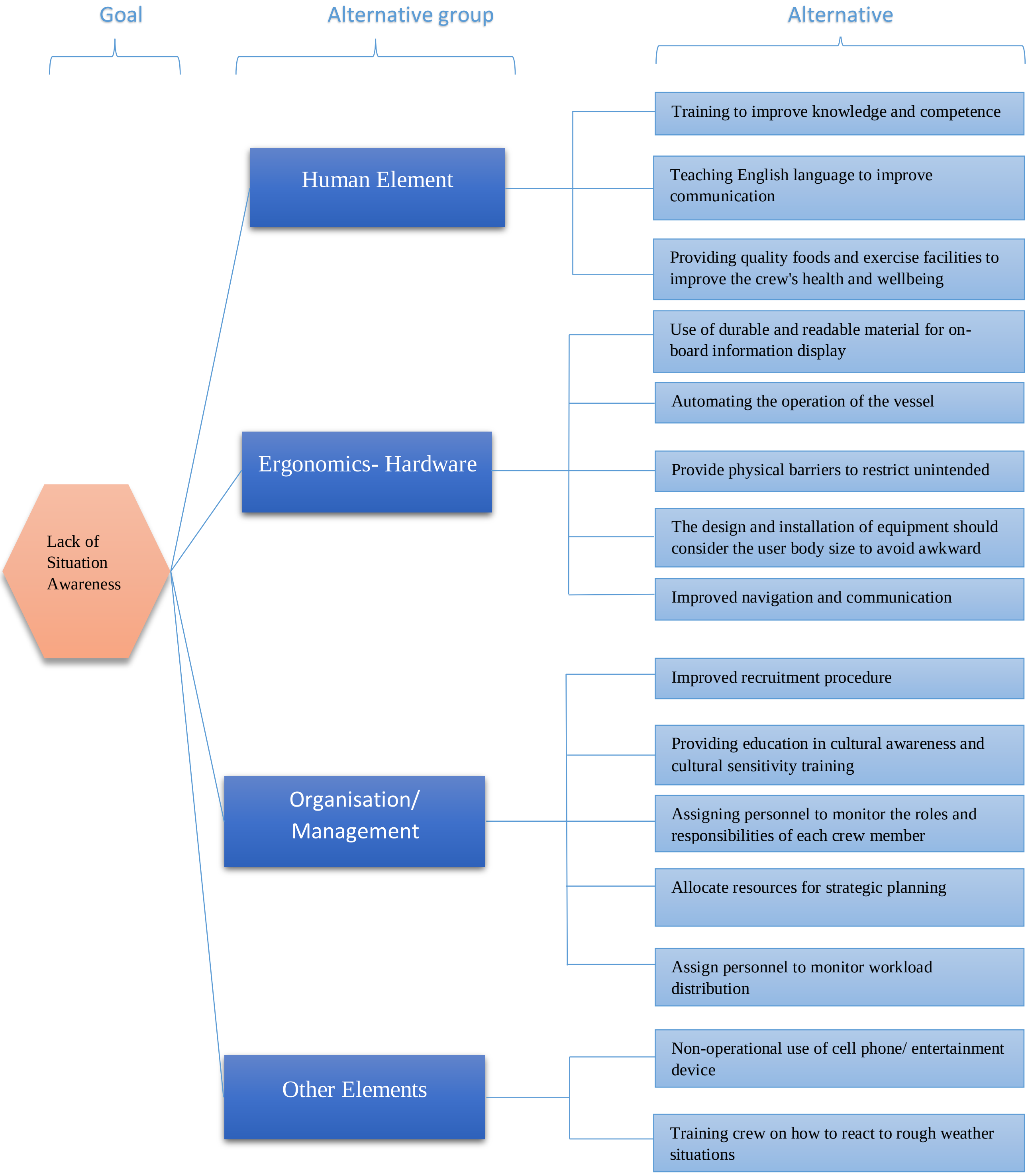

Figure 33: Hierarchical structure of RCOs for preventing the lack of situation awareness in AMSSO

5.8.2.1 Determining dependence among alternatives and sub-alternatives

The selection of a practical and cost-effective RCO in preventing or reducing/controlling risks is one of the most important tasks in marine and offshore risk management and decision sciences. The selected alternative group and alternatives represented in Figure 34, do not necessarily need to be independent of each other in real life. However, a check for the dependency of alternatives and sub-alternatives can be started by organising a checklist that is intended to capture the presence of interdependencies among alternatives and sub-alternatives. This checklist is comprised of blocks that are checked only if any of the alternative column data influences any of the sub-alternative data.

In addition, the questionnaires having the checklist are circulated among N members of the decision-maker's team. Once the questionnaire is completed, Equation 5.9 is employed to ascertain which blocks of the interdependency matrix $m \times m$ are fit to represent interdependency (Rajesri et al., 2015).

$$Q = \frac{N}{2} \qquad 5.9$$

If $v_{ij} \geq Q$, block is qualified

If $v_{ij} \leq Q$, block is disqualified

where N is the number of decision makers, v_{ij} is the overall number of votes allocated to the block matching to the i^{th} row and the j^{th} column of the interdependencies matrix, and $i, j = 1,2, \dots, m$. This implies that blocks that were earlier voted for by at least more than half of the decision-makers will be accepted as interdependent blocks.

However, in order to satisfy all doubts on the problems of alternative dependencies, decision- makers should pay more attention to the final list, that is, the sub alternatives in this context, of the RCO selection process, as the quality of the selection phase heavily depends on the final stage of the RCO selection process.

In the absence of interdependency among various levels in a network, AHP can assess the dependency of criteria in a specific level, and can also measure the relative importance or strength of impacts on a given criterion within a specific hierarchy level (Hashemi et al., 2015).

5.9 A test case of using AHP for order preference by similarity to the ideal solution (AHP-TOPSIS) methodology in risk control and management of AMSSO

The procedure represented in Figure 33 is demonstrated on an average size (76.8m × 16m) PC seismic vessel having an approximately 40-crew unit, operating in the GIN Sea. In this section, the feasibility of the AHP-TOPSIS methodology on selecting the most suitable RCO from various RCOs and criteria is illustrated. This hybrid methodology is achieved by incorporating expert judgement into the AHP-TOPSIS to realise a safe and efficient operation through an outright reduction of the alarming "lack of situation awareness" risk in AMSSO.

In developing the several RCOs and associated criteria, knowledge from previous sections are screened and tailored to accommodate the present study in order to arrive at a more effective risk prevention and control strategy. The most suitable RCO is targeted to control the risk of "lack of situational awareness" in GINS AMSSO.

5.9.1 Experts selection

A pre-elicitation meeting was organised in May 2018 with all the research Directors of Studies (DoS). The goals were: 1) to identify experts in the field of Arctic marine services, 2) to define the scope of the elicitation exercise and 3) to develop and set out the important questions that would be used to seek experts' subjective opinions. Having established the important questions to consider, 20 experts were targeted with the questionnaires owing to their specific experience. Consequently, only nine responses were deemed valid. The experience and nature of business of each of the four experts that contributed their knowledge and opinion are presented in Table 25.

Table 25: Expert's knowledge and experience

Experts	Company	Experience
1	A leading independent international seismic survey services company in the UK	11-20 years as a safety officer
2-4	A leading marine geophysical services company in Norway	6-10 years as a seismic survey crew member
5-6	A leading University in China	6-10 years as an Arctic risk management researcher
7-8	A leading marine service company in the UK	11-20 years as a marine assurance manager
9	A leading marine service company in the UK	11-20 years as a marine quality assurance advisor

A total of nine experts, whose backgrounds appear in Table 25, have supplied information regarding the RCOs and the associated criteria to carry out a case study to demonstrate the feasibility of the proposed AHP-TOPSIS methodology in selecting the most suitable RCO for preventing or controlling “lack of situation awareness” risk.

5.9.2 A Description of the risk level of “Lack of Situation Awareness” in AMSSO

Several hazard events and sources that pose a risk to the safety and the smooth running of AMSSO have been discussed thoroughly in Chapter 3. The Introduction of Fuzzy Rule-based Bayesian Network (FRBN) in Chapter 3 meant that the results from the advanced risk analysis method could be relied on. The hybrid FRBN and the ER methods that can be used to simplify the complex nature of operational risks in AMSSO both reveal that “lack of situational awareness” when assessed locally and globally presented an unaccepted risk level. The 59.84% (from local risk assessment) risk level of lack of situation awareness, having a RIF of 2.24, lies within the intolerable region of the FRBN benchmark risk. Due to the present risk level of “lack of situational awareness", strategic measures need to be identified and adopted with the aim of achieving a safe and efficient AMSSO since the Arctic region is still in the present state, underdeveloped and misunderstood (Mollitor, 2018).

5.9.3 Risk Control Options (RCOs) and linked criteria

In this section, the list of RCOs earlier presented in Figure 34 to reduce or prevent the risk of “lack of situational awareness” in AMSSO will be incorporated into the AHP-TOPSIS decision-making methodology. An AHP-TOPSIS hierarchy structure for the strategic risk control and prevention of lack of situation awareness in AMSSO is developed in Figure 35. The hierarchy structure in Figure 35 is clearly divided into three levels, with level one having the goal, level two having the criteria, and level three having the alternatives (RCOs) for controlling "lack of situational awareness".

The application of all RCOs will depend on the given criteria. The technical and operational risk control and prevention steps in Figure 33 starts from the identification of RCOs and linked criteria that can be referred to as the strategic selection of the most suitable RCO for a safe and efficient AMSSO.

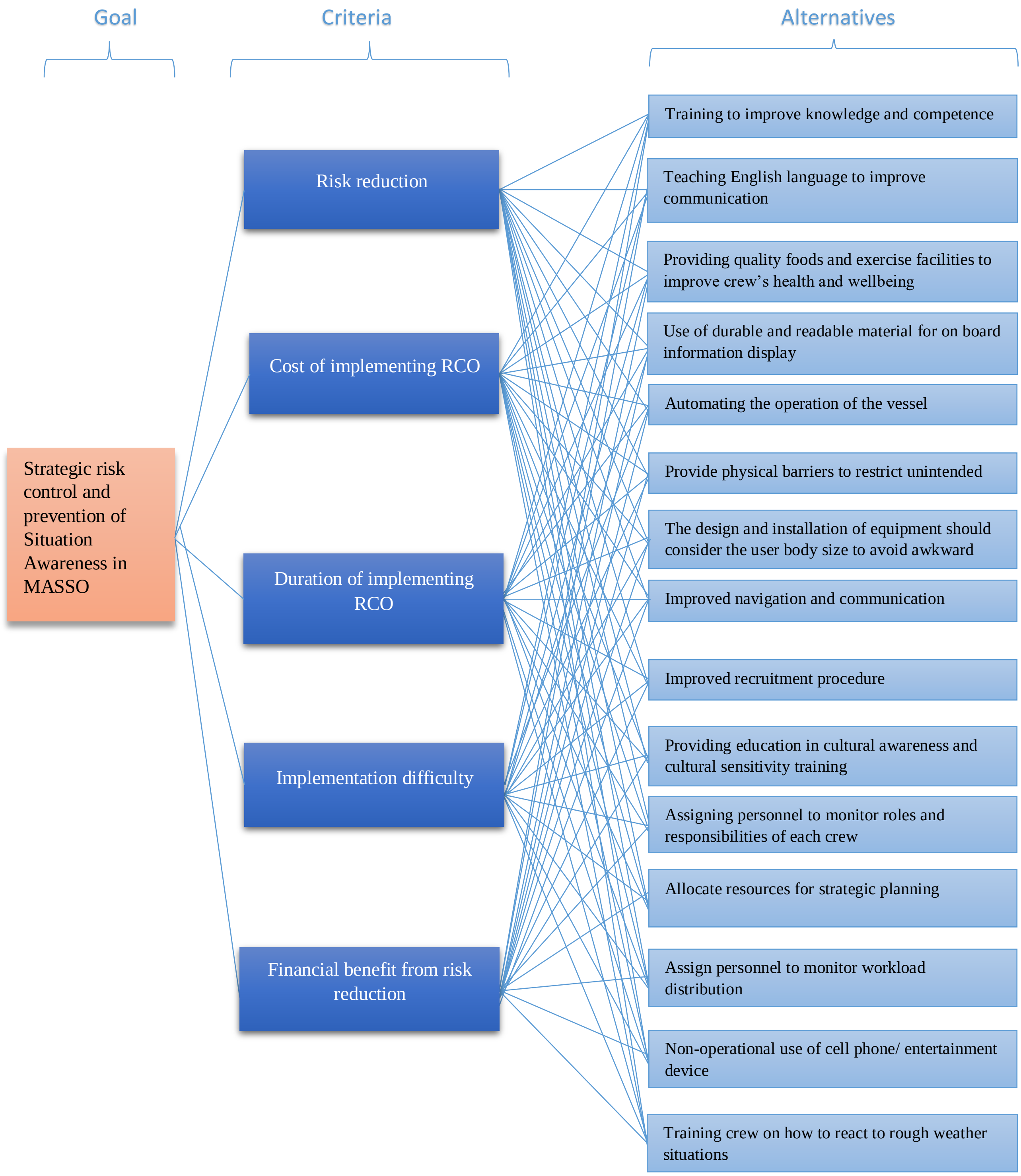

Figure 34: An AHP–TOPSIS hierarchical structure for the strategic risk control and prevention of lack of situation Awareness in AMSSO

The five criteria and fifteen alternatives that are more suited to preventing and controlling the risk of “lack of situation awareness” in AMSSO are identified based on expert opinions and through a thorough literature review as described in Table 24.

5.9.3.1 *Categorising the five criteria into Cost and Benefit in the Prevention and Control of “Lack of Situation Awareness” risk*

Risk reduction and financial benefit from risk reduction both fall under "benefit" (B) category, while the cost of implementing an RCO, duration of implementing an RCO and the technical difficulty of implementing an RCO all fall under "cost" (C) category. The lower the value of "cost", the more effective the RCO, and the higher the value of "benefit", the more sustainable the RCO. These two categories of "B" and "C" dividing into the five criteria for risk prevention and control is represented in Table 26.

Table 26: Benefit and Cost category

Criteria	Description	Category
C1	Risk reduction	B
C2	Cost of implementing RCO	C
C3	Duration of implementing RCO	C
C4	Technical difficulty of implementing an RCO	C
C5	Financial benefit from risk reduction	B

The definition of the five criteria in Table 26 has been described in section 5.8.1.

5.9.4 Evaluate the ratings of alternatives with respect to each criterion

In order to choose the most suitable RCO, experts are presented with a questionnaire. The assessment for the criteria through the questionnaire is set in a way that the experts can feel confident in contributing their experience. A group of four experts out of the nine whose background and experience have been presented in Table 25, judged each criterion with regard to each corresponding alternative. The evaluation of all alternatives with respect to both qualitative and quantitative criteria is presented in Table 27.

The column of financial benefit from risk reduction, C5 is calculated by multiplying the "risk reduction" by the cost of averting a fatality, £6,000,000GBP.

Table 27: Expert Judgement on the RCO values with respect to each criterion

Alternatives	Expert	C1	C2 in £	C3 in months	C4	C5
						Real Data
Training to improve knowledge and competence	Expert 1	VH-100	400000	4	L-3	5,383,200
	Expert 2	H- 80	46000	1	L- 3	
	Expert 3	VH- 90	NA	12	VH- 9	
	Expert 4	VH- 90	40000	1	L-2	
Teaching English language to improve communication	Expert 1	VH 90	100000	3	M- 5	4,408,800
	Expert 2	VH- 90	20000	1	M- 4	
	Expert 3	M- 40	NA	3	M- 4	
	Expert 4	VH- 90	16200	1	M- 6	
Providing quality foods and exercise facilities to improve crew's health and wellbeing	Expert 1	H- 70	100000	1	VL- 1	3,715,200
	Expert 2	H- 70	400000	12	L- 3	
	Expert 3	M- 50	NA	12	M- 4	
	Expert 4	M- 60	520000	12	L- 2	
Use of durable and readable material for on-board information display	Expert 1	H- 80	25000	1	VL- 1	3,741,600
	Expert 2	VH- 90	800000	8	H- 8	
	Expert 3	L- 30	NA	3	H- 7	
	Expert 4	H- 70	1000000	6	H- 7	
Automating the operation of the vessel	Expert 1	VH- 90	500000	3	M- 6	3,381,000
	Expert 2	M- 60	350000000	12	VH- 9	
	Expert 3	H- 70	NA	36	M- 6	
	Expert 4	L- 30	200000000	12	VH- 10	

Alternatives	Expert	C1	C2 in £	C3 in months	C4	C5 Real Data
Providing physical barriers to restrict unintended access to important controllers	Expert 1	H- 70	10000	1	M- 5	4,178,400
	Expert 2	H- 80	75000	6	H- 7	
	Expert 3	M- 60	NA	12	H- 7	
	Expert 4	H- 70	50000	6	H- 7	
The design and installation of equipment should consider the user body size to avoid awkward posture	Expert 1	H - 80	10000	1	M- 5	3,108,000
	Expert 2	H- 80	75000	12	H- 8	
	Expert 3	L- 30	NA	36	L- 3	
	Expert 4	M- 50	50000	12	M- 5	
Improve navigation and communication equipment	Expert 1	VH- 100	500000	3	H- 7	5,055,600
	Expert 2	VH- 90	80000	12	M- 5	
	Expert 3	H- 70	NA	36	H- 8	
	Expert 4	H- 80	60000	6	M- 5	
Improved recruitment procedure	Expert 1	H- 80	50000	6	M- 4	4,281,000
	Expert 2	VH- 90	10000	1	VL- 1	
	Expert 3	M- 40	NA	12	M- 6	
	Expert 4	VH- 90	5000	1	L- 2	
Providing education in cultural awareness and cultural sensitivity	Expert 1	H- 70	50000	1	M- 5	3,146,400
	Expert 2	VH- 90	15000	1	VL- 1	
	Expert 3	L- 20	NA	12	L- 2	
	Expert 4	H- 70	8000	1	L- 2	
Assigning personnel to monitor the roles and responsibility of each crew member	Expert 1	H- 80	50000	1	M- 4	3,381,000
	Expert 2	H- 70	35000	1	VL- 1	
	Expert 3	L- 30	NA	3	L- 3	
	Expert 4	H- 80	33600	1	VL- 1	
Allocate resources for strategic planning	Expert 1	VH- 90	50000	3	M- 5	4,156,800
	Expert 2	VH- 90	100000	1	VL- 1	
	Expert 3	M- 40	NA	3	M- 5	
	Expert 4	H- 80	200000	1	M- 6	
Assign personnel to monitor workload distribution	Expert 1	H- 80	20000	3	M- 4	4,178,400
	Expert 2	H- 70	35000	1	VL- 1	
	Expert 3	M- 60	NA	1	M- 6	

Alternatives	Expert	C1	C2 in £	C3 in months	C4	C5
						Real Data
	Expert 4	H- 80	33600	1	VL- 1	
Non-operational use of cell phones/entertainment devices	Expert 1	H- 80	20000	1	L- 3	3,574,800
	Expert 2	H- 70	5000	1	VL- 1	
	Expert 3	M- 50	NA	1	M- 4	
	Expert 4	M- 40	2000	1	L- 2	
Training crew on how to react to rough weather situations	Expert 1	VH- 90	150000	1	M- 4	5,091,000
	Expert 2	VH- 90	20000	1	L-3	
	Expert 3	VH- 90	NA	12	VH-10	
	Expert 4	H- 80	16200	1	L- 2	

5.9.5 Identification of Weights of Criteria for Optimal AMSSO using the AHP Methodology

AHP methodology is used to estimate the weights of the five criteria considered in controlling and preventing the risk of “lack of situational awareness" in the GIN Sea during an AMSSO. For the AHP methodology, five responses were received from the questionnaires that were sent out to 20 concerned experts as mentioned previously in section 5.9.1. An Excel spreadsheet is utilised in the pairwise comparison of the RCOs’ criteria in order to simplify Equation 4.2 and to represent the subjective judgement of each expert. The result from the Excel spreadsheet is represented in tabular form. Thereafter, a geometric mean is taken for the five responses to converge the subjective judgement of the five valid responses as shown in Table 28.

Table 28: Geometric Mean of subjective judgement of expert 1 to #5

	C1	C2	C3	C4	C5
C1	1.00	3.94	5.38	3.22	2.82
C2	0.25	1.00	4.36	2.91	1.32
C3	0.17	0.24	1.00	1.00	0.36
C4	0.32	0.34	1.00	1.00	0.62
C5	0.32	0.74	2.78	1.57	1.00
Sum=$\sum_1^5 A$	2.06	6.26	14.52	9.7	6.12

C1 to C5 have been defined in Table 26. The weighting vector of each element in the pairwise comparison matrix, representing the priority of the five criteria can be obtained using Equation 4.2 and simplified in Table 29.

Table 29: Prioritization of the RCOs' criteria

	C1	C2	C3	C4	C5	w_k
C1	0.49	0.63	0.37	0.33	0.46	0.46
C2	0.12	0.16	0.30	0.30	0.22	0.22
C3	0.08	0.04	0.07	0.10	0.06	0.07
C4	0.16	0.05	0.07	0.10	0.10	0.10
C5	0.16	0.12	0.19	0.16	0.16	0.16

The excel spreadsheet calculation reveals that:

W_{C1}= 0.46 (risk reduction).

W_{C2}= 0.22 (cost of implementing a RCO)

W_{C3}= 0.07 (duration of implanting a RCO).

W_{C4}= 0.10 (Technical difficulty of implementing a RCO).

W_{C5}= 0.16 (financial benefit of risk reduction).

These weights W_{C1} to W_{C5} only present relative importance between the criteria.

The values of weights (i.e. w_k) obtained in the subjective pairwise comparison need to be checked for consistency. This can be done using Equations 4.4, 4.5 and 4.6. The values of CI and λ_{max} are also revealed from the consistency check. The Random Index number which depends on the number of criteria being compared in a pairwise comparison evaluation is obtained from Saaty table (Saaty, 1980). CR value is obtained from the maximum Eigenvalue of the comparison matrix in Table 31.

Table 30: Maximum Eigenvalue of the comparison matrix

	C1	C2	C3	C4	C5	Sum	Sum /Weight
C1	0.46	0.87	0.38	0.32	0.45	2.48	5.39
C2	0.12	0.22	0.31	0.29	0.21	1.15	5.23
C3	0.08	0.05	0.07	0.10	0.06	0.36	5.14
C4	0.15	0.07	0.07	0.10	0.10	0.49	4.90
C5	0.15	0.16	0.19	0.16	0.16	0.82	5.13
λ_{max}							5.16

Table 31: Consistency Index and Ratio of the comparison matrix

λ_{max} (Lambda Max)	5.16
CI	0.04
CR	0.035

From the consistency check, it is revealed that there is great consistency in the subjective judgements of all experts; hence, the CR value equals 0.035 (less than 0.1)

5.9.6 Synthesising TOPSIS methodology in identifying the most suitable RCO for controlling and preventing the risk of "Lack of Situational Awareness" in AMSSO

Here, the TOPSIS mechanism is employed to enable the ranking of all RCOs. In dovetailing AHP with TOPSIS, all the criteria linked with the RCOs are classed as monotonic, as represented in Figure 34. A successful application of the TOPSIS method will mean that the criteria will be divided into two categories as represented in Table 26.

5.9.6.1 Development of TOPSIS Decision Matrix

By means of Equation 5.1, the development of a decision matrix can be obtained. Criteria categorised as *B*, are risk reduction, financial benefit from risk reduction, while the criteria categorised as *C*, are the duration of implementing an RCO, cost of implementing an RCO, and the technical difficulty of implementing an RCO. The various RCOs identified in this study will be rated around the five criteria. In order to rate the RCOs, experts are provided with an easy to understand questionnaire to rate the RCOs with respect to the criteria categorised as B as represented in Table 32. The criteria categorised, as C will be rated by taking data from the questionnaire feedbacks.

A summary of Table 27, that is, the expert judgement in the RCO values with respect to the five criteria is presented in a decision matrix table shown in Table 33.

Table 32: Benefit rating scale

Very Low %		Low %		Medium %			High %		Very High %	
0	10	20	30	40	50	60	70	80	90	100

Table 33: TOPSIS Decision Matrix

RCO	Cost of implementing RCO (£)	Financial benefit of risk reduction (£)	Risk reduction (%)	Technical difficulty of implementing an RCO	Duration of implementing an RCO
Training to improve knowledge and competence	90287.15	5,383,200	89.72	3.57	2.63
Teaching English language to improve communication	31879.76	4,408,800	73.48	4.68	1.73
Provide quality foods and exercise facilities to improve the crew's health and wellbeing	275013.8	3,715,200	61.92	2.63	6.45
Use of durable and readable material for on-board information display	271441.8	3,741,600	62.36	5.86	3.46
Automating the operation of the vessel	3271066	3,381,000	56.35	7.84	7.67
Providing physical barriers to restrict unintended access to important controllers	33471.65	4,178,400	69.64	6.09	4.56
The design and installation of equipment should consider the user body size to avoid awkward posture	33471.65	3,108,000	51.8	4.95	8.49
Improve navigation and communication equipment	133886.6	5,055,600	84.26	5.89	6.45

RCO	Cost of implementing RCO (£)	Financial benefit of risk reduction (£)	Risk reduction (%)	Technical difficulty of implementing an RCO	Duration of implementing an RCO
Improved recruitment procedure	13572.09	4281000	71.35	3.03	2.21
Providing education in cultural awareness and cultural sensitivity	18171.21	3,146,400	52.44	2.11	1.86
Assigning personnel to monitor the roles and responsibility of each crew member	83777.19	3,381,000	56.35	1.97	1.57
Allocate resources for strategic planning	100000	4,156,800	69.28	5.69	1.73
Assign personnel to monitor workload distribution	61727.56	4,178,400	69.64	2.34	1.32
Non-operational use of cell phones/entertainment devices	5848.04	3,574,800	59.58	2.00	1.32
Training crew on how to react to rough weather situations	36493.21	5,091,000	84.85	4.36	2.21

The cost of implementing “training to improve knowledge and competence” to address the risk of “lack of situation awareness” is £90,287.15 as represented in Table 33. The £90,287.15 is the geometric mean of £46,000, £400,000 and £40,000 as estimated by three experts respectively. In the same manner, the cost of implementing other RCOs is found. In addition, the risk reduction of implementing "training to improve knowledge and competence” is found to be 89.72% in Table 33. The 89.72% is the geometric mean of 100%, 90%, 90% and 80% as estimated by four experts respectively - the experts utilised the benefit rating scale presented in Table 32. In the same manner, the "risk reduction", "Technical difficulty of implementing an RCO" and "duration of implementing an RCO" on other RCOs are found.

Consequently, approximate values in Table 33 can be simplified and represented as $r_{i,j}$, where i- the row number while j- the column number as shown in Table 34.

Table 34: Decision-making evaluation

RCO	Cost of implementing RCO (£)	Financial benefit of risk reduction (£)	Risk reduction (%)	Technical difficulty of implementing an RCO	Duration of implementing an RCO
Training to improve knowledge and competence	$r_{1,1}$ = 90287.15	$r_{1,2}$ = 5,383,200	$r_{1,3}$ = 89.72	$r_{1,4}$ = 3.57	$r_{1,5}$ = 2.63
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
Training crew on how to react to rough weather situations	$r_{15,1}$ = 36493.21	$r_{15,2}$ = 5,091,000	$r_{15,3}$ = 84.85	$r_{15,4}$ = 4.36	$r_{15,5}$ = 2.21
$X_{ij} = \sqrt{\Sigma_{i=1}^{m} r_{ij}^2}$, $i = 1,2,\dots,m; j = 1,2,\dots,n$	3301701.33	15919203.12	265.320052	17.66429449	16.70207772

5.9.6.2 Construction of TOPSIS Normalised Decision Matrix

Data in Table 34 is normalised employing Equation 5.2. This is carried out to adjust the data values measured on different scales such as percentage, currency, and etc., to a notionally common scale. Two criteria need to be normalised, namely cost and benefit. Concerning the cost criterion, all values obtained are in British Pound Sterling (£)

units/year. In order to normalise the values in the cost category, Equation 5.2 is introduced. For example, the £90,287.15 cost of implementing "training to improve knowledge and competence" can be normalised by dividing £90,287.15 with the obtained value from $X_{ij} = \sqrt{\Sigma_{i=1}^{m} r_{ij}^2}$ in the "cost of implementing an RCO" column, which is £3,301,701.33.

In a similar way, the 89.72% risk reduction when "training to improve knowledge and competence" is implemented to reduce the risk of "lack of situation awareness", can be normalised by dividing 89.72 with the obtained value from $X_{ij} = \sqrt{\Sigma_{i=1}^{m} r_{ij}^2}$ in the "risk reduction" column, which is 265.320052. Other values are obtained in the same manner and represented in Table 35.

Table 35: TOPSIS Normalised Decision Matrix

RCO	Cost of implementing RCO (£)	Financial benefit of risk reduction (£)	Risk reduction (%)	Technical difficulty of implementing an RCO	Duration of implementing an RCO
Training to improve knowledge and competence	0.0273	0.3382	0.3382	0.2021	0.1575
Teaching English language to improve communication	0.0097	0.2769	0.2769	0.2649	0.1036
Provide quality foods and exercise facilities to improve the crew's health and wellbeing	0.0833	0.2334	0.2334	0.1489	0.3862
Use of durable and readable material for on-board information display	0.0822	0.2350	0.2350	0.3317	0.2072
Automating the operation of the vessel	0.9907	0.2124	0.2124	0.4438	0.4592
Providing physical barriers to restrict	0.0101	0.2625	0.2625	0.3448	0.2730

RCO	Cost of implementing RCO (£)	Financial benefit of risk reduction (£)	Risk reduction (%)	Technical difficulty of implementing an RCO	Duration of implementing an RCO
unintended access to important controllers					
The design and installation of equipment should consider the user body size to avoid awkward posture	0.0101	0.1952	0.1952	0.2802	0.5083
Improve navigation and communication equipment	0.0406	0.3176	0.3176	0.3334	0.3862
Improved recruitment procedure	0.0041	0.2689	0.2689	0.1715	0.1323
Providing education in cultural awareness and cultural sensitivity	0.0055	0.1976	0.1976	0.1195	0.1114
Assigning personnel to monitor the roles and responsibility of each crew member	0.0254	0.2124	0.2124	0.1115	0.0940
Allocate resources for strategic planning	0.0303	0.2611	0.2611	0.3221	0.1036
Assign personnel to monitor workload distribution	0.0187	0.2625	0.2625	0.1325	0.0790
Non-operational use of cell phones/entertainment devices	0.0018	0.2246	0.2246	0.1132	0.0790
Training crew on how to react to rough weather situations	0.0111	0.3198	0.3198	0.2468	0.1323

Here in Table 35, the obtained values can be described as $X_{1,1}$, $X_{1,2}$, ..., $X_{15,5}$. This numbering follows the order in Table 34, where for example, $X_{1,1}$= 0.0273.

5.9.6.3 Construction of TOPSIS Weighted Normalised Decision Matrix

Equation 5.3 is utilised to transform the normalised decision matrix to the weighted normalised decision matrix. Since weight is one of the variables in Equation 5.3, then, the values of risk reduction, cost of implementing an RCO, duration of implementing an RCO, Technical difficulty of implementing an RCO and the financial benefit from risk reduction needs to be incorporated in order to enable the development of weighted normalised decision matrix. The weights of the criteria are presented in the following order:

W_{C1}= 0.46 (risk reduction).

W_{C2}= 0.22 (cost of implementing a RCO).

W_{C5}= 0.16 (financial benefit of risk reduction).

W_{C4}= 0.10 (Technical difficulty of implementing an RCO).

W_{C3}= 0.07 (duration of implanting a RCO).

The application of Equation 5.3 resulted in the development of the weighted normalised decision matrix in Table 36.

Table 36: TOPSIS Weighted Normalised Decision Matrix

RCO	Cost of implementing RCO (£)	Financial benefit of risk reduction (£)	Risk reduction (%)	Technical difficulty of implementing an RCO	Duration of implementing an RCO
Training to improve knowledge and competence	0.0060	0.0541	0.1556	0.0202	0.0110
Teaching English language to improve communication	0.0021	0.0443	0.1274	0.0265	0.0073
Provide quality foods and exercise facilities to improve the crew's health and wellbeing	0.0183	0.0373	0.1074	0.0149	0.0270
Use of durable and readable material for on-board information display	0.0181	0.0376	0.1081	0.0332	0.0145
Automating the operation of the vessel	0.2180	0.0340	0.0977	0.0444	0.0321
Providing physical barriers to restrict unintended access to important controllers	0.0022	0.0420	0.1208	0.0345	0.0191
The design and installation of equipment should consider the user body size to avoid awkward posture	0.0022	0.0312	0.0898	0.0280	0.0356
Improve navigation and communication equipment	0.0089	0.0508	0.1461	0.0333	0.0270
Improved recruitment procedure	0.0009	0.0430	0.1237	0.0172	0.0093
Providing education in cultural awareness and cultural sensitivity	0.0012	0.0316	0.0909	0.0120	0.0078
Assigning personnel to monitor the roles and responsibility of each crew member	0.0056	0.0340	0.0977	0.0112	0.0066
Allocate resources for strategic planning	0.0067	0.0418	0.1201	0.0322	0.0073

RCO	Cost of implementing RCO (£)	Financial benefit of risk reduction (£)	Risk reduction (%)	Technical difficulty of implementing an RCO	Duration of implementing an RCO
Assign personnel to monitor workload distribution	0.0041	0.0420	0.1208	0.0133	0.0055
Non-operational use of cell phones/entertainment devices	0.0004	0.0359	0.1033	0.0113	0.0055
Training crew on how to react to rough weather situations	0.0024	0.0512	0.1471	0.0247	0.0093

In Table 36, the 0.0060 value for "training to improve knowledge and competence" with respect to "cost of implementing an RCO" is found as a result of multiplying W_{C1} (i.e. 0.46) with $X_{1,1}$, (i.e. 0.0273). In a similar way, other values of $V_{i,j}$ are calculated and represented in Table 36. The values in Table 36 can be described as $V_{1,1}$, $V_{1,2}$, …, $V_{15,5}$, this numbering follows the order described in Table 34.

5.9.6.4 Determination of Positive Ideal Solution, PIS, V^+

The value of $V_{1,1}$, $V_{1,2}$, $V_{1,3}$, … and $V_{15,5}$ with the introduction of Equations 5.4 and 5.5 will be used to calculate the $V^+$and V^- respectively. Therefore, V^+= $\{V_1{}^+$, $V_2{}^+$, $V_3{}^+$, $V_4{}^+$, $V_5{}^+\}$ =$\{0.0004, 0.0312, 0.1556, 0.0444, 0.0356\}$. These five values of V^+ are selected from each column of "cost of implementing an RCO", "financial benefit of risk reduction", "risk reduction", "technical difficulty of implementing an RCO" and "duration of implementing an RCO" in Table 36. These values are selected in line with Equation 5.4, that is, the selection of minimum values in each column of the criteria categorised as "C" and maximum values in each column of criteria categorised as "B".

5.9.6.5 Determination of Negative Ideal Solution, PIS, V^-

For the repeated time, five value are selected from the normalised weighted matrix to calculate the V^-. The $V^- = \{V_1{}^-, V_2{}^-, V_3{}^-, V_4{}^-, V_5{}^-\}$. Therefore, the $V^- = \{0.218, 0.0541, 0.0898, 0.0112, 0.055\}$. These five values of the V^- are selected from the column of "cost of implementing an RCO", "financial benefit of risk reduction", "risk reduction", "technical difficulty of implementing an RCO" and the "duration of implementing an RCO" in Table 36 in agreement with Equation 5.5. The principle in Equation 5.5 highlights that the maximum values are to be selected from each criterion categorised as "C", while minimum values are to be selected from each column of criteria in the "B" category.

5.9.6.6 Determination of the Distance Separation Measure for the PIS, $D_i{}^+$

It is necessary to calculate the distance separation, $D_i{}^+$ to facilitate the measurement of all the alternatives with their PIS. Since the values of V^+ and V^- have been revealed, then, $D_i{}^+$ can be calculated by applying Equation 5.6 with the calculated V^+ values, and the data presented in Table 36. Here, the row for "training to improve knowledge and competence" is linked with $V_{1,1}$, $V_{1,2}$, $V_{1,3}$, $V_{1,4}$, $V_{1,5}$ (0.0060, 0.0541, 0.1556, 0.0202 and 0.0110) with their corresponding values of $V_1{}^+$, $V_2{}^+$, $V_3{}^+$, $V_4{}^+$and $V_5{}^+$. Note that the $V_{1,1}$, $V_{1,4}$ and $V_{1,5}$ fall under the cost category while $V_{1,2}$ and $V_{1,3}$ fall under the benefit category. In view of this, values of $V_{1,1}$, $V_{1,2}$, $V_{1,3}$, $V_{1,4}$ and $V_{1,5}$ and those related to $V_1{}^+$, $V_2{}^+$, $V_3{}^+$, $V_4{}^+$, $V_5{}^+$ will be utilised to calculate the $D_i{}^-$ values as follows.

In summary, Table 37 is presented to simplify the extraction of data in the calculation of $D_i{}^+$ and $D_i{}^-$.

Table 37: Different values of V_j^+ and V_j^-

V_1^+	0.0004
V_2^+	0.0541
V_3^+	0.1556
V_4^+	0.0112
V_5^+	0.0055
V_1^-	0.218
V_2^-	0.0312
V_3^-	0.0898
V_4^-	0.0444
V_5^-	0.0356

Therefore, D_i^+can be calculated using Equation 5.6 as follows:

$$D_1^+ = \sqrt{\sum_{j=1}^{5} (V_{1j} - V_j^+)^2} =$$

$$\sqrt{(V_{1,1} - V_1^+)^2 + (V_{1,2} - V_2^+)^2 + (V_{1,3} - V_3^+)^2 + (V_{1,4} - V_4^+)^2 + (V_{1,5} - V_5^+)^2}$$

$$= \sqrt{(0.006 - 0.0004)^2 + (0.0541 - 0.0541)^2 + (0.1556 - 0.1556)^2 + (0.0202 - 0.0112)^2 + (0.0110 - 0.0055)^2}$$

= 0.0119

In a similar way, $D_2^+$to D_{15}^+ for the remaining fourteen RCOs are calculated. Please refer to Appendix 4-2.

5.9.6.7 Determination of the Distance Separation Measure for the PIS, D_i^-

The distance separation measure for the NIS, D_i^- for the fifteen RCOs can be calculated using their respective $V_{i,j}$ and V^- values. Note that the values of V_1^-, V_2^- , V_3^-, V_4^-, V_5^- has been revealed in Table 36. However, Equation 5.7 can be introduced to calculate the fifteen RCOs distance separation for the NIS, D_i^-. To commence the calculation for the D_i^-, the row of RCO for instance, termed "training to improve knowledge and competence", with the values of $V_{1,1}$, $V_{1,2}$, $V_{1,3}$, $V_{1,4}$, $V_{1,5}$ having 0.0060, 0.541, 0.1556, 0.202 and 0.0110 values respectively in Table 36 need to be categorised as value for benefit or cost criteria. $V_{1,1}$, $V_{1,2}$ fall under the cost category while $V_{1,3}$, $V_{1,4}$, $V_{1,5}$ fall under the benefit category. In view of this, values of $V_{1,1}$, $V_{1,2}$, $V_{1,3}$, $V_{1,4}$ and $V_{1,5}$ and those related to V_1^-, V_2^-, V_3^-, V_4^-, V_5^- will be utilised to calculate the D_i^- values as follows:

$$D_1^- = \sqrt{\sum_{j=1}^{5} (V_{1j} - V_j^-)^2} =$$

$$\sqrt{(V_{1,1} - V_1^-)^2 + (V_{1,2} - V_2^-)^2 + (V_{1,3} - V_3^-)^2 + (V_{1,4} - V_4^-)^2 + (V_{1,5} - V_5^-)^2}$$

$$= \sqrt{(0.006 - 0.218)^2 + (0.0541 - 0.0312)^2 + (0.1556 - 0.0898)^2 + (0.0202 - 0.0444)^2 + (0.0110 - 0.0356)^2}$$

$$= 0.2258$$

In a similar way, D_2^- to D_{15}^- for the remaining fourteen RCOs are calculated. Please refer to Appendix 4-3.

5.9.6.8 Determination of the Relative Closeness to Ideal Solution, RC_i^+

The determination of the relative closeness to Ideal Solution will enable the decision-making process. In this section, the RC_i^+ values of the fifteen RCOs will be utilised to represent the importance of each RCO, thereby offering a ranking mechanism for all the RCOs. The RCO with the highest RC_i^+ value will be more important than the ones below it in the hierarchy. Equation 5.8 will be introduced to commence the ranking process. The calculated values of D_i^+ and D_i^- are incorporated in Equation 5.8 to calculate their various relative closeness values thus:

$$RC_1^+ = \frac{D_1^-}{D_1^+ + D_1^-} = = \frac{0.2258}{0.0119 + 0.2258} = 0.949937$$

In a similar way, $RC_1{}^+$ values for the remaining fourteen RCOs are calculated. Please refer to Appendix 4-4.

In view of this, the prioritisation of the fifteen RCOs are presented in Table 38 as follows:

Table 38: $RC_i{}^+$ results and prioritisation of the fifteen RCOs

Alternatives	$D_i{}^+$	$D_i{}^-$	$RC_i{}^+$	Rank order
Training to improve knowledge and competence	0.0119	0.2258	0.949937	1
Teaching English language to improve communication	0.0336	0.2221	0.868596	3
Provide quality foods and exercise facilities to improve crew's health and wellbeing	0.0583	0.2029	0.776799	11
Use of durable and readable material for on-board information display	0.0584	0.2023	0.775988	12
Automating the operation of the vessel	0.2276	0.0091	0.038445	15
Providing physical barriers to restrict unintended access to important controllers	0.0457	0.2191	0.827417	8
The design and installation of equipment should consider the user body size to avoid awkward posture	0.0679	0.2164	0.761168	14
Improve navigation and communication equipment	0.0335	0.2179	0.866746	4
Improved recruitment procedure	0.0345	0.2233	0.866175	5
Providing education in cultural awareness and cultural sensitivity	0.0685	0.2210	0.763385	13
Assigning personnel to monitor roles and responsibility of each crew member	0.0615	0.2145	0.777174	10

Alternatives	D_i^+	D_i^-	RC_i^+	Rank order
Allocate resources for strategic planning	0.0435	0.2159	0.832305	7
Assign personnel to monitor workload distribution	0.0371	0.2186	0.854908	6
Non-operational use of cell phones/entertainment devices	0.0554	0.2206	0.799275	9
Training crew on how to react to rough weather situations	0.0168	0.2264	0.930921	2

5.9.7 An Ideal risk prevention and control strategy for the risk of "Lack of Situation Awareness" in AMSSO

Based on the results shown in Table 38, the most suitable solutions in preventing and controlling the risk of "lack of situation awareness" in AMSSO are those related to improving human elements. The most suitable RCO is measured against cost, the amount of risk reduced, the technical difficulty of implementing an RCO, the number of lives and property that can be saved from implementing the RCO and the duration to implement the RCO.

The most suitable RCO in tackling the lack of situation awareness in AMSSO when compared with other important RCOs is by investing in the training of crew members to improve knowledge and competence. The second choice on the RCO hierarchy will be the effective training of crew members on how to react to rough weather situations. The third choice on the RCO hierarchy will be the teaching of English language to improve communication. The fourth choice on the RCO hierarchy will be the improvement of navigation and communication equipment in the Arctic region and so on.

5.9.8 Model validation process

Testing the logicality and reliability of the results delivered in the proposed model is done through sensitivity analysis. Testing is imperative, mainly because of the participation of subjective elements in the generated methodology (Yang et al., 2008a). Testing the sensitivity in the developed AHP-TOPSIS method offers a logical and reliable subjective judgment for the conclusions of RCOs prioritisation.

In carrying out the sensitivity of the proposed model, the weight matched with one criterion is increased separately by 10, 20 and 30% while simultaneously decreasing the weights matched with other criteria by compensating the increment percentage on the increased criterion. These alterations are observed against the final ranking. It is observed that a slight increase in the value of distance separation measure for the PIS, D_i^+ for an RCO, resulted in a decrease of the relative closeness to an ideal solution, for that particular RCO.

The sensitivity of the fifteen RCOs has been analysed when the most important criterion "risk reduction" is increased separately by 10, 20 and 30% sequentially. The result achieved is presented in Figure 35. With such recursive increments, it is observed that some RCOs (such as R5 in Figure 36) go further away to the negative ideal solution. The negative value has no significance to the result since the sensitivity of the result is only meant to show how changes in the result can affect the AHP-TOPSIS RCOs.

Figure 35: Risk Reduction weight increments analysis

5.9.9 Results and Discussion

Sensitivity analysis is carried out to analyse the effect in the output data given a slight change in the most important criteria. It can be revealed from the sensitivity analysis that training of crew members to improve their competence and skills offers the most suitable solution in preventing and controlling the risk of "lack of situation awareness" in AMSSO. The analysis also further reveals that the "risk reduction" weight increment by 10, 20 and 30% did not have much effect on the final RCOs hierarchy. The slight alteration on the ${RC_i}^+$ of all RCOs can be observed visibly in Table 39:

Table 39: Risk-reduction weight increment influence on the fifteen RCOs

Alternatives	Original RC_i^+	With a 10% increase	With a 20% increase	With a 30% increase
Training to improve knowledge and competence	0.949937	0.849921	0.768921	0.678021
Teaching English language to improve communication	0.868596	0.788496	0.709596	0.619596
Provide quality foods and exercise facilities to improve the crew's health and wellbeing	0.776799	0.696599	0.613599	0.522699
Use of durable and readable material for on-board information display	0.775988	0.695588	0.613588	0.523288
Automating the operation of the vessel	0.038445	-0.042455	-0.121455	-0.212255
Providing physical barriers to restrict unintended access to important controllers	0.827417	0.747307	0.660307	0.569407
The design and installation of equipment should consider the user body size to avoid awkward posture	0.761168	0.680868	0.599868	0.509168
Improve navigation and communication equipment	0.866746	0.786246	0.706246	0.615446
Improved recruitment procedure	0.866175	0.785575	0.705575	0.615475
Providing education in cultural awareness and cultural sensitivity	0.763385	0.683485	0.602485	0.511685
Assigning personnel to monitor the roles and responsibility of each crew member	0.777174	0.696874	0.616274	0.526274
Allocate resources for strategic planning	0.832305	0.751805	0.670905	0.580105
Assign personnel to monitor workload distribution	0.854908	0.773908	0.693408	0.602608
Non-operational use of cell phones/entertainment devices	0.799275	0.719165	0.638865	0.547865

Alternatives	Original RC_i^+	With a 10% increase	With a 20% increase	With a 30% increase
Training crew on how to react to rough weather situations	0.930921	0.850621	0.768121	0.677921

5.10 Conclusion

Developing a highly efficient risk-based decision strategy in AMSSO risk prevention and control depends on the type of technique(s) selected, which would enable the precise assessment of risk priority and successfully take into account the various RCOs, especially in the absence of precise Cost-Benefit Assessment.

It is revealed in this chapter that, "training of crew members still remains a major priority in tacking risks. Training of staff to improve competence has been emphasised over the years to reduce marine accidents. For example, Recommendation 39 of The 1960 International Conference on the Safety of Life at Sea, called upon all contracting parties to 'take all practicable steps to ensure that the education and training of seafarers was kept satisfactorily up to date' (Lamson, 1987). It is therefore necessary to identify new training techniques that will give crew members/trainees the capacity to assess a situation accurately and quickly, and to carry out satisfactory actions.

In a bid to achieve a highly efficient risk-based decision strategy, this chapter presented a joint modelling and strategic decision-making technique for the selection of the most suitable AMSSO risk prevention and control. The joint AHP-TOPSIS approach presented in this chapter has demonstrated its ability to tackle the selection of fifteen RCOs under various hybrid criteria and alternatives. The application of the AHP-TOPSIS approach is new in the selected study, and it can be applied to situations where qualitative and quantitative data have to be synthesised both in normal and extraordinary situations.

The AHP-TOPSIS mechanism formulates a hybrid approach to investigate the weight of all identified criteria including the financial benefit from risk reduction, which was obtained by multiplying the risk reduction from expert data by the cost of averting a fatality. These investigated weights provided a ranking order for the identified RCOs. This new approach offers the most suitable solutions and the most preferred risk prevention and control strategy that is capable of tackling both risk reduction and operational efficiency in AMSSO. The proposed hybrid approach can be suited to tackle other risk factors in the Ship-Ice collision model and in other risk factors in AMSSO.

Chapter 6– Discussion

Overview

This chapter highlights the theoretical framework and models that have been developed to manage the dynamic risks in AMSSO, and thus offers a logical relationship connecting the developed framework with the models. The developed framework and models provide effective risk measurement and management strategies that can help Arctic marine seismic survey companies, including safety engineers, risk and Quality Assurance Managers, and other stakeholders in the oil and gas sector, to reduce risks in tapping the enormous natural resources in the Arctic region. However, there are other risk concerns in tapping the enormous natural resources in the Arctic that require further research, and the most significant ones are outlined in this chapter.

6.1 Research Contribution

AMSSO project is a high investment mission, with operational and financial risks having a close link in determining the safety and efficiency of a prospect project. Mitigating these risks is an important goal in ensuring the continued E&P of oil and gas and other natural resources in the Arctic region. Chapter 1 clearly reveals the copious amount of hydrocarbon resources in terms of oil and natural gas present in the Arctic, and as a result attracting mariners, politicians, and prospectors to all turn towards the North Pole. However, the pressure on the Arctic oil and gas resources only exacerbates the risks operating in such a poorly understood and underdeveloped region of the earth.

The continued over-reliance on fossil fuels and under-reliance on renewable energy resources prompted the dire need to establish a sensible risk-based methodology to prevent and control the known and envisaged risks in AMSSO. It is fair to mention the recent efforts made by the IMO and the Polar Code to ensure safety in Arctic shipping has been effective. However, no mention is made of the use of seismic survey vessels in the Arctic. A clear distinction arises between the use of seismic survey vessels and other vessels in the Arctic seas especially in the peculiar grid navigation of a seismic survey vessel. Hence, the lack of a suitable risk management structure to prevent and control the peculiar and dynamic risks of AMSSO is discussed extensively in Chapter 2. More details on some notable systematic structures to manage risks proactively such as the use of FSA and POLARIS and to deal with the intricacies of risk are detailed in Chapter 2.

A practical application of an adopted risk management framework, that is advanced and thorough in nature, to guarantee safe and efficient operation in AMSSO have been undertaken in Chapters 3, 4 and 5, through the development of modern novel risk-based models. The structure of the robust risk management framework carried out in this research has been executed in a way that it can be suited for a broader application in other engineering fields and management systems. Following the comprehensive risk management structure carried out in this research, decision-makers can easily prioritise risks or unwanted events in order to evaluate, predict and/or improve their system and/or reliability performance.

The advanced risk management framework described in Chapters 3, 4 and 5 begins by first describing the general scenario of risks in Arctic shipping. Although the identification and the description of risks/accidents are common to AMSSO, it was revealed from expert opinion and from the literature review in Chapter 2 that the identified risks associated with different categories of ships and activities vary tremendously. Hence, further investigation presented a comprehensive list of known and envisaged risk factors or otherwise termed “hazard events” typical to AMSSO. The description and identification of hazard events brought to bear a more specific goal of the investigation, termed “Ship-Ice Collision”. The Ship-Ice Collision constitutes largely to all significant issues related to all activities carried out in the Arctic waters as revealed from experts' judgement and from an extensive literature review. The description and identification of risk and the goal of investigation represent the first phase of the risk analysis section in Chapter 3.

The second phase of Chapter 3 involved the rationalisation of the *DoB* distribution in FMEA risk analysis. With the lack of properly documented historic accident data, it is hard to obtain objective information about a failure or hazard event. To overcome the shortage of objective data, an expert approximation is often used. Experts’ professional knowledge, first-hand experience and, sometimes, instinct can offer the required data. The introduction of rationalisation of the *DoB* distribution with an expert approximation was to overcome the complexity and bad interpretability of the approximated results in FMEA risk analysis.

This proportion method describes the relationship between risk parameters (*i.e.*, L, C, P, and I) in the antecedent (IF) part and risk levels in the consequent (THEN) part. In conjunction with the *DoBs*, a set of rules were established having fuzzy logic functions, this combination also referred to as “Fuzzy rule-base (FRB)” was developed in order to address uncertainty in data in order to arrive at the most critical hazard event(s). The introduction of BN in the risk-based FRB using Hugin Lite 8.0 can provide a platform for decision-makers to achieve a safe and efficient AMSSO by evaluating each hazard event locally, and thus, providing a reliable ranking order for hazard events. Details of the application of FRBN with a real-life case can be referred to in Chapter 3.

The final phase of the risk analysis section (see Chapter 4) which is all encompassing the risk analysis of the whole AMSSO system, involved a case study and development of AHP and ER using IDS software. The final phase of this risk analysis is introduced to ascertain the RIF of each hazard event to the global Ship-Ice Collision model.

The latter part of this section presented a new sensitivity analysis derived from the AHP-ER risk-based model, which provided a new global hazard event prioritisation, whilst taking into account all the hazard events' specific risk weights locally and their RI globally. More details of the AHP-ER mechanism can be seen in Chapter 4.

The safety engineer or stakeholder can rely on the joint risk analysis method as it addresses both event dependability and uncertainty in data. This joint methodology can help decision- makers to evaluate risks and to improve the safety and efficiency of the operational performance in AMSSO. The results obtained from this joint methodology are reliable and transparent, and hence risk reduction measures can be applied confidently to areas with high-risk values measured against the developed FRBN benchmark risk (see Chapter 3).

The description of the various risk reduction measures with their corresponding criteria represents the final phase (see Chapter 5) of the advanced risk management framework carried out in this research. The risk reduction measures also referred to as RCO, and their corresponding criteria were determined through literature review and through expert knowledge. The method to guarantee that an informed decision has been taken to prevent and control the high risk in AMSSO, involved the introduction of AHP and TOPSIS. The most suitable RCO to prevent an AMSSO accident will be an alternative that is

1. Practical,

2. Effective and yet
3. Economically sound.

The TOPSIS methodology offered a mechanism to find a non-monotonic utility output that answers the above three requirements. The utility output must be the one that minimises cost and maximises benefit (benefit such as risk prevention).

However, because of the inability of the TOPSIS methodology to tackle sufficiently the uncertainty of the weights/importance of criteria and imprecision inherent in the process of representing the perceptions of decision-makers, AHP is introduced to overcome this weakness of TOPSIS. Therefore, the utility output from the AHP-TOPSIS hybrid technique is transparent, reliable and has the full potential of tackling data uncertainty in risk control and prevention strategies. More details on the strategic process of selecting not just any RCO but those relevant to Ship-Ice Collision, and the validation process of the hybrid AHP-TOPSIS method are presented in Chapter 5.

Although this is the first time that AHP-TOPSIS will be utilised to select the most suitable RCO to control and prevent the high risks in AMSSO. A prominent scientific novelty in this research also lies in the fact that FRBN, with AHP-ER, have not been used in the related field as well. To this end, this research contributes hugely to both the risk analysis literature, and the technical treatment of risks and uncertainty in AMSSO and in Arctic shipping in general.

The new FRBN, with the AHP-ER have been developed in sequential order with an in-depth description and validation. These new models provide an integrated technique to prioritise risk and increase the reliability of AMSSO. The sequential order of arrangement of the proposed models is shown in the flow chart in Figure 37.

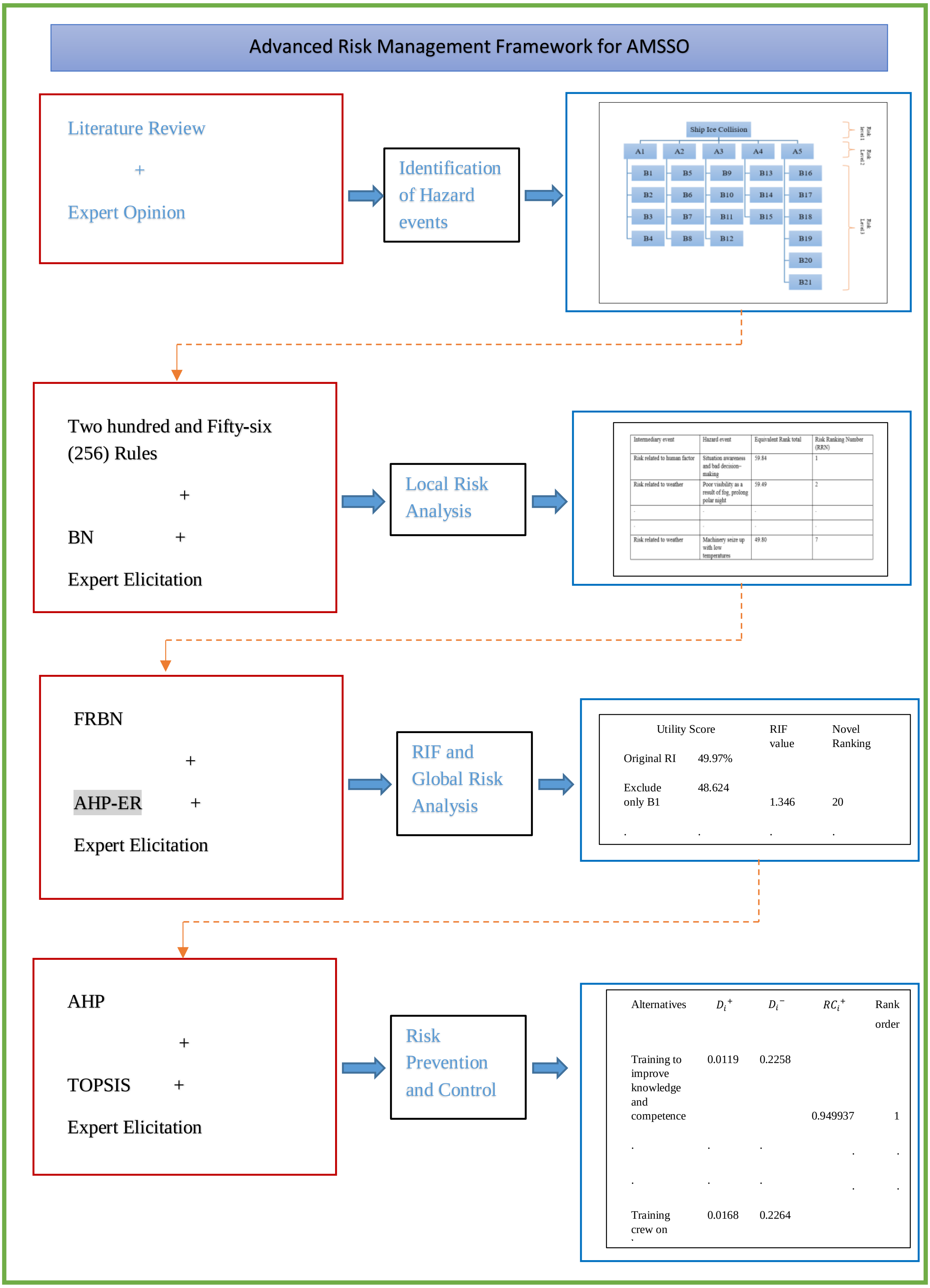

Figure 36: Overview of presented work

6.2 Research Limitations

This research mainly focussed on reducing and managing the risks in operation of an AMSSO. Although the scope of this research also extended to the management of the financial risks in AMSSO, other aspects of AMSSO such as the political, environmental and socio-economic impacts of AMSSO were not included in this research. In addition, the risk analysis carried out on Ship-Ice Collision in AMSSO using a new set of a hybrid tool revealed a list of significant hazard events. Further investigation on reducing the identified significant risks only focussed on the most critical risk on the list – there was no extension of investigation on the causes and effects of other hazard events. These constricted investigations only point to the fact that a full-scale investigation on preventing and managing other aspects of AMSSO concerns would be too voluminous to execute.

The FMEA technique with fuzzy logic referred to as the FRBN methodology, has limitations in the risk analysis of complex systems such as AMSSO. The main limitation points to the fact that the fuzzy reasoning approaches lack the ability to conduct inference inversely, meaning it is only a one-way technique. In other words, when a model is provided with a set of inputs, the IF-THEN only predict the output and not the THEN-IF backward route. In addition, the FRBN mechanism requires too much information, in the form of prior probabilities. However, this can be time-consuming and difficult to arrive at a complex system with multiple variables.

Lastly, the weight distribution of the risk parameters (*i.e.*, *L*, *C*, *P*, and *I*) have been assumed to be equal in the risk analysis section. However, in a practical sense, *C* might be greater than *L* or in any other proportion.

In conclusion, the major difficulty in choosing experts for their recognizable experience in the present research points to the fact that AMSSO is a new hot topic and hence, only a handful of experts filled and returned the questionnaires.

6.3 Suggestions for Future Research

Further examinations will consider a practical weight distribution for the risk parameters using any reliable technique such as AHP before the FRBN risk analysis can be carried out. Other suggested areas for future research are described as follows.

The dependency model for the Ship-Ice collision in Chapter 3 is presently set in a hierarchical tree also referred to as risk dendrogram. This might not be exact in the real world. The current topology compels each hazard event to have one, and only one parent attribute. With the present FRBN demonstrated in Chapter 3, an input attribute is only an input to one output but it is theoretically possible for an input attribute to contribute to more than one output attribute, by transforming the linear layout into a belief network. Nevertheless, further research will look into extending the linear tree to a network if practically possible.

With the current global warming trend, it is envisaged that the Arctic Sea will become more accessible; hence, more operation, and traffic will be more evident in the near future. More activities in the Arctic means more experience and lessons-learnt. Hence, there might be the hope of including more experts in future work; this suggestion will help to reduce the thoughts of bias if present in the current research subjective judgements.

This research only analysed one of the most critical risk factors in AMSSO namely “lack of situational awareness”. It appears beneficial to take into consideration other risk factors in AMSSO, and include other important threats influencing oil and gas E&P in the Arctic seas. Preventing and controlling threats such as policy implication, political, socio–

economic, environmental, and managerial concerns and threats to marine lives are suggested for further research.

However, the proposed risk management framework and models in this research have the ability to expedite the risk analysis of a system from the design stage to the process (operation) stage. The framework and models will need to be suitably fitted to study other new and trendy topics in and outside the maritime industry to provide practical help on the steps taken to implement an action plan for best practice. Thus, enhancing the risk management efficiency of the whole system.

Chapter 7– Conclusion

The pressure on the Arctic oil and gas resources, inevitably, attract human safety issues. Even though the operational safety and efficiency of exploring natural oil and gas in this region have been dealt with in previous chapters, it is fair to mention that the political, environmental and socio-economic impacts of Arctic resource exploration activity are as worrisome as the former.

The operational safety and efficiency of AMSSO as carried out in this research depended on a set of a thorough risk management strategy, taking into account the lack of historical accident/failure data, shortage of primary observations, hazard data uncertainty and uncertainty inherent in the AMSSO risk diagnostic models. The robust risk management strategy as utilised in this research has been achieved through an integration of a modern risk-based methodology and a set of MCDM techniques.

It is, therefore, appropriate to recap on the previous chapters in hierarchical order to ensure that the aims and objectives of this research have been realised, thus revealing the purpose behind every technique chosen in fulfilling the aim and objectives of this research.

The aim and objective of this research can be summarised thus:

1. Review the complex activities in the AMSSO to identify all critical hazard events including human factors influencing risks to AMSSOs.
2. Review the risk assessment and decision-making methods, that are capable of dealing with uncertainty and incompleteness of risk data both qualitatively and quantitatively, which have extensively been developed and used in the maritime domain.

3. Develop a bespoke advanced risk analysis model to support the proposed research objective.
4. Apply a bespoke technique to allocate scarce resources more practically and cost-effectively.
5. Analyse data to validate the risk management framework and techniques both for risk analysis and risk prevention via a trial application of the proposed framework and models.
6. Validate the risk outcome as well as the risk analysis and the decision-making models via sensitivity tests and logicalities.

Chapter 2 reviews the complex activities in the AMSSO as well as the statistical accident data from high-quality reference materials and publications. Several risk factors including those originating from the environment, human, technical, management and political factors were identified in Chapter 2. Also revealed in Chapter 2, are the intolerable risks of AMSSO. Besides, reports and statistics from 2009 to 2018 show over 486 cases, including 15 reported total vessels lost within the Arctic Circle.

It is revealed in Chapter 2 that integrating thinking offers one of the most reliable solutions to tackle some of the drawbacks of conventional risk analysis methodologies, and in the decision- making of the best allocation of scarce resources to prevent and reduce risks.

In Chapters 3 and 4, novel hybrid risk-based methodologies are presented to solve the main issues with the risk analysis of a complex system. In Chapter 5, a robust ready-to-use hybrid technique is offered to sensibly allocate resources for risk prevention and control.

An FRBN– a Bayesian Belief Network with fuzzy logic in FMEA methodology in Chapter 3–, has demonstrated the efficacy of the novel hybrid methodology in 1) treating failure data uncertainties, 2) permitting the dependability of hazard events and 3) taking into account multiple risk parameters. This last can take into account, the dynamic nature of the hazard events in the AMSSO.

The AHP-ER methodology, used in Chapter 4 to measure the global safety performance of AMSSO, agreed largely with the accident reports and statistics from Chapter 2, as AMSSO safety level is seen far above the ALARP region of the developed FRBN benchmark risk in Chapter 3.

AHP-TOPSIS methodology utilised in Chapter 5, has proved its efficacy in selecting the most suitable RCO in the presence of several criteria, in reducing the critical risks in AMSSO to a tolerable limit. The most suitable RCO with their matched criteria in the present study agrees– to a great extent–, with other similar studies carried out in similar fields.

Several approaches were reviewed to validate the knowledge-based risk analysis and control techniques; however, common sense and sensitivity analysis were a preferred option, since subjective data were mostly used in the risk management of the AMSSO system.

In conclusion, the risk management framework presented in this research can assist safety engineers to measure their safety performance and to ensure that important steps are not overlooked in AMSSO risk management projects.

The combination of more than one risk-based methodologies as used in this research, offered a more realistic approach to describe input hazard data and facilitated an easy update of the risk analysis, and real-time safety evaluation of AMSSO. This combination not only offers a means to tackle major risk analysis concerns (such as dynamic event risk analysis, hazard data uncertainties, and hazard event dependencies) but helped to dilute the possibility of misjudgement in the risk data and offered a more thorough strategy to assess and control the risks in AMSSO.

Since it was necessary to obtain a suitable balance among benefits, costs, and resources for risk reduction and prevention, it became inevitable to apply a hybrid MCDM methodology, capable of offering a non-monotonic utility output. AHP-TOPSIS hybrid methodology was utilised to offer a non-monotonic utility output, having a maximum utility located somewhere in the middle of the RCOs' range. This consequently guaranteed a cost effective RCO to reduce and prevent the critical risks in AMSSO.

Roughly, 600 websites and PDFs results were found in the course of this study. Criteria for the AMSSO risk-management topic search via an advanced Google search on the 8th of January 2019 included:

- all these words: accident analysis risk management of Arctic operation
- this exact word or phrase: "Arctic seismic exploration"
- any of these words: Arctic geo-data acquisition OR Arctic oil and gas exploration.

However, most of the results highlighted Arctic navigation, Arctic shipping and operations, and Arctic drilling, but none dedicated to AMSSO risk management. Therefore, the scope of the work presented has not only been drawn from Arctic oil and gas explorations but also, in studies related to other complex systems, including marine and nuclear domains.

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Publications

1. FORMAL SAFETY ASSESSMENT OF A MARINE SEISMIC SURVEY VESSEL OPERATION, INCORPORATING RISK MATRIX AND FAULT TREE ANALYSIS

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2. ADVANCED RISK MANAGEMENT OF AN ARCTIC MARINE SEISMIC SURVEY OPERATION: A LITERATURE REVIEW
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Advanced risk management of an Arctic Marine Seismic Survey Operation: a literature review

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Abstract:

Arctic marine accidents are important failure events, which significantly affect Arctic navigation and Arctic oil and gas exploration. A review of accident statistics within the Arctic Circle from 2009 to 2018 reveals 486 accidents/incidents and 15 total losses of vessels over 100GT. The consequences and magnitude of these accidents can be catastrophic for Arctic Marine Seismic Survey Operation (AMSSO), society, and the environment. This highlights the significance of an appropriate risk management framework for analysing and preventing the associated risks. Through an extensive literature review on various formal-risk analysis methodologies, it can be inferred that integrating thinking offers one of the most reliable approaches to understand, tackle and mitigate the high risks in a complex system such as AMSSO. This concept offers a viable option to close the gap between theory and practical risk management. A structured methodological framework– FSA methodology–, issued by the International Maritime Organization (IMO) is adopted in this paper to reduce and prevent the possible catastrophic accidents in AMSSO as an economically viable strategy. It is worth mentioning that the literature herein is only intended to provide a framework for the risk management of AMSSO.

Keywords: *Arctic Marine Seismic Survey Operation, Risk modelling, Decision-making, Formal Safety Assessment, Risk management*

APPENDICES

Appendix 1-1: FRB with Belief Structures for Chapter 3

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
No	(L)	(C)	(P)	(I)	V.Low (R1)	Low (R2)	Medium (R3)	High (R4)
1	V.Low (L1)	V.Low (C1)	V.Low (P1)	V.Low (I1)	1	0	0	0
2	V.Low (L1)	V.Low (C1)	V.Low (P1)	Low (I2)	0.75	0.25	0	0
3	V.Low (L1)	V.Low (C1)	V.Low (P1)	Medium (I3)	0.75	0	0.25	0
4	V.Low (L1)	V.Low(C1)	V.Low (P1)	High (I4)	0.75	0	0	0.25
5	V.Low (L1)	Low (C2)	V.Low (P1)	V.Low (I1)	0.75	0.25	0	0
6	V.Low (L1)	Low (C2)	V.Low (P1)	Low (I2)	0.5	0.5	0	0
7	V.Low (L1)	Low (C2)	V.Low (P1)	Medium (I3)	0.5	0.25	0.25	0
8	V.Low (L1)	Low (C2)	V.Low (P1)	High (I4)	0.5	0.25	0	0.25
9	V.Low (L1)	Medium (C3)	V.Low (P1)	V.Low (I2) (I1)	0.75	0	0.25	0
10	V.Low (L1)	Medium (C3)	V.Low (P1)	Low (I2)	0.5	0.25	0.25	0
11	V.Low (L1)	Medium (C3)	V.Low (P1)	Medium (I3)	0.5	0	0.5	0
12	V.Low (L1)	Medium (C3)	V.Low (P1)	High (I4)	0.5	0	0.25	0.25

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
13	V.Low (L1)	High (C4)	V.Low (P1)	V.Low (I1)	0.75	0	0	0.25
14	V.Low (L1)	High (C4)	V.Low (P1)	Low (I2)	0.5	0.25	0	0.25
15	V.Low (L1)	High (C4)	V.Low (P1)	Medium (I3)	0.5	0	0.25	0.25
16	V.Low (L1)	High (C4)	V.Low (P1)	High (I4)	0.5	0	0	0.5
17	V.Low (L1)	V.Low (C1)	Low (P2)	V.Low (I1)	0.75	0.25	0	0
18	V.Low (L1)	V.Low (C1)	Low (P2)	Low (I2)	0.5	0.5	0	0
19	V.Low (L1)	V.Low (C1)	Low (P2)	Medium (I3)	0.5	0.25	0.25	0
20	V.Low (L1)	V.Low (C1)	Low (P2)	High (I4)	0.5	0.25	0	0.25
21	V.Low (L1)	Low (C2)	Low (P2)	V.Low (I1)	0.5	0.5	0	0
22	V.Low (L1)	Low (C2)	Low (P2)	Low (I2)	0.25	0.75	0	0
23	V.Low (L1)	Low (C2)	Low (P2)	Medium (I3)	0.25	0.5	0.25	0
24	V.Low (L1)	Low (C2)	Low (P2)	High (I4)	0.25	0.5	0	0.25
25	V.Low (L1)	Medium (C3)	Low (P2)	V.Low (I1)	0.5	0.25	0.25	0
26	V.Low (L1)	Medium (C3)	Low (P2)	Low (I2)	0.25	0.5	0.25	0

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
27	V.Low (L1)	Medium (C3)	Low (P2)	Medium (I3)	0.25	0.25	0.5	0
28	V.Low (L1)	Medium (C3)	Low (P2)	High (I4)	0.25	0.25	0.25	0.25
29	V.Low (L1)	High (C4)	Medium (P3)	V.Low (I1)	0.5	0	0.25	0.25
30	V.Low (L1)	High (C4)	Medium (P3)	Low (I2)	0.25	0.25	0.25	0.25
31	V.Low (L1)	High (C4)	Medium (P3)	Medium (I3)	0.25	0	0.5	0.25
32	V.Low (L1)	High (C4)	Medium (P3)	High (I4)	0.25	0	0.25	0.5
33	V.Low (L1)	V.Low (C1)	Medium (P3)	V.Low (I1)	0.75	0	0.25	0
34	V.Low (L1)	V.Low (C1)	Medium (P3)	Low (I2)	0.5	0.25	0.25	0
35	V.Low (L1)	V.Low (C1)	Medium (P3)	Medium (I3)	0.5	0	0.5	0
36	V.Low (L1)	V.Low (C1)	Medium (P3)	High (I4)	0.5	0	0.25	0.25
37	V.Low (L1)	Low (C2)	Medium (P3)	V.Low (I1)	0.5	0.25	0.25	0
38	V.Low (L1)	Low (C2)	Medium (P3)	Low (I2)	0.25	0.5	0.25	0
39	V.Low (L1)	Low (C2)	Medium (P3)	Medium (I3)	0.25	0.25	0.5	0
40	V.Low (L1)	Low (C2)	Medium (P3)	High (I4)	0.25	0.25	0.25	0.25

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
41	V.Low (L1)	Medium (C3)	Medium (P3)	V.Low (I1)	0.5	0	0.5	0
42	V.Low (L1)	Medium (C3)	Medium (P3)	Low (I2)	0.25	0.25	0.5	0
43	V.Low (L1)	Medium (C3)	Medium (P3)	Medium (I3)	0.25	0	0.75	0
44	V.Low (L1)	Medium (C3)	Medium (P3)	High (I4)	0.25	0	0.5	0.25
45	V.Low (L1)	High (C4)	High (P4)	V.Low (I1)	0.5	0	0	0.5
46	V.Low (L1)	High (C4)	High (P4)	Low (I2)	0.25	0.25	0	0.5
47	V.Low (L1)	High (C4)	High (P4)	Medium (I3)	0.25	0	0.25	0.5
48	V.Low (L1)	High (C4)	High (P4)	High (I4)	0.25	0	0	0.75
49	V.Low (L1)	V.Low (C1)	High (P4)	V.Low (I1)	0.75	0	0	0.25
50	V.Low (L1)	V.Low (C1)	High (P4)	Low (I2)	0.5	0.25	0	0.25
51	V.Low (L1)	V.Low (C1)	High (P4)	Medium (I3)	0.5	0	0.25	0.25
52	V.Low (L1)	V.Low (C1)	High (P4)	High (I4)	0.5	0	0	0.5
53	V.Low (L1)	Low (C2)	High (P4)	V.Low (I1)	0.5	0.25	0	0.25
54	V.Low (L1)	Low (C2)	High (P4)	Low (I2)	0.25	0.5	0	0.25

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
55	V.Low (L1)	Low (C2)	High (P4)	Medium (I3)	0.25	0.25	0.25	0.25
56	V.Low (L1)	Low (C2)	High (P4)	High (I4)	0.25	0.25	0	0.5
57	V.Low (L1)	Medium (C3)	High (P4)	V.Low (I1)	0.5	0	0.25	0.25
58	V.Low (L1)	Medium (C3)	High (P4)	Low (I2)	0.25	0.25	0.25	0.25
59	V.Low (L1)	Medium (C3)	High (P4)	Medium (I3)	0.25	0	0.5	0.25
60	V.Low (L1)	Medium (C3)	High (P4)	High (I4)	0.25	0	0.25	0.5
61	V.Low (L1)	High (C4)	V.Low (P1)	V.Low (I1)	0.75	0	0	0.25
62	V.Low (L1)	High (C4)	V.Low (P1)	Low (I2)	0.5	0.25	0	0.25
63	V.Low (L1)	High (C4)	V.Low (P1)	Medium (I3)	0.5	0	0.25	0.25
64	V.Low (L1)	High (C4)	V.Low (P1)	High (I4)	0.5	0	0	0.5
65	Low (L2)	V.Low (C1)	V.Low (P1)	V.Low (I1) (C1)	0.75	0.25	0	0
66	Low (L2)	V.Low (C1)	V.Low (P1)	Low (I2)	0.5	0.5	0	0
67	Low (L2)	V.Low (C1)	V.Low (P1)	Medium (I3)	0.5	0.25	0.25	0
68	Low (L2)	V.Low (C1)	V.Low (P1)	High (I4)	0.5	0.25	0	0.25

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
69	Low (L2)	Low (C2)	V.Low (P1)	V.Low (I1) (C1)	0.5	0.5	0	0
70	Low (L2)	Low (C2)	V.Low (P1)	Low (I2)	0.25	0.75	0	0
71	Low (L2)	Low (C2)	V.Low (P1)	Medium (I3)	0.25	0.5	0.25	0
72	Low (L2)	Low (C2)	V.Low (P1)	High (I4)	0.25	0.5	0	0.25
73	Low (L2)	Medium (C3)	V.Low (P1)	V.Low (I1) (C1)	0.5	0.25	0.25	0
74	Low (L2)	Medium (C3)	V.Low (P1)	Low (I2)	0.25	0.5	0.25	0
75	Low (L2)	Medium (C3)	V.Low (P1)	Medium (I3)	0.25	0.25	0.5	0
76	Low (L2)	Medium (C3)	V.Low (P1)	High (I4)	0.25	0.25	0.25	0.25
77	Low (L2)	High (C4)	Low (P2)	V.Low (I1)	0.25	0.5	0	0.25
78	Low (L2)	High (C4)	Low (P2)	Low (I2)	0	0.75	0	0.25
79	Low (L2)	High (C4)	Low (P2)	Medium (I3)	0	0.5	0.25	0.25
80	Low (L2)	High (C4)	Low (P2)	High (I4)	0	0.5	0	0.5
81	Low (L2)	V.Low (C1)	Low (P2)	V.Low (I1)	0.5	0.5	0	0
82	Low (L2)	V.Low (C1)	Low (P2)	Low (I2)	0.25	0.75	0	0
83	Low (L2)	V.Low (C1)	Low (P2)	Medium (I3)	0.25	0.5	0.25	0
84	Low (L2)	V.Low (C1)	Low (P2)	High (I4)	0.25	0.5	0	0.25
85	Low (L2)	Low (C2)	Low (P2)	V.Low (I1)	0.25	0.75	0	0
86	Low (L2)	Low (C2)	Low (P2)	Low (I2)	0	1	0	0

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
87	Low (L2)	Low (C2)	Low (P2)	Medium (I3)	0	0.75	0.25	0
88	Low (L2)	Low (C2)	Low (P2)	High (I4)	0	0.75	0	0.25
89	Low (L2)	Medium (C3)	Low (P2)	V.Low (I1)	0.25	0.5	0.25	0
90	Low (L2)	Medium (C3)	Low (P2)	Low (I2)	0	0.75	0.25	0
91	Low (L2)	Medium (C3)	Low (P2)	Medium (I3)	0	0.5	0.5	0
92	Low (L2)	Medium (C3)	Low (P2)	High (I4)	0	0.5	0.25	0.25
93	Low (L2)	High (C4)	Medium (P3)	V.Low (I1)	0.25	0.25	0.25	0.25
94	Low (L2)	High (C4)	Medium (P3)	Low (I2)	0	0.5	0.25	0.25
95	Low (L2)	High (C4)	Medium (P3)	Medium (I3)	0	0.25	0.5	0.25
96	Low (L2)	High (C4)	Medium (P3)	High (I4)	0	0.25	0.25	0.5
97	Low (L2)	V.Low (C1)	Medium (P3)	V.Low (I1)	0.5	0.25	0.25	0
98	Low (L2)	V.Low (C1)	Medium (P3)	Low (I2)	0.25	0.5	0.25	0
99	Low (L2)	V.Low (C1)	Medium (P3)	Medium (I3)	0.25	0.25	0.5	0
100	Low (L2)	V.Low (C1)	Medium (P3)	High (I4)	0.25	0.25	0.25	0.25
101	Low (L2)	Low (C2)	Medium (P3)	V.Low (I1)	0.25	0.5	0.25	0

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
102	Low (L2)	Low (C2)	Medium (P3)	Low (I2)	0	0.75	0.25	0
103	Low (L2)	Low (C2)	Medium (P3)	Medium (I3)	0	0.5	0.5	0
104	Low (L2)	Low (C2)	Medium (P3)	High (I4)	0	0.5	0.25	0.25
105	Low (L2)	Medium (C3)	Medium (P3)	V.Low (I1)	0.25	0.25	0.5	0
106	Low (L2)	Medium (C3)	Medium (P3)	Low (I2)	0	0.5	0.5	0
107	Low (L2)	Medium (C3)	Medium (P3)	Medium (I3)	0	0.25	0.75	0
108	Low (L2)	Medium (C3)	Medium (P3)	High (I4)	0	0.25	0.5	0.25
109	Low (L2)	High (C4)	High (P4)	V.Low (I1)	0.25	0.25	0	0.5
110	Low (L2)	High (C4)	High (P4)	Low (I2)	0	0.5	0	0.5
111	Low (L2)	High (C4)	High (P4)	Medium (I3)	0	0.25	0.25	0.5
112	Low (L2)	High (C4)	High (P4)	High (I4)	0	0.25	0	0.75
113	Low (L2)	V.Low (C1)	High (P4)	V.Low (I1)	0.5	0.25	0	0.25
114	Low (L2)	V.Low (C1)	High (P4)	Low (I2)	0.25	0.5	0	0.25
115	Low (L2)	V.Low (C1)	High (P4)	Medium (I3)	0.25	0.25	0.25	0.25
116	Low (L2)	V.Low (C1)	High (P4)	High (I4)	0.25	0.25	0	0.5
117	Low (L2)	Low (C2)	High (P4)	V.Low (I1)	0.25	0.5	0	0.25
118	Low (L2)	Low (C2)	High (P4)	Low (I2)	0	0.75	0	0.25
119	Low (L2)	Low (C2)	High (P4)	Medium (I3)	0	0.5	0.25	0.25

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
120	Low (L2)	Low (C2)	High (P4)	High (I4)	0	0.5	0	0.5
121	Low (L2)	Medium (C3)	High (P4)	V.Low (I1)	0.25	0.25	0.25	0.25
122	Low (L2)	Medium (C3)	High (P4)	Low (I2)	0	0.5	0.25	0.25
123	Low (L2)	Medium (C3)	High (P4)	Medium (I3)	0	0.25	0.5	0.25
124	Low (L2)	Medium (C3)	High (P4)	High (I4)	0	0.25	0.25	0.5
125	Low (L2)	High (C4)	V.Low (P1)	V.Low (I1)	0.5	0.25	0	0.25
126	Low (L2)	High (C4)	V.Low (P1)	Low (I2)	0.25	0.5	0	0.25
127	Low (L2)	High (C4)	V.Low (P1)	Medium (I3)	0.25	0.25	0.25	0.25
128	Low (L2)	High (C4)	V.Low (P1)	High (I4)	0.25	0.25	0	0.5
129	Medium (L3)	V.Low (C1)	V.Low (P1)	V.Low (I1)	0.75	0	0.25	0
130	Medium (L3)	V.Low (C1)	V.Low (P1)	Low (I2)	0.5	0.25	0.25	0
131	Medium (L3)	V.Low (C1)	V.Low (P1)	Medium (I3)	0.5	0	0.5	0
132	Medium (L3)	V.Low (C1)	V.Low (P1)	High (I4)	0.5	0	0.25	0.25
133	Medium (L3)	Low (C2)	V.Low (P1)	V.Low (I1)	0.5	0.25	0.25	0
134	Medium (L3)	Low (C2)	V.Low (P1)	Low (I2)	0.25	0.5	0.25	0

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
135	Medium (L3)	Low (C2)	V.Low (P1)	Medium (I3)	0.25	0.25	0.5	0
136	Medium (L3)	Low (C2)	V.Low (P1)	High (I4)	0.25	0.25	0.25	0.25
137	Medium (L3)	Medium (C3)	V.Low (P1)	V.Low (I1)	0.5	0	0.5	0
138	Medium (L3)	Medium (C3)	V.Low (P1)	Low (I2)	0.25	0.25	0.5	0
139	Medium (L3)	Medium (C3)	V.Low (P1)	Medium (I3)	0.25	0	0.75	0
140	Medium (L3)	Medium (C3)	V.Low (P1)	High (I4)	0.25	0	0.5	0.25
141	Medium (L3)	High (C4)	Low (P2)	V.Low (I1)	0.25	0.25	0.25	0.25
142	Medium (L3)	High (C4)	Low (P2)	Low (I2)	0	0.5	0.25	0.25
143	Medium (L3)	High (C4)	Low (P2)	Medium (I3)	0	0.25	0.5	0.25
144	Medium (L3)	High (C4)	Low (P2)	High (I4)	0	0.25	0.25	0.5
145	Medium (L3)	V.Low (C1)	Low (P2)	V.Low (I1)	0.5	0.25	0.25	0
146	Medium (L3)	V.Low (C1)	Low (P2)	Low (I2)	0.25	0.5	0.25	0
147	Medium (L3)	V.Low (C1)	Low (P2)	Medium (I3)	0.25	0.25	0.5	0
148	Medium (L3)	V.Low (C1)	Low (P2)	High (I4)	0.25	0.25	0.25	0.25
150	Medium (L3)	Low (C2)	Low (P2)	V.Low (I1)	0.25	0.5	0.25	0
151	Medium (L3)	Low (C2)	Low (P2)	Low (I2)	0	0.75	0.25	0

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
152	Medium (L3)	Low (C2)	Low (P2)	Medium (I3)	0	0.5	0.5	0
153	Medium (L3)	Low (C2)	Low (P2)	High (I4)	0	0.5	0.25	0.25
154	Medium (L3)	Medium (C3)	Low (P2)	V.Low (I1)	0.25	0.25	0.5	0
155	Medium (L3)	Medium (C3)	Low (P2)	Low (I2)	0	0.5	0.5	0
156	Medium (L3)	Medium (C3)	Low (P2)	Medium (I3)	0	0.25	0.75	0
157	Medium (L3)	Medium (C3)	Low (P2)	High (I4)	0	0.25	0.5	0.25
158	Medium (L3)	High (C4)	Medium (P3)	V.Low (I1)	0.25	0	0.5	0.25
159	Medium (L3)	High (C4)	Medium (P3)	Low (I2)	0	0.25	0.5	0.25
160	Medium (L3)	High (C4)	Medium (P3)	Medium (I3)	0	0	0.75	0.25
161	Medium (L3)	High (C4)	Medium (P3)	High (I4)	0	0	0.5	0.5
162	Medium (L3)	V.Low (C1)	Medium (P3)	V.Low (I1)	0.5	0	0.5	0
163	Medium (L3)	V.Low (C1)	Medium (P3)	Low (I2)	0.25	0.25	0.5	0
164	Medium (L3)	V.Low (C1)	Medium (P3)	Medium (I3)	0.25	0	0.75	0
165	Medium (L3)	V.Low (C1)	Medium (P3)	High (I4)	0.25	0	0.5	0.25
166	Medium (L3)	V.Low (C1)	Medium (P3)	V.Low (I1)	0.5	0	0.5	0

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
167	Medium (L3)	Low (C2)	Medium (P3)	Low (I2)	0	0.5	0.5	0
168	Medium (L3)	Low (C2)	Medium (P3)	Medium (I3)	0	0.25	0.75	0
169	Medium (L3)	Low (C2)	Medium (P3)	High (I4)	0	0.25	0.5	0.25
170	Medium (L3)	Low (C2)	Medium (P3)	V.Low (I1)	0.25	0.25	0.5	0
171	Medium (L3)	Medium (C3)	Medium (P3)	Low (I2)	0	0.25	0.75	0
172	Medium (L3)	Medium (C3)	Medium (P3)	Medium (I3)	0	0	1	0
173	Medium (L3)	Medium (C3)	Medium (P3)	High (I4)	0	0	0.75	0.25
174	Medium (L3)	Medium (C3)	High (P4)	V.Low (I1)	0.25	0	0.5	0.25
175	Medium (L3)	High (C4)	High (P4)	Low (I2)	0	0.25	0.25	0.5
176	Medium (L3)	High (C4)	High (P4)	Medium (I3)	0	0	0.5	0.5
177	Medium (L3)	High (C4)	High (P4)	High (I4)	0	0	0.25	0.75
178	Medium (L3)	High (C4)	High (P4)	V.Low (I1)	0.25	0	0.25	0.5
179	Medium (L3)	V.Low (C1)	High (P4)	Low (I2)	0.25	0.25	0.25	0.25
180	Medium (L3)	V.Low (C1)	High (P4)	Medium (I3)	0.25	0	0.5	0.25
181	Medium (L3)	V.Low (C1)	High (P4)	High (I4)	0.25	0	0.25	0.5
182	Medium (L3)	V.Low (C1)	High (P4)	V.Low (I1)	0.5	0	0.25	0.25

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
183	Medium (L3)	Low (C2)	High (P4)	Low (I2)	0	0.5	0.25	0.25
184	Medium (L3)	Low (C2)	High (P4)	Medium (I3)	0	0.25	0.5	0.25
185	Medium (L3)	Low (C2)	High (P4)	High (I4)	0	0.25	0.25	0.5
186	Medium (L3)	Low (C2)	High (P4)	V.Low (I1)	0.25	0.25	0.25	0.25
187	Medium (L3)	Medium (C3)	High (P4)	Low (I2)	0	0.25	0.5	0.25
188	Medium (L3)	Medium (C3)	High (P4)	Medium (I3)	0	0	0.75	0.25
189	Medium (L3)	Medium (C3)	High (P4)	High (I4)	0	0	0.5	0.5
190	Medium (L3)	Medium (C3)	V.Low (P1)	V.Low (I1)	0.5	0	0.5	0
191	Medium (L3)	High (C4)	V.Low (P1)	Low (I2)	0.25	0.25	0.25	0.25
192	Medium (L3)	High (C4)	V.Low (P1)	Medium (I3)	0.25	0	0.5	0.25
193	High (L4)	High (C4)	V.Low (P1)	High (I4)	0.25	0	0	0.75
194	High (L4)	High (C4)	V.Low (P2) (P1)	V.Low (I1)	0.5	0	0	0.5
195	High (L4)	V.Low (C1)	V.Low (P2) (P1)	Low (I2)	0.5	0.25	0	0.25
196	High (L4)	V.Low (C1)	V.Low (P2) (P1)	Medium (I3)	0.5	0	0.25	0.25
197	High (L4)	V.Low (C1)	V.Low (P2) (P1)	High (I4)	0.5	0	0	0.5

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
198	High (L4)	V.Low (C1)	V.Low (P2) (P1)	V.Low (I1)	0.75	0	0	0.25
199	High (L4)	Low (C2)	V.Low (P2) (P1)	Low (I2)	0.25	0.5	0	0.25
200	High (L4)	Low (C2)	V.Low (P2) (P1)	Medium (I3)	0.25	0.25	0.25	0.25
201	High (L4)	Low (C2)	V.Low (P2) (P1)	High (I4)	0.25	0.25	0	0.5
202	High (L4)	Low (C2)	V.Low (P2) (P1)	V.Low (I1)	0.5	0.25	0	0.25
203	High (L4)	Medium (C3)	V.Low (P2) (P1)	Low (I2)	0.25	0.25	0.25	0.25
204	High (L4)	Medium (C3)	V.Low (P2) (P1)	Medium (I3)	0.25	0	0.5	0.25
205	High (L4)	Medium (C3)	V.Low (P2) (P1)	High (I4)	0.25	0	0.25	0.5
206	High (L4)	Medium (C3)	Low (P2)	V.Low (I1)	0.25	0.25	0.25	0.25
207	High (L4)	High (C4)	Low (P2)	Low (I2)	0	0.5	0	0.5
208	High (L4)	High (C4)	Low (P2)	Medium (I3)	0	0.25	0.25	0.5
209	High (L4)	High (C4)	Low (P2)	High (I4)	0	0.25	0	0.75
210	High (L4)	High (C4)	Low (P2)	V.Low (I1)	0.25	0.25	0	0.5
211	High (L4)	V.Low (C1)	Low (P2)	Low (I2)	0.25	0.5	0	0.25
212	High (L4)	V.Low (C1)	Low (P2)	Medium (I3)	0.25	0.25	0.25	0.25
213	High (L4)	V.Low (C1)	Low (P2)	High (I4)	0.25	0.25	0	0.5
214	High (L4)	V.Low (C1)	Low (P2)	V.Low (I1)	0.5	0.25	0	0.25

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
215	High (L4)	Low (C2)	Low (P2)	Low (I2)	0	0.75	0	0.25
216	High (L4)	Low (C2)	Low (P2)	Medium (I3)	0	0.5	0.25	0.25
217	High (L4)	Low (C2)	Low (P2)	High (I4)	0	0.5	0	0.5
218	High (L4)	Low (C2)	Low (P2)	V.Low (I1)	0.25	0.5	0	0.25
219	High (L4)	Medium (C3)	Low (P2)	Low (I2)	0	0.5	0.25	0.25
220	High (L4)	Medium (C3)	Low (P2)	Medium (I3)	0	0.25	0.5	0.25
221	High (L4)	Medium (C3)	Low (P2)	High (I4)	0	0.25	0.25	0.5
222	High (L4)	Medium (C3)	Medium (P3)	V.Low (I1)	0.25	0	0.5	0.25
223	High (L4)	High (C4)	Medium (P3)	Low (I2)	0	0.25	0.25	0.5
224	High (L4)	High (C4)	Medium (P3)	Medium (I3)	0	0	0.5	0.5
225	High (L4)	High (C4)	Medium (P3)	High (I4)	0	0	0.25	0.75
226	High (L4)	High (C4)	Medium (P3)	V.Low (I1)	0.25	0	0.25	0.5
227	High (L4)	V.Low (C1)	Medium (P3)	Low (I2)	0.25	0.25	0.25	0.25
228	High (L4)	V.Low (C1)	Medium (P3)	Medium (I3)	0.25	0	0.5	0.25
229	High (L4)	V.Low (C1)	Medium (P3)	High (I4)	0.25	0	0.25	0.5
230	High (L4)	V.Low (C1)	Medium (P3)	V.Low (I1)	0.5	0	0.25	0.25

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
231	High (L4)	Low (C2)	Medium (P3)	Low (I2)	0	0.5	0.25	0.25
232	High (L4)	Low (C2)	Medium (P3)	Medium (I3)	0	0.25	0.5	0.25
233	High (L4)	Low (C2)	Medium (P3)	High (I4)	0	0.25	0.25	0.5
234	High (L4)	Low (C2)	Medium (P3)	V.Low (I1)	0.25	0.25	0.25	0.25
235	High (L4)	Medium (C3)	Medium (P3)	Low (I2)	0	0.25	0.5	0.25
236	High (L4)	Medium (C3)	Medium (P3)	Medium (I3)	0	0	0.75	0.25
237	High (L4)	Medium (C3)	Medium (P3)	High (I4)	0	0	0.5	0.5
238	High (L4)	Medium (C3)	High (P4)	V.Low (I1)	0.25	0	0.25	0.5
239	High (L4)	High (C4)	High (P4)	Low (I2)	0	0.25	0	0.75
240	High (L4)	High (C4)	High (P4)	Medium (I3)	0	0	0.25	0.75
241	High (L4)	High (C4)	Medium (P3)	Medium (I3)	0	0	0.5	0.5
242	High (L4)	High (C4)	High (P4)	V.Low (I1)	0.25	0	0	0.75
243	High (L4)	V.Low (C1)	High (P4)	Low (I2)	0.25	0.25	0	0.5
244	High (L4)	V.Low (C1)	High (P4)	Medium (I3)	0.25	0	0.25	0.5
245	High (L4)	V.Low (C1)	High (P4)	High (I4)	0.25	0	0	0.75
246	High (L4)	V.Low (C1)	High (P4)	V.Low (I1)	0.5	0	0	0.5
247	High (L4)	Low (C2)	High (P4)	Low (I2)	0	0.5	0	0.5

Rules	Four risk parameters in the IF portion				DoB in the THEN portion			
248	High (L4)	Low (C2)	High (P4)	Medium (I3)	0	0.25	0.25	0.5
249	High (L4)	Low (C2)	High (P4)	High (I4)	0	0.25	0	0.75
250	High (L4)	Low (C2)	High (P4)	V.Low (I1)	0.25	0.25	0	0.5
251	High (L4)	Medium (C3)	High (P4)	Low (I2)	0	0.25	0.25	0.5
252	High (L4)	Medium (C3)	High (P4)	Medium (I3)	0	0	0.5	0.5
253	High (L4)	Medium (C3)	High (P4)	High (I4)	0	0	0.25	0.75
254	High (L4)	Medium (C3)	Medium (P3)	V.Low (I1)	0.25	0	0.5	0.25
255	High (L4)	High (C4)	Medium (P3)	Low (I2)	0	0.25	0.25	0.5
256	High (L4)	High (C4)	High (P4)	High (I4)	0	0	0	1

Appendix 2-1: Questionnaire Used for hazard events evaluation in Chapter 3

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18 October 2017

Survey Title: Advanced Risk Management of an Arctic Marine Seismic Survey Operation

A research project at Liverpool John Moores University is currently being carried out with regards to the Arctic shipping safety, and it is specific on the Arctic offshore seismic survey (geo-data gathering) operation. This subject would become a critical topic in the maritime community internationally, due to the world's rising demand on natural oil and gas in untested environments such as the Arctic region.

The aim of this study is to investigate and examine the current safety level of offshore exploration in the Arctic, and to evaluate the most significant failure events on the safety management of a desired arctic seismic operation. At the end of this research, a theoretical methodology and an advanced model would be generated that can be used by geologists and safety engineers to investigate and mitigate the risk of ship-Ice Collison affecting the operation of the seismic vessel and its associated vessels (ships), and to obtain a cost effective strategy to reduce and prevent risks. To achieve the above aim, the research objectives are as follows:

1. To tackle the issue of failure data uncertainty in risk analysis of AMSSO.

2. To investigate the high significant failure events in ship-Ice collision influencing the safety level of the arctic offshore seismic operation by using a probable risks or root cause technique.

A number of evaluation criteria have been determined in this research. All the evaluation criteria need to be measured by using the two techniques that have been mentioned above. This process is required to provide reliable data by identifying an expert opinion of each evaluation parameter. A set of questionnaires is compiled in this letter.

I will be most grateful if you could kindly spend your valuable time to complete the accompanying questionnaire and email it at the address shown above. Your vital feedback will greatly benefit and contribute to the formulation of an industry wide opinion. I can assure you that the confidentiality of your response will be honoured and respected.

Regards,

Gregory Asuelimen

PhD researcher, school of engineering, technology and maritime operations

Liverpool Logistics Offshore and Marine Research Institute

Room 2.23, LOOM Research Institute.

The procedures and plans for answering this set of questionnaires are explained as follows:

Definition of parameters
Table 1: Likelihood assignment

Assigned Rating	If the frequency is:
Extremely Remote	Very Low: Might occur every 6 to 10 years and beyond
Remote	Low: Might occur once every 7 months to once every 1 to 5 years
Reasonably Probable	Medium: Might occur once in 2 months to twice a year
Frequent	High: Might occur monthly or weekly or daily

Table 2: Consequence assignment

Assigned Rating	If the consequence is:
Insignificant	Very Low: Injury requiring little or no first aid, no significant harm to people, vessel and environment
Minor	Low: Minor damage (dents and scratches) degradation of the vessel strength (local damage to the structure), or causing between 1 and 9 major injuries or causing injury requiring more than first aid
Major	Medium: Major damage/ degradation of the vessel strength, or causing between 10 and 100 major injuries
Catastrophic	High: Total loss of life, vessel or severe damage to the environment

Table 3: Probability of a hazard being undetected definition

Assigned Rating	If the probability to detect a failure is:
Very Low	Possible to be detected through regular checks or easily observed with less attention
Low	Possible to be detected through mere diagnosis or observed with proper attention
Medium	Difficult to be detected through mere diagnosis or proper attention

Assigned Rating	If the probability to detect a failure is:
High	Impossible to be detected through mere diagnosis or regular checks or proper attention

Table 4: Impact of hazard to operation

Assigned Rating	If the impact of failure to operation is:
Very Low	Negligible impact on operations capability of the vessel
Low	Little impact on the operations capability of the vessel
Medium	Degraded operations capability or readiness to halt operation
High	Loss of ability to accomplish the operations or operation failure in the vessel

An expert is required to give a possible judgement to all questions based on his/her expertise and experience in Marine Arctic Seismic Survey Operation. The total assessment for each parameter (likelihood, consequence severity, probability of failure undetected, and impact of failure to operation) must not exceed 10. The judgment process should be focused on how to achieve the assessment goal.

In the below example, the goal is to evaluate the identified hazard “Brake Failure" of a moving vehicle. The description of the qualitative judgement "very Low", "Low", "Medium", and "High" is explained above.

Example of an answered questionnaire

Attribute	Likelihood (L)				Consequent severity (C)				Probability of failures being undetected (P)				Impact of failure to operation (I)			
Failure Event	Very Low	Low	Medium	High	Very Low	Low	Medium	High	Very Low	Low	Medium	High	Very Low	Low	Medium	High
A1. Risk related to a moving vehicle																
Brake failure	1	2	4	3	0	0	2	8	5	3	1	1	1	1	2	6

Must not exceed 10   Must not exceed 10   Must not exceed 10   Must not exceed 10

Explanation of the above example

- The likelihood of having a brake failure in a moving car is not very likely to occur assumed it is brand vehicle hence a low score of 3 is given for “High”. It is 4 “Medium” which is occasionally possible. “Low” and “Very Low” have the lowest scores (2, 1) respectively because it is not very common to have a brake failure incident.
- The consequence severity of having a brake failure in a moving car is 8 “high” because of the catastrophic outcome. It is 2 for “Medium” because it is possible that the consequence severity of the incident is not catastrophic, it is 0 for both “Low” and “Very Low” because it is impossible for any brake failure of a moving car not to result in some amount of significant penalties.
- The probability of detecting a brake failure is somewhat unnoticed until brakes are being applied so the score of 5 for “very low” was allotted. “High”, “Medium” and “Low” have been scored 1, 1 and 3 respectively because it is very likely to have brake failure and not notice it until it is applied.
- Impact of brake failure to operation is 6 “High” which is above average, meaning in the event of brake failure, work could eventually stop. It is 2, 1, 1 for “Medium”, “Low” and “Very Low” respectively because the impact of brake failure cannot be undermined.

Questionnaire

Twenty-One hazard events have been identified in a ship-Ice collision scenario. Please estimate your rating using the linguistic rating variables described above.

The Attributes description

“L” describes the failure occurrence probability. It suggests the rate of failure occurring in a chosen period, which directly represents the number of failure frequencies during the design life span of a particular system.

“C” describes the consequences/ severity of a failure. It suggests the magnitude of possible loss when risk happens, which is graded according to the severity of failure effects.

“P” describes the probability of failures being undetected (P). It refers to the probability that possible failure can be undetected before occurrence.

“I” defines the influence of a failure to the operation. It refers to the chance of Arctic Marine Seismic Operation being disrupted due to a failure or the probability that possible disruption happens given the occurrence of a failure event.

Note: The Probability of the failure mode should be set on an annual basis.

Attribute / Failure Event	Likelihood				Consequent severity				Probability of hazard being undetected				Impact of hazard to operation			
	Very Low	Low	Medium	High	Very Low	Low	Medium	High	Very Low	Low	Medium	High	Very Low	Low	Medium	High
A1. Risk related to Vessel navigation system																
Limited radio communication																
Limited sophisticated electronic navigation equipment (such as radar, sonar, infrared, and microwave radiation sensors on-board satellite)																
Failure in establishment and maintenance of external aids to navigation																
Poor ice chart (Not updated)																
Faults in winch/ cable																
Insufficient manoeuvring characteristics of vessel not specifically built for ice breaking or quick manoeuvring for rapid change of ice conditions.																
Insufficient hull strength/ horsepower																

Attribute	Likelihood	Consequent severity	Probability of hazard being undetected	Impact of hazard to operation
Operational incapacitation of other vessels (such as icebreaker, tugs)				
Snow accumulation on the seismic equipment and super structures				
Poor visibility as a result of fog, prolong Polar night				
Machinery seize up with low temperatures				
Sea sickness caused by sea state				
Ice restrictions which affects the vessel's movement and force to change direction and speed				
Pieces of floating multiyear ice/icebergs causing machinery damage				
Streamer, air hose entangled in ice				
Practical incompetency for duty such as experience, skills, local knowledge of waters, usage of devices.				

Attribute	Likelihood				Consequent severity				Probability of hazard being undetected				Impact of hazard to operation			
Inappropriate design of task or operation such as night navigation, route planning, anchoring etc.																
Available warning mechanism is insufficiently developed and used.																
Work load-causing stress, fatigue, bad mood as a result of very short daylight																
Situation awareness and bad decision making																
Inadequate communication																

Appendix 2-2: All Experts Evaluation Table in Chapter 3

Hazards	Experts	Likelihood				Consequence severity				Probability of failure undetected				Impact of failure to operation			
Limited radio communication		VL	L	M	H	VL	L	M	H	VL	L	M	H	VL	L	M	H
	A	30	30	20	20	10	30	50	10	40	50	10	0	10	20	50	20
	B	0	20	50	30	80	20	0	0	80	20	0	0	0	30	70	0
	C	20	30	30	20	30	40	30	10	10	10	50	30	50	30	20	0
	D	60	20	20	0	40	30	20	10	50	50	0	0	10	40	40	10
	E	50	30	0	20	0	30	70	0	70	30	0	0	0	0	20	80
	Av Prior probability	**32**	**26**	**24**	**18**	**32**	**30**	**34**	**6**	**50**	**32**	**12**	**6**	**14**	**24**	**40**	**22**
Limited sophisticated electronic navigation (radar, on board satellite)	A	50	30	20	0	0	10	30	60	80	10	10	0	0	0	10	90
	B	0	30	60	10	70	30	0	0	80	20	0	0	0	30	70	0
	C	20	30	40	10	40	20	30	10	60	40	0	0	0	10	30	60
	D	60	20	20	0	30	30	30	10	70	20	10	0	10	40	40	10
	E	80	20	0	0	0	0	30	70	70	30	0	0	0	0	20	80
	Ave Prior probability	**42**	**26**	**28**	**4**	**28**	**18**	**24**	**30**	**72**	**24**	**4**	**0**	**2**	**16**	**34**	**48**
Failure to establish and maintain external aids to navigation	A	70	20	10	0	0	10	20	70	70	20	10	0	0	10	10	80
	B	0	60	40	0	0	30	70	0	60	30	10	0	0	20	70	10
	C	40	30	20	10	10	20	20	50	70	20	10	0	0	10	30	60
	D	20	30	30	20	0	40	40	20	20	30	30	20	10	30	40	20
	E	50	50	0	0	0	20	80	0	0	40	60	0	0	40	60	0
	Av Prior probability	**36**	**38**	**20**	**6**	**2**	**24**	**46**	**28**	**44**	**28**	**24**	**4**	**2**	**22**	**42**	**34**
Poor ice chart (Ice chart not updated)	A	30	30	20	10	10	10	30	40	20	50	20	10	0	0	20	80
	B	20	70	10	0	20	70	10	0	80	20	0	0	10	70	20	0
	C	20	30	30	20	0	10	30	60	50	30	10	10	10	10	30	50
	D	40	40	20	0	0	30	50	20	10	30	30	30	10	20	50	20
	E	50	50	0	0	0	20	80	0	0	40	60	0	0	40	60	0
	Prior probability	**32**	**44**	**16**	**6**	**6**	**28**	**40**	**24**	**32**	**34**	**24**	**10**	**6**	**28**	**36**	**30**
Faults in winch/ cable	A	40	30	20	0	10	30	40	20	80	20	0	0	20	30	30	20
	B	0	70	30	0	10	50	30	10	50	30	20	0	0	20	70	10
	C	50	30	10	10	20	10	30	40	10	10	30	50	0	20	20	60

Hazards	Experts	Likelihood				Consequence severity				Probability of failure undetected				Impact of failure to operation			
	D	10	60	20	10	0	20	70	10	10	50	30	10	20	20	30	30
	E	0	0	20	80	80	20	0	0	10	80	10	0	0	0	30	70
	Prior probability	**20**	**38**	**20**	**20**	**24**	**26**	**34**	**16**	**32**	**38**	**18**	**12**	**8**	**18**	**36**	**38**
Insufficient manoeuvring characteristics of vessel not specifically built for ice breaking or quick manoeuvring for rapid change ice conditions	A	60	20	10	10	0	10	20	70	70	20	10	0	0	10	10	80
	B	0	60	30	10	50	30	20	0	50	30	20	0	0	0	80	20
	C	50	40	10	0	20	20	20	40	60	20	10	10	10	10	20	60
	D	60	30	10	0	10	20	40	30	30	30	30	10	10	20	30	40
	E	80	20	0	0	0	0	30	70	90	10	0	0	0	0	20	80
	GM probability	**43**	**31**	**12**	**10**	**16**	**16**	**25**	**36**	**56**	**20**	**14**	**10**	**10**	**11**	**25**	**50**
	Prior probability	**50**	**34**	**12**	**4**	**16**	**16**	**26**	**42**	**60**	**22**	**14**	**4**	**4**	**8**	**32**	**56**
Insufficient hull strength	A	90	10	0	0	0	0	10	90	80	20	0	0	0	0	20	80
	B	0	80	20	0	50	20	20	10	60	30	10	0	10	60	20	10
	C	40	40	20	0	30	30	20	20	50	40	10	0	10	20	20	50
	D	60	30	10	0	10	20	40	30	30	30	30	10	10	20	30	40
	E	80	20	0	0	0	0	20	80	90	10	0	0	0	0	20	80
	Prior probability	**54**	**36**	**10**	**0**	**18**	**14**	**22**	**46**	**62**	**26**	**10**	**2**	**6**	**20**	**22**	**52**
Operational incapability of other vessels (tugs, icebreakers)	A	80	20	0	0	80	20	0	0	80	20	0	0	0	50	50	0
	B	0	80	20	0	70	20	10	0	0	0	20	80	0	20	70	10
	C	30	30	20	20	20	20	40	20	50	30	20	0	10	20	40	30
	D	50	40	10	0	0	30	40	30	60	20	20	0	0	30	40	30
	E	10	50	20	20	60	40	0	0	0	0	10	90	0	0	20	80
	Prior probability	**34**	**44**	**14**	**8**	**46**	**26**	**18**	**10**	**38**	**14**	**14**	**34**	**2**	**24**	**44**	**30**
Snow accumulation on the seismic equipment and super structures	A	30	30	40	0	40	30	20	10	90	10	0	0	40	30	20	10
	B	0	80	20	0	70	20	10	0	0	0	60	40	10	20	60	10
	C	20	20	30	30	40	30	20	10	50	50	0	0	20	20	30	30
	D	0	30	30	40	20	50	30	0	60	40	0	0	20	30	30	20
	E	0	0	10	90	0	10	30	60	100	0	0	0	0	20	30	50
	Prior probability	**10**	**32**	**26**	**32**	**34**	**28**	**22**	**16**	**60**	**20**	**12**	**8**	**18**	**24**	**34**	**24**
Poor visibility as a result of fog, prolong polar night	A	20	30	40	10	20	20	30	30	20	20	40	20	20	30	40	10
	B	0	0	40	60	0	80	20	0	0	0	70	30	20	50	30	0
	C	10	20	40	30	10	10	40	40	10	0	0	0	10	20	30	40

Hazards	Experts	Likelihood				Consequence severity				Probability of failure undetected				Impact of failure to operation			
	D	0	50	50	0	0	50	50	0	80	20	0	0	0	30	60	10
	E	0	0	10	90	0	0	10	90	10	0	0	0	0	0	0	100
	Prior probability	**6**	**20**	**36**	**38**	**6**	**32**	**30**	**32**	**24**	**8**	**22**	**10**	**10**	**26**	**32**	**32**
Machinery seize up with low temperatures	A	80	20	0	0	0	0	20	80	100	0	0	0	0	0	30	70
	B	0	0	30	70	20	70	10	0	10	50	30	10	30	60	10	0
	C	70	30	0	0	0	0	30	70	80	20	0	0	0	10	30	60
	D	10	10	80	0	10	30	30	30	60	40	0	0	20	40	40	20
	E	60	40	0	0	0	0	50	50	40	60	0	0	0	0	20	80
	Prior probability	**44**	**20**	**22**	**14**	**6**	**20**	**28**	**46**	**58**	**34**	**6**	**2**	**10**	**22**	**26**	**46**
Sea sickness caused by sea state	A	0	0	50	50	50	30	20	0	90	10	0	0	20	40	30	0
	B	0	30	70	0	30	50	20	0	0	30	50	20	0	30	70	0
	C	20	20	40	20	40	30	20	10	80	20	0	0	40	30	10	10
	D	50	30	10	10	0	10	80	10	0	50	50	0	20	20	50	20
	E	0	0	30	70	20	80	0	0	100	0	0	0	10	70	10	10
	Prior probability	**14**	**16**	**40**	**30**	**28**	**40**	**28**	**4**	**54**	**22**	**20**	**4**	**18**	**38**	**34**	**8**
Ice restrictions which affects the vessel's movement and force to change direction and speed	A	80	20	0	0	0	0	20	80	100	0	0	0	0	0	30	70
	B	0	10	60	30	30	60	10	0	0	10	60	30	0	20	60	20
	C	0	30	30	40	40	40	10	10	60	40	0	0	0	10	30	60
	D	0	60	40	0	0	50	50	0	40	60	0	0	10	40	40	10
	E	0	0	20	80	50	50	0	0	100	0	0	0	0	0	50	50
	GM probability	**15**	**20**	**27**	**25**	**23**	**36**	**16**	**15**	**47**	**19**	**14**	**12**	**10**	**15**	**40**	**33**
	Prior probability	**16**	**24**	**30**	**30**	**24**	**40**	**18**	**18**	**60**	**22**	**12**	**6**	**2**	**14**	**42**	**42**
Pieces of floating multi-year ice/icebergs causing machinery damage	A	100	0	0	0	0	0	0	100	100	0	0	0	0	0	0	100
	B	0	70	30	0	0	70	30	0	30	60	10	0	0	60	40	0
	C	30	30	20	20	20	30	30	20	40	40	10	10	10	10	40	40
	D	0	60	40	0	10	10	50	30	0	20	70	10	0	20	50	30
	E	90	10	0	0	0	20	80	0	60	40	0	0	0	0	0	100
	Prior probability	**44**	**34**	**18**	**4**	**6**	**26**	**38**	**30**	**46**	**32**	**18**	**4**	**2**	**18**	**26**	**54**
Streamer, Air hose entangled in ice	A	10	30	40	20	10	30	40	20	100	0	0	0	20	20	30	30
	B	0	30	60	10	30	60	10	0	20	60	20	0	0	40	60	0
	C	30	30	30	10	40	40	20	0	40	40	10	10	30	30	30	10

Hazards	Experts	Likelihood				Consequence severity				Probability of failure undetected				Impact of failure to operation			
	D	10	50	40	0	30	30	30	10	40	50	10	0	20	20	50	10
	E	0	0	10	90	0	20	80	0	100	0	0	0	0	0	0	100
	Prior probability	**10**	**28**	**36**	**26**	**22**	**36**	**36**	**6**	**60**	**30**	**8**	**2**	**14**	**22**	**34**	**30**
Practical incompetency for duty such as experience, skills, local knowledge of waters, usage of devices	A	10	20	50	20	0	20	30	50	50	30	20	0	20	30	50	0
	B	0	60	30	10	50	40	10	0	30	50	20	0	0	60	40	0
	C	20	40	30	10	10	10	40	40	20	20	30	30	20	20	30	30
	D	30	40	30	0	0	50	50	0	10	40	30	20	20	30	30	20
	E	0	30	60	10	0	20	80	0	50	50	0	0	10	40	40	10
	Prior probability	**12**	**38**	**40**	**10**	**12**	**28**	**42**	**18**	**32**	**38**	**20**	**10**	**14**	**36**	**38**	**12**
Inappropriate design of task or operation such as night navigation, route planning	A	100	0	0	0	0	0	20	80	100	0	0	0	0	10	20	70
	B	0	60	30	10	60	30	10	0	30	50	20	0	0	70	30	0
	C	30	40	20	10	10	10	40	40	40	30	30	0	20	20	30	30
	D	20	50	30	0	0	20	50	30	0	80	20	0	0	10	70	20
	E	20	80	0	0	0	20	80	0	0	10	80	10	0	0	50	50
	Prior probability	**34**	**46**	**16**	**4**	**14**	**16**	**40**	**30**	**34**	**34**	**30**	**2**	**4**	**22**	**40**	**34**
Available warning mechanism is insufficiently developed and used	A	70	20	10	0	0	20	40	30	80	20	0	0	0	10	20	70
	B	0	70	30	0	70	20	10	0	40	50	10	0	20	70	10	0
	C	20	20	30	30	20	20	30	30	20	10	30	40	0	10	30	60
	D	20	40	40	0	10	40	40	10	0	50	50	0	20	50	20	10
	E	20	80	0	0	0	30	70	0	0	20	80	0	0	30	30	40
	Prior probability	**26**	**46**	**22**	**6**	**20**	**26**	**38**	**14**	**28**	**30**	**34**	**8**	**8**	**34**	**22**	**36**
Prolong night and work load causing stress, fatigue	A	20	30	40	10	20	20	30	30	20	20	40	20	20	30	40	10
	B	0	60	30	10	50	30	20	0	0	60	30	10	10	40	50	0
	C	30	30	30	10	20	20	30	30	30	30	30	10	30	20	30	20
	D	10	40	40	10	0	30	50	20	10	50	20	20	0	30	50	20
	E	0	0	0	100	0	0	20	80	70	30	0	0	0	0	50	50
	Prior probability	**12**	**32**	**28**	**28**	**18**	**20**	**30**	**32**	**26**	**38**	**24**	**12**	**12**	**24**	**44**	**20**
Situation awareness and bad decision making	A	40	30	30	0	10	20	30	40	20	30	40	10	10	20	30	40
	B	0	50	30	20	40	50	10	0	0	10	60	30	0	20	70	10
	C	30	40	20	10	10	10	30	50	10	20	30	40	10	20	20	50
	D	30	30	30	10	10	30	40	10	20	30	40	10	0	30	40	30

Hazards	Experts	Likelihood				Consequence severity				Probability of failure undetected				Impact of failure to operation			
	E	0	0	0	100	0	0	0	100	70	30	0	0	0	0	0	100
	Prior probability	**20**	**30**	**22**	**28**	**14**	**22**	**22**	**40**	**24**	**24**	**34**	**18**	**4**	**18**	**32**	**46**
Inadequate communication	A	20	40	30	10	10	40	30	20	40	30	20	10	10	30	30	30
	B	0	20	50	30	20	60	20	0	20	60	10	10	10	50	40	0
	C	40	20	20	20	20	10	30	40	30	30	20	20	10	10	40	40
	D	40	30	20	10	30	30	30	10	0	30	60	10	10	20	50	20
	E	0	0	10	90	10	10	20	80	0	40	50	10	10	20	50	20
	Prior probability	**20**	**22**	**26**	**32**	**18**	**30**	**26**	**30**	**18**	**38**	**32**	**12**	**10**	**26**	**42**	**22**

Appendix 3-1: The Questionnaire used for AHP Technique in Chapter 4

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30 May 2018

Survey Title: Advanced Risk Management of an Arctic Marine Seismic Survey Operation

A research project at Liverpool John Moores University is currently being carried out with regards to the Arctic shipping safety, and it is specific on the Arctic offshore seismic survey (geo-data gathering) operation. This subject would become a critical topic in the maritime community internationally, due to the world's rising demand on natural oil and gas in untested environments such as the Arctic region.

The aim of this study is to investigate and examine the current safety level of offshore exploration in the Arctic, and to evaluate the most significant failure events on the safety management of a desired arctic seismic operation. At the end of this research, a theoretical methodology and an advanced model would be generated that can be used by geologists and safety engineers to investigate and mitigate the risk of ship-Ice Collison affecting the operation of the seismic vessel and its associated vessels (ships), and to obtain a cost effective strategy to reduce and prevent risks. To achieve the above aim, the research objectives are as follows:

1. To tackle the issue of failure data uncertainty in risk analysis of AMSSO.

2. To investigate the most important risk factor(s) influencing the safety of AMSSO by using a "pair-wise comparison" technique.

A number of evaluation criteria have been determined in this research. All the evaluation criteria need to be measured by using the technique specified above. This process is required to provide reliable data by identifying an expert opinion of each evaluation parameter. A set of questionnaires is compiled in this letter.

I will be most grateful if you could kindly spend your valuable time to complete the accompanying questionnaire and email it at the address shown above. Your vital feedback will greatly benefit and contribute to the formulation of an industry wide opinion. I can assure you that the confidentiality of your response will be honoured and respected.

Regards,

Gregory Asuelimen

PhD researcher, school of engineering, technology and maritime operations

Liverpool Logistics Offshore and Marine Research Institute

Room 2.23, LOOM Research Institute.

Introduction to *Pair-wise Comparison* Technique

The goal of this study is to determine which risk factor(s) have greater influence on the ship-Ice Collision risk model of Arctic Marine Seismic Survey Operation. The risk criteria focus on five risk factors, namely

i) the risk related to vessel navigation system,
ii) the risk related to vessel operational system,
iii) the risk related weather,
iv) the risk related to ice and
v) the risk related to human factor.

This part of the questionnaire consists of a Pairwise Comparison of the risk criteria mentioned above. The risk factors leading to ship-Ice Collision in Arctic Marine Seismic Survey Operation are outlined in figure 1

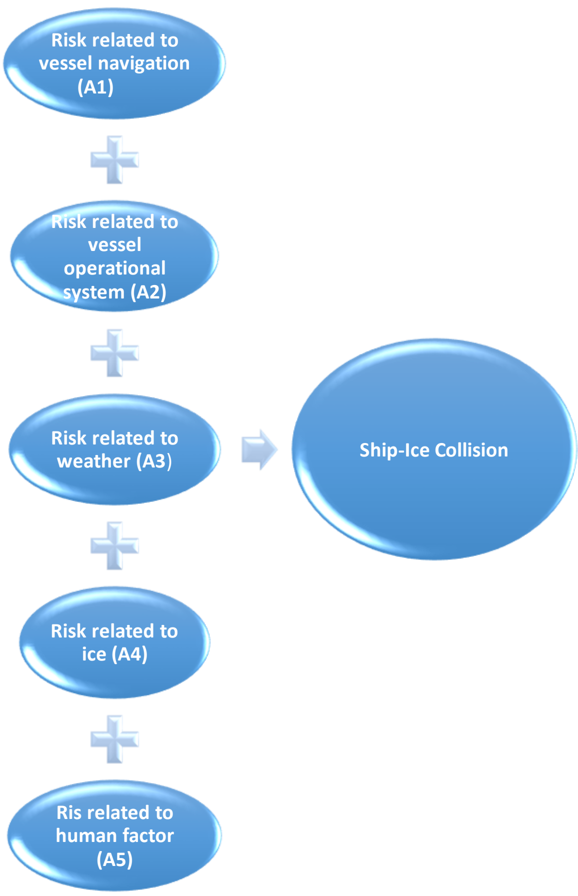

Figure 1: Risk factors leading to ship-Ice Collision in Arctic Marine Seismic Survey Operation

To proceed with the *Pair-wise Comparison* technique, one should first understand the weighting measurement used in the study. Table 1 contains two weighting scales for “IMPORTANT” and “UNIMPORTANT”, along with an explanation of what each weighting denotes.

Table 1: Weighting scale for the Pair-wise Comparison

IMPORTANT		UNIMPORTANT	
Numerical Weighting	**Explanation**	**Numerical Weighting**	**Explanation**
1	Equally important	1	Equally important
3	A little important	1/3	A little unimportant
5	Important	1/5	Unimportant
7	Very important	1/7	Very unimportant
9	Extremely important	1/9	Extremely unimportant
2, 4, 6, 8	Intermediate important values	1/2, 1/4, 1/6, 1/8,	Intermediate unimportant values

Using Table 1 as a reference, it is required that possible judgement to all questions is to be given based upon one's expertise and experience in the Arctic Marine Seismic Surveying /Arctic shipping. The judgement provided should be focused on the objective presented for each section, and to do this please 'mark' (*) the importance weighting of each general attribute or intermediate hazard event in the presented column. The following is a brief example of how to apply Table 1.

Objective: To select the most important elements of a car.

1) The Steering Wheel

	Unimportant								Equally Important	Important							
	1/9	**1/8**	**1/7**	**1/6**	**1/5**	**1/4**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
To achieve the stated objective, how important is a Steering Wheel, compared to the Radio/Sound System?																	*
To achieve the stated objective, how important is a Steering Wheel, compared to a Rear View Mirror?											*						
To achieve the stated objective, how important is a Steering Wheel, compared to the Engine?	*																

Explanation of the given example:

- The Steering Wheel is 9 times more IMPORTANT that the Radio/Sound System. This is because it is still possible to operate the car if the Radio/Sound System is not functioning.
- The Steering Wheel is 3 times more IMPORTANT than the Rear View Mirror. This is because, while it is harder to operate a car without the rear view mirror, one can still navigate with the side mirrors and moving ones head to see traffic.
- The Steering Wheel is 1/9 times more UNIMPORTANT that the Engine. This is because without the engine, the car would not function.

Questionnaire

General Attributes

Objective: To select the most important general attributes relating to the Ship-Ice Collision.

	Unimportant								Equally Important	Important							
	1/9	**1/8**	**1/7**	**1/6**	**1/5**	**1/4**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
To achieve the stated objective, how important is risk related to vessel navigational system compared to risk related to vessel operational system?																	
To achieve the stated objective, how important is risk related to navigational system compared to risk related to weather?																	
To achieve the stated objective, how important is vessel navigational system compared to risk related to ice?																	
To achieve the stated objective, how important is vessel navigational system compared to risk related to human factor?																	
To achieve the stated objective, how important is risk related to vessel operational system compared to risk related to weather?																	
To achieve the stated objective, how important is risk related to vessel operational system compared to risk related to ice?																	
To achieve the stated objective, how important is risk related to vessel operational system compared to risk related to human factor?																	

	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is risk related to weather compared to risk related to ice?																	
To achieve the stated objective, how important is risk related to weather compared to risk related to human factor?																	
To achieve the stated objective, how important is risk related to ice compared to risk related to human factor?																	

Appendix 4-1: The Questionnaire used for AHP-TOPSIS Technique in Chapter 5

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7 November 2018

Survey Title: Advanced Risk Management of an Arctic Marine Seismic Survey Operation

A research project at Liverpool John Moores University is currently being carried out with regards to the Arctic shipping safety, and it is specific on the Arctic Marine Seismic Survey Operation. This subject would become a critical topic in the maritime community internationally, due to the world's rising demand on natural oil and gas in untested environments such as the Arctic region.

At the end of this research, a conceptual model would be generated that can be used by geologists and safety engineers to prevent and mitigate the risk putting in danger the safe Arctic Marine Seismic Survey Operation. To achieve the above aim, the research objective is as follows:

1. To support the decision-making system by selecting the optimal measure/s to mitigate the risk of Ship-Ice Collision in Arctic Marine Seismic Survey Operation.

Your vital feedback will greatly benefit and contribute to the formulation of an industry wide opinion. I can assure you that the confidentiality of your response will be honoured and respected.

Any refusal or incomplete questionnaire will be excluded without any responsibility on the participant. Completion of the questionnaire will indicate your willingness to participate in this study. If you require additional information or have questions, please contact me at the above addresses.

If you are not satisfied with the manner in which this study is being conducted, you may report any complaints to the LJMU-LOOM research centre with the link below:

(https://www.ljmu.ac.uk/research/centres-and-institutes/faculty-of-engineering-and-technology-research-institute/loom)

Regards,

Gregory Asuelimen

PhD researcher, school of engineering, technology and maritime operations

Liverpool Logistics Offshore and Marine Research Institute

Room 2.23, LOOM Research Institute.

Introduction to questionnaire

The aim of this study is to support the decision-making model in order to select the appropriate Arctic Marine Seismic Survey Operation safety plan to optimise the operational efficiency. The most significant hazard events in the Arctic Marine Seismic Survey Operation safety level operations have been investigated both locally (for each individual hazard) and globally (for all hazard events combined collectively). As a result, the most critical hazard event capable of putting in danger an Arctic Marine Seismic Survey Operation is the "lack of situation awareness" due to human error.

A number of alternatives or Risk Control Options (RCOs) have been determined in this research. All the RCOs criteria need to be measured by using AHP and TOPSIS techniques. This process is required to provide reliable data by identifying an expert opinion of each evaluation parameter.

The procedures and guidelines for answering this set of questionnaire are given in Sections 1 and 2 below:

Section 1: Part A- *Introduction*

The goal of this study is to determine which criteria have greater influence in causing the "lack of situation awareness" in Arctic Marine Seismic Survey Operation. The below risk criteria focus on preventing or reducing the risk of "lack of situation awareness" in Arctic Marine Seismic Survey Operation:

1. Risk reduction
2. Cost of implementing RCO (procurement and training costs)
3. Duration of implementing RCO
4. Implementation difficulty
5. Financial benefit of risk reduction

This part of the questionnaire consists of a Pair-wise Comparison of the five risk criteria mentioned above.

To proceed with the Pair-wise Comparison technique, one should first understand the weighting measurement used in the study. Table 1 contains two weighting scales for "IMPORTANT" and "UNIMPORTANT", along with an explanation of what each weighting denotes.

Table 1: Weighting scale for the Pairwise Comparison

IMPORTANT		**UNIMPORTANT**	
Numerical Weighting	**Explanation**	**Numerical Weighting**	**Explanation**
1	Equally important	1	Equally important
3	A little important	1/3	A little unimportant
5	Important	1/5	Unimportant
7	Very important	1/7	Very unimportant
9	Extremely important	1/9	Extremely unimportant
2, 4, 6, 8	Intermediate important values	1/2, 1/4, 1/6, 1/8,	Intermediate unimportant values

Using Table 1 as a reference, it is required that possible judgement to all questions is to be given based upon one's expertise and experience in ship building, repairs and controls. The judgement provided should be focused on the objective presented for each section, and to do this please 'mark' (+) the importance weighting of each general attribute or intermediate unwanted event in the presented column. The following is a brief example of how to apply Table 1.

Objective: To select the most important elements of a car.

1) The Steering Wheel

	Unimportant								**Equally Important**	**Important**							
	1/9	**1/8**	**1/7**	**1/6**	**1/5**	**1/4**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
To achieve the stated objective, how important is a Steering Wheel, compared to the Radio/Sound System?																	+
To achieve the stated objective, how important is a Steering Wheel, compared to a Rear View Mirror?											+						
To achieve the stated objective, how important is a Steering Wheel, compared to the Engine?	+																

Explanation of the example:

- The Steering Wheel is 9 times more IMPORTANT that the Radio/Sound System. This is because it is still possible to operate the car if the Radio/Sound System is not functioning.
- The Steering Wheel is 3 times more IMPORTANT than the Rear View Mirror. This is because, while it is harder to operate a car without the rear view mirror, one can still navigate with the side mirrors and moving ones head to see traffic.
- The Steering Wheel is 1/9 times more UNIMPORTANT that the Engine. This is because without the engine, the car would not function.

Section 1: Part B - *Pairwise Comparison*

Note: Your judgement should be centred on an average size (76.8m x 16m) polar class seismic vessel having approximately 40-crew unit.

Objective: To select the most important criteria to control or mitigate the "*lack of situation awareness*" hazard event.

	Unimportant								**Equally Important**	**Important**							
	1/9	**1/8**	**1/7**	**1/6**	**1/5**	**1/4**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
To achieve the stated objective, how important is risk reduction compared to cost of implementing RCO?																	
To achieve the stated objective, how important is risk reduction compared to duration of implementing RCO?																	
To achieve the stated objective, how important is risk reduction compared to implementation difficulty?																	
To achieve the stated objective, how important is risk reduction compared to financial benefit of risk reduction?																	
To achieve the stated objective, how important is cost of implementing RCO compared to duration of implementing RCO?																	
To achieve the stated objective, how important is cost of implementing RCO compared to																	

	Unimportant								Equally Important	Important							
	1/9	**1/8**	**1/7**	**1/6**	**1/5**	**1/4**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
implantation difficulty?																	
To achieve the stated objective, how important is cost of implementing RCO compared to financial benefit of risk reduction?																	
To achieve the stated objective, how important is duration of implementing RCO compared risk related to implementation difficulty?																	
To achieve the stated objective, how important is duration of implementing RCO compared to financial benefit of risk reduction?																	
To achieve the stated objective, how important is implementation difficulty compared to financial benefit of risk reduction?																	

Section 2: Part A- *Introduction*

The goal of section 2 is to compare each of the five criteria mentioned above in section 1 with the identified alternatives or RCOs to reduce “situation awareness” hazard event in Marine Arctic Seismic Survey Operation (MASSO). The below alternatives or RCOs focus on reducing “situation awareness” hazard event:

1. Training crew to improve knowledge and competence
2. Teaching English language to improve communication
3. Providing quality foods and exercise facilities to improve crew’s health and wellbeing
4. Use of durable and readable material for on board information display
5. Automating the operation of the vessel
6. Provide physical barriers to restrict unintended access to important controllers

7. The design and installation of equipment should consider the user body size to avoid awkward posture
8. Improved navigation and communication equipment
9. Improved recruitment procedure
10. Providing education in cultural awareness and cultural sensitivity training
11. Assigning personnel to monitor roles and responsibilities of each crew
12. Allocate resources for strategic planning
13. Assign personnel to monitor work-load distribution
14. Non-operational use of cell phone/ entertainment device
15. Training of crew on how to react to rough weather situations

Section 2: Part B- *Questionnaire*

Select the most appropriate alternative or RCO that eliminates and/or mitigates the hazard of *"situation awareness"* during marine Arctic seismic survey operation.

1. What would be the *implementation difficulty* if you decide to apply the following alternatives or RCOs?

S/N	Alternative or RCO	Very Low		Low		Medium			High		Very High	
		0	1	2	3	4	5	6	7	8	9	10
1	Training to improve knowledge and competence											
2	Teaching English language to improve communication											
3	Providing quality foods and exercise facilities to improve crew's health and wellbeing											
4	Use of durable and readable material for on board information display											
5	Automating the operation of the vessel											
6	Provide physical barriers to restrict unintended access to important controllers											
7	The design and installation of equipment should consider the user body size to avoid awkward posture											
8	Improved navigation and communication equipment											

S/N	Alternative or RCO	Very Low		Low		Medium			High		Very High	
		0	1	2	3	4	5	6	7	8	9	10
9	Improved recruitment procedure											
10	Providing education in cultural awareness and cultural sensitivity training											
11	Assigning personnel to monitor roles and responsibilities of each crew											
12	Allocate resources for strategic planning											
13	Assign personnel to monitor work-load distribution											
14	Non-operational use of cell phone/ entertainment device											
15	Training crew on how to react to rough weather situations											

2. What would be the *cost of implementing the alternative or RCO/year* if you decide to apply the following alternatives or RCOs?

S/N	Alternative or RCO	Cost (£)	S/N	Alternatives	Cost (£)
1	Training to improve knowledge and competence		9	Improved recruitment procedure	
2	Teaching English language to improve communication		10	Providing education in cultural awareness and cultural sensitivity training	
3	Providing quality foods and exercise facilities to improve crew's health and wellbeing		11	Assigning personnel to monitor roles and responsibilities of each crew	
4	Use of durable and readable material for on board information display		12	Allocate resources for strategic planning	
5	Automating the operation of the vessel		13	Assign personnel to monitor work-load distribution	

S/N	Alternative or RCO	Cost (£)	S/N	Alternatives	Cost (£)
6	Provide physical barriers to restrict unintended access to important controllers		14	Non-operational use of cell phone/ entertainment device	£5,000
7	The design and installation of equipment should consider the user body size to avoid awkward posture		15	Training crew on how to react to rough weather situations	£20,000
8	Improved navigation and communication equipment				

3. What would be the *duration of implementing the alternative or RCO* if you decide to apply the following alternatives or RCOs?

S/N	Alternative or RCO	Duration in months		Alternative or RCO	Duration in months
1	Training to improve knowledge and competence		14	Non-operational use of cell phone/ entertainment device	
2	Teaching English language to improve communication		15	Providing education in cultural awareness and cultural sensitivity training	
3	Providing quality foods and exercise facilities to improve crew's health and wellbeing				
4	Use of durable and readable material for on board information display				
5	Automating the operation of the vessel				
6	Provide physical barriers to restrict unintended access to important controllers				
7	The design and installation of equipment should consider the user body size to avoid awkward posture				
8	Improved navigation and communication equipment				

S/N	Alternative or RCO	Duration in months		Alternative or RCO	Duration in months
9	Improved recruitment procedure				
10	Providing education in cultural awareness and cultural sensitivity training				
11	Assigning personnel to monitor roles and responsibilities of each crew				
12	Allocate resources for strategic planning				
13	Assign personnel to monitor work-load distribution				

4. What would be the *risk reduction* if you decide to apply the following alternatives or RCOs?

S/N	Alternative or RCO	Very Low %		Low %		Medium %			High %		Very High %	
		0	10	20	30	40	50	60	70	80	90	100
1	Training to improve knowledge and competence											
2	Teaching English language to improve communication											
3	Providing quality foods and exercise facilities to improve crew's health and wellbeing											
4	Use of durable and readable material for on board information display											
5	Automating the operation of the vessel											

S/N	Alternative or RCO	Very Low %		Low %		Medium %			High %		Very High %	
		0	10	20	30	40	50	60	70	80	90	100
6	Provide physical barriers to restrict unintended access to important controllers											
7	The design and installation of equipment should consider the user body size to avoid awkward posture											
8	Improved navigation and communication equipment											
9	Improved recruitment procedure											
10	Providing education in cultural awareness and cultural sensitivity training											
11	Assigning personnel to monitor roles and responsibilities of each crew											
12	Allocate resources for strategic planning											
13	Assign personnel to monitor work-load distribution											
14	Non-operational use of cell phone/ entertainment device											
15	Training crew on how to react to											

S/N	Alternative or RCO	Very Low %		Low %		Medium %			High %		Very High %	
		0	10	20	30	40	50	60	70	80	90	100
	rough weather situations											

Appendix 4-2: Calculation of D_2^+ to D_{15}^+ for fourteen RCOs in Chapter 5

$$D_2^+ = \sqrt{\sum_{j=1}^{5} (V_{2j} - V_j^+)^2} =$$

$$\sqrt{(V_{2,1} - V_1^+)^2 + (V_{2,2} - V_2^+)^2 + (V_{2,3} - V_3^+)^2 + (V_{2,4} - V_4^+)^2 + (V_{2,5} - V_5^+)^2}$$

$$= \sqrt{(0.0021 - 0.0004)^2 + (0.0443 - 0.0541)^2 + (0.1274 - 0.1556)^2 + (0.0265 - 0.0112)^2 + (0.0073 - 0.0055)^2}$$

= 0.0336

$$D_3^+ = \sqrt{\sum_{j=1}^{5} (V_{3j} - V_j^+)^2} =$$

$$\sqrt{(V_{3,1} - V_1^+)^2 + (V_{3,2} - V_2^+)^2 + (V_{3,3} - V_3^+)^2 + (V_{3,4} - V_4^+)^2 + (V_{3,5} - V_5^+)^2}$$

$$= \sqrt{(0.0183 - 0.0004)^2 + (0.0373 - 0.0541)^2 + (0.1074 - 0.1556)^2 + (0.0149 - 0.0112)^2 + (0.0270 - 0.0055)^2}$$

= 0.0583

$$D_4^+ = \sqrt{\sum_{j=1}^{5} (V_{4j} - V_j^+)^2} =$$

$$\sqrt{(V_{4,1} - V_1^+)^2 + (V_{4,2} - V_2^+)^2 + (V_{4,3} - V_3^+)^2 + (V_{4,4} - V_4^+)^2 + (V_{4,5} - V_5^+)^2}$$

$$= \sqrt{(0.0181 - 0.0004)^2 + (0.0376 - 0.0541)^2 + (0.1081 - 0.1556)^2 + (0.0332 - 0.0112)^2 + (0.0145 - 0.0055)^2}$$

= 0.0584

$$D_5^+ = \sqrt{\sum_{j=1}^{5} (V_{5j} - V_j^+)^2} =$$

$$\sqrt{(V_{5,1} - V_5^+)^2 + (V_{5,2} - V_2^+)^2 + (V_{5,3} - V_3^+)^2 + (V_{5,4} - V_4^+)^2 + (V_{5,5} - V_5^+)^2}$$

$$= \sqrt{(0.2180 - 0.0004)^2 + (0.0340 - 0.0541)^2 + (0.0977 - 0.1556)^2 + (0.0112 - 0.0112)^2 + (0.0321 - 0.0055)^2}$$

= 0.2276

$$D_6{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{6j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{6,1} - V_1{}^{+})^2 + (V_{6,2} - V_2{}^{+})^2 + (V_{6,3} - V_3{}^{+})^2 + (V_{6,4} - V_4{}^{+})^2 + (V_{6,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0022 - 0.0004)^2 + (0.0420 - 0.0541)^2 + (0.1208 - 0.1556)^2 + (0.0345 - 0.0112)^2 + (0.0191 - 0.0055)^2}$$

= 0.0457

$$D_7{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{7j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{7,1} - V_7{}^{+})^2 + (V_{7,2} - V_2{}^{+})^2 + (V_{7,3} - V_3{}^{+})^2 + (V_{7,4} - V_4{}^{+})^2 + (V_{7,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0022 - 0.0004)^2 + (0.0541 - 0.0541)^2 + (0.0898 - 0.1556)^2 + (0.0280 - 0.0112)^2 + (0.0055 - 0.0055)^2}$$

= 0.0679

$$D_8{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{8j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{8,1} - V_8{}^{+})^2 + (V_{8,2} - V_2{}^{+})^2 + (V_{8,3} - V_3{}^{+})^2 + (V_{8,4} - V_4{}^{+})^2 + (V_{8,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0089 - 0.0004)^2 + (0.0508 - 0.0541)^2 + (0.1461 - 0.1556)^2 + (0.0333 - 0.0112)^2 + (0.0270 - 0.0055)^2}$$

= 0.0335

$$D_9{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{9j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{9,1} - V_9{}^{+})^2 + (V_{9,2} - V_2{}^{+})^2 + (V_{9,3} - V_3{}^{+})^2 + (V_{9,4} - V_4{}^{+})^2 + (V_{9,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0009 - 0.0004)^2 + (0.0430 - 0.0541)^2 + (0.1237 - 0.1556)^2 + (0.0172 - 0.0112)^2 + (0.0093 - 0.0055)^2}$$

= 0.0345

$$D_{10}{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{10j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{10,1} - V_{10}{}^{+})^2 + (V_{10,2} - V_2{}^{+})^2 + (V_{10,3} - V_3{}^{+})^2 + (V_{10,4} - V_4{}^{+})^2 + (V_{10,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0012 - 0.0004)^2 + (0.0316 - 0.0541)^2 + (0.0909 - 0.1556)^2 + (0.0120 - 0.0112)^2 + (0.0078 - 0.0055)^2}$$

= 0.0685

$$D_{11}{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{11j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{11,1} - V_{11}{}^{+})^2 + (V_{11,2} - V_2{}^{+})^2 + (V_{11,3} - V_3{}^{+})^2 + (V_{11,4} - V_4{}^{+})^2 + (V_{11,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0056 - 0.0004)^2 + (0.0340 - 0.0541)^2 + (0.0977 - 0.1556)^2 + (0.0112 - 0.0112)^2 + (0.0066 - 0.0055)^2}$$

= 0.0615

$$D_{12}{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{12j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{12,1} - V_{12}{}^{+})^2 + (V_{12,2} - V_2{}^{+})^2 + (V_{12,3} - V_3{}^{+})^2 + (V_{12,4} - V_4{}^{+})^2 + (V_{12,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0067 - 0.0004)^2 + (0.0418 - 0.0541)^2 + (0.1201 - 0.1556)^2 + (0.0322 - 0.0112)^2 + (0.0073 - 0.0055)^2}$$

= 0.0435

$$D_{13}{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{13j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{13,1} - V_{13}{}^{+})^2 + (V_{13,2} - V_2{}^{+})^2 + (V_{13,3} - V_3{}^{+})^2 + (V_{13,4} - V_4{}^{+})^2 + (V_{13,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0041 - 0.0004)^2 + (0.0420 - 0.0541)^2 + (0.1208 - 0.1556)^2 + (0.0133 - 0.0112)^2 + (0.0055 - 0.0055)^2}$$

= 0.0371

$$D_{14}{}^{+} = \sqrt{\sum_{j=14}^{5} (V_{14j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{14,1} - V_1{}^{+})^2 + (V_{14,2} - V_2{}^{+})^2 + (V_{14,3} - V_3{}^{+})^2 + (V_{14,4} - V_4{}^{+})^2 + (V_{14,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0004 - 0.0004)^2 + (0.0359 - 0.0541)^2 + (0.1033 - 0.1556)^2 + (0.0113 - 0.0112)^2 + (0.0055 - 0.0055)^2}$$

$= 0.0554$

$$D_{15}{}^{+} = \sqrt{\sum_{j=1}^{5} (V_{15j} - V_j{}^{+})^2} =$$

$$\sqrt{(V_{15,1} - V_1{}^{+})^2 + (V_{15,2} - V_2{}^{+})^2 + (V_{15,3} - V_3{}^{+})^2 + (V_{15,4} - V_4{}^{+})^2 + (V_{15,5} - V_5{}^{+})^2}$$

$$= \sqrt{(0.0024 - 0.0004)^2 + (0.0512 - 0.0541)^2 + (0.1471 - 0.1556)^2 + (0.0247 - 0.0112)^2 + (0.0093 - 0.0055)^2}$$

$= 0.0168$

Appendix 4-3: Calculation of D_2^- to D_{15}^- for the fourteen RCOs in Chapter 5

$$D_2^- = \sqrt{\sum_{j=1}^{5} (V_{2j} - V_j^-)^2} =$$

$$\sqrt{(V_{2,1} - V_1^-)^2 + (V_{2,2} - V_2^-)^2 + (V_{2,3} - V_3^-)^2 + (V_{2,4} - V_4^-)^2 + (V_{2,5} - V_5^-)^2}$$

$$= \sqrt{(0.0021 - 0.218)^2 + (0.0443 - 0.0312)^2 + (0.1274 - 0.0898)^2 + (0.0265 - 0.0444)^2 + (0.0073 - 0.0356)^2}$$

= 0.2221

$$D_3^- = \sqrt{\sum_{j=1}^{5} (V_{3j} - V_j^-)^2} =$$

$$\sqrt{(V_{3,1} - V_1^-)^2 - (V_{3,2} - V_2^-)^2 - (V_{3,3} - V_3^-)^2 - (V_{3,4} - V_4^-)^2 - (V_{3,5} - V_5^-)^2}$$

$$= \sqrt{(0.0183 - 0.218)^2 + (0.0373 - 0.0312)^2 + (0.1074 - 0.0898)^2 + (0.0149 - 0.0444)^2 + (0.0270 - 0.0356)^2}$$

= 0.2029

$$D_4^- = \sqrt{\sum_{j=1}^{5} (V_{4j} - V_j^-)^2} =$$

$$\sqrt{(V_{4,1} - V_1^-)^2 - (V_{4,2} - V_2^-)^2 - (V_{4,3} - V_3^-)^2 - (V_{4,4} - V_4^-)^2 - (V_{4,5} - V_5^-)^2}$$

$$= \sqrt{(0.0181 - 0.218)^2 + (0.0376 - 0.0312)^2 + (0.1081 - 0.0898)^2 + (0.0332 - 0.0444)^2 + (0.0145 - 0.0356)^2}$$

= 0.2023

$$D_5^- = \sqrt{\sum_{j=1}^{5} (V_{5j} - V_j^-)^2} =$$

$$\sqrt{(V_{5,1} - V_5^-)^2 - (V_{5,2} - V_2^-)^2 - (V_{5,3} - V_3^-)^2 - (V_{5,4} - V_4^-)^2 - (V_{5,5} - V_5^-)^2}$$

$$= \sqrt{(0.2180 - 0.218)^2 + (0.0340 - 0.0312)^2 + (0.0977 - 0.0898)^2 + (0.0444 - 0.0444)^2 + (0.0321 - 0.0356)^2}$$

= 0.0091

$$D_6{}^{-} = \sqrt{\sum_{j=1}^{5} (V_{6j} - V_j{}^{-})^2} =$$

$$\sqrt{(V_{6,1} - V_1{}^{-})^2 - (V_{6,2} - V_2{}^{-})^2 - (V_{6,3} - V_3{}^{-})^2 - (V_{6,4} - V_4{}^{-})^2 - (V_{6,5} - V_5{}^{-})^2}$$

$$= \sqrt{(0.0022 - 0.218)^2 + (0.0420 - 0.0312)^2 + (0.1208 - 0.0898)^2 + (0.0345 - 0.0444)^2 + (0.0191 - 0.0356)^2}$$

= 0.2191

$$D_7{}^{-} = \sqrt{\sum_{j=1}^{5} (V_{7j} - V_j{}^{-})^2} =$$

$$\sqrt{(V_{7,1} - V_7{}^{-})^2 - (V_{7,2} - V_2{}^{-})^2 - (V_{7,3} - V_3{}^{-})^2 - (V_{7,4} - V_4{}^{-})^2 - (V_{7,5} - V_5{}^{-})^2}$$

$$= \sqrt{(0.0022 - 0.218)^2 + (0.0312 - 0.0312)^2 + (0.0898 - 0.0898)^2 + (0.0280 - 0.0444)^2 + (0.0356 - 0.0356)^2}$$

= 0.2164

$$D_8{}^{-} = \sqrt{\sum_{j=1}^{5} (V_{8j} - V_j{}^{-})^2} =$$

$$\sqrt{(V_{8,1} - V_8{}^{-})^2 - (V_{8,2} - V_2{}^{-})^2 - (V_{8,3} - V_3{}^{-})^2 - (V_{8,4} - V_4{}^{-})^2 - (V_{8,5} - V_5{}^{-})^2}$$

$$= \sqrt{(0.0089 - 0.218)^2 + (0.0508 - 0.0312)^2 + (0.1461 - 0.0898)^2 + (0.0333 - 0.0444)^2 + (0.0270 - 0.0356)^2}$$

= 0.2179

$$D_9{}^{-} = \sqrt{\sum_{j=1}^{5} (V_{9j} - V_j{}^{-})^2} =$$

$$\sqrt{(V_{9,1} - V_9{}^{-})^2 - (V_{9,2} - V_2{}^{-})^2 - (V_{9,3} - V_3{}^{-})^2 - (V_{9,4} - V_4{}^{-})^2 - (V_{9,5} - V_5{}^{-})^2}$$

$$= \sqrt{(0.0009 - 0.218)^2 + (0.0430 - 0.0312)^2 + (0.1237 - 0.0898)^2 + (0.0172 - 0.0444)^2 + (0.0093 - 0.0356)^2}$$

= 0.2233

$$D_{10}{}^{-} = \sqrt{\sum_{j=1}^{5} (V_{10j} - V_j{}^{-})^2} =$$

$$\sqrt{(V_{10,1} - V_{10}{}^{-})^2 - (V_{10,2} - V_2{}^{-})^2 - (V_{10,3} - V_3{}^{-})^2 - (V_{10,4} - V_4{}^{-})^2 - (V_{10,5} - V_5{}^{-})^2}$$

$$= \sqrt{(0.0012 - 0.218)^2 + (0.0316 - 0.0312)^2 + (0.0909 - 0.0898)^2 + (0.0120 - 0.0444)^2 + (0.0078 - 0.0356)^2}$$

$= 0.2210$

$$D_{11}^{-} = \sqrt{\sum_{j=1}^{5} (V_{11j} - V_j^{-})^2} =$$

$$\sqrt{(V_{11,1} - V_{11}^{-})^2 - (V_{11,2} - V_2^{-})^2 - (V_{11,3} - V_3^{-})^2 - (V_{11,4} - V_4^{-})^2 - (V_{11,5} - V_5^{-})^2}$$

$$= \sqrt{(0.0056 - 0.218)^2 + (0.0340 - 0.0312)^2 + (0.0977 - 0.0898)^2 + (0.0444 - 0.0444)^2 + (0.0066 - 0.0356)^2}$$

$= 0.2145$

$$D_{12}^{-} = \sqrt{\sum_{j=1}^{5} (V_{12j} - V_j^{-})^2} =$$

$$\sqrt{(V_{12,1} - V_{12}^{-})^2 - (V_{12,2} - V_2^{-})^2 - (V_{12,3} - V_3^{-})^2 - (V_{12,4} - V_4^{-})^2 - (V_{12,5} - V_5^{-})^2}$$

$$= \sqrt{(0.0067 - 0.218)^2 + (0.0418 - 0.0312)^2 + (0.1201 - 0.0898)^2 + (0.0322 - 0.0444)^2 + (0.0073 - 0.0356)^2}$$

$= 0.2159$

$$D_{13}^{-} = \sqrt{\sum_{j=1}^{5} (V_{13j} - V_j^{-})^2} =$$

$$\sqrt{(V_{13,1} - V_{13}^{-})^2 - (V_{13,2} - V_2^{-})^2 - (V_{13,3} - V_3^{-})^2 - (V_{13,4} - V_4^{-})^2 - (V_{13,5} - V_5^{-})^2}$$

$$= \sqrt{(0.0041 - 0.218)^2 + (0.0420 - 0.0312)^2 + (0.1208 - 0.0898)^2 + (0.0133 - 0.0444)^2 + (0.0356 - 0.0356)^2}$$

$= 0.2186$

$$D_{14}^{-} = \sqrt{\sum_{j=14}^{5} (V_{14j} - V_j^{-})^2} =$$

$$\sqrt{(V_{14,1} - V_1^{-})^2 - (V_{14,2} - V_2^{-})^2 - (V_{14,3} - V_3^{-})^2 - (V_{14,4} - V_4^{-})^2 - (V_{14,5} - V_5^{-})^2}$$

$$= \sqrt{(0.0004 - 0.218)^2 + (0.0359 - 0.0312)^2 + (0.1033 - 0.0898)^2 + (0.0113 - 0.0444)^2 + (0.0356 - 0.0356)^2}$$

$= 0.2206$

$$D_{15}^{-} = \sqrt{\sum_{j=1}^{5} (V_{15j} - V_j^{-})^2} =$$

$$\sqrt{(V_{15,1} - V_1^{-})^2 - (V_{15,2} - V_2^{-})^2 - (V_{15,3} - V_3^{-})^2 - (V_{15,4} - V_4^{-})^2 - (V_{15,5} - V_5^{-})^2}$$

$$= \sqrt{(0.0024 - 0.218)^2 + (0.0512 - 0.0312)^2 + (0.1471 - 0.0898)^2 + (0.0247 - 0.0444)^2 + (0.0093 - 0.0356)^2}$$

$= 0.2264$

Appendix 4-4: Calculation of RC_2^+ to RC_{15}^+ in Chapter 5

$$RC_2^+ = \frac{D_2^-}{D_2^+ + D_2^-} = = \frac{0.2221}{0.0336 + 0.2221} = 0.868596$$

$$RC_3^+ = \frac{D_3^-}{D_3^+ + D_3^-} = = \frac{0.2029}{0.0583 + 0.2029} = 0.776799$$

$$RC_4^+ = \frac{D_4^-}{D_4^+ + D_4^-} = = \frac{0.2023}{0.0584 + 0.2023} = 0.775988$$

$$RC_5^+ = \frac{D_5^-}{D_5^+ + D_5^-} = = \frac{0.0091}{0.2276 + 0.0091} = 0.038445$$

$$RC_6^+ = \frac{D_6^-}{D_6^+ + D_6^-} = = \frac{0.2191}{0.0457 + 0.2191} = 0.827417$$

$$RC_7^+ = \frac{D_7^-}{D_7^+ + D_7^-} = = \frac{0.2164}{0.0679 + 0.2164} = 0.761168$$

$$RC_8^+ = \frac{D_8^-}{D_8^+ + D_8^-} = = \frac{0.2179}{0.0335 + 0.2179} = 0.866746$$

$$RC_9^+ = \frac{D_9^-}{D_9^+ + D_9^-} = = \frac{0.2233}{0.0345 + 0.2233} = 0.866175$$

$$RC_{10}^+ = \frac{D_{10}^-}{D_{10}^+ + D_{10}^-} = = \frac{0.2210}{0.0685 + 0.2210} = 0.763385$$

$$RC_{11}^+ = \frac{D_{11}^-}{D_{11}^+ + D_{11}^-} = = \frac{0.2145}{0.0615 + 0.2145} = 0.777174$$

$$RC_{12}^+ = \frac{D_{12}^-}{D_{12}^+ + D_{12}^-} = = \frac{0.2159}{0.0435 + 0.2159} = 0.832305$$

$$RC_{13}^+ = \frac{D_{13}^-}{D_{13}^+ + D_{13}^-} = = \frac{0.2186}{0.0371 + 0.2186} = 0.854908$$

$$RC_{14}^+ = \frac{D_{14}^-}{D_{14}^+ + D_{14}^-} = = \frac{0.2206}{0.0554 + 0.2206} = 0.799275$$

$$RC_{15}^+ = \frac{D_{15}^-}{D_{15}^+ + D_{15}^-} = = \frac{0.2264}{0.0168 + 0.2264} = 0.930921$$