ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

RISK ASSESSMENT AND MARINE ACCIDENT ANALYSIS IN ICE-COVERED WATERS

Ph.D. THESIS

Bekir ŞAHİN

Department of Maritime Transportation Engineering

Maritime Transportation Engineering Programme

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Bekir ŞAHİN
(512112005)

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Thesis Advisor: Assoc. Prof. Dr. Serdar KUM

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BUZLU SULARDA RİSK DEĞERLENDİRMESİ VE DENİZ KAZA ANALİZİ

DOKTORA TEZİ

Bekir ŞAHİN
(512112005)

Deniz Ulaştırma Mühendisliği Anabilim Dalı

Deniz Ulaştırma Mühendisliği Programı

Tez Danışmanı: Doç. Dr. Serdar KUM

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Bekir ŞAHİN, a Ph.D. student of ITU Graduate School of Science Engineering and Technology 512112005 successfully defended the thesis entitled **"RISK ASSESSMENT AND MARINE ACCIDENT ANALYSIS IN ICE-COVERED WATERS"**, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Assoc. Prof. Dr. Serdar KUM** Istanbul Technical University	....
Jury Members :	**Asst. Prof. Dr. Cemil YURTÖREN** Istanbul Technical University	....
	Assoc. Prof. Dr. Özcan ARSLAN Istanbul Technical University	....
	Assoc. Prof. Dr. Vural AKSAKALLI Istanbul Şehir University	....
	Assoc. Prof. Dr. Fuat ALARÇİN Yıldız Technical University	....

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To my family

FOREWORD

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Bekir ŞAHİN
(Research Assistant)

TABLE OF CONTENTS

Page

ABBREVIATIONS

AA : Average Agreement
AHP : Analytical Hierarchy Process
AMSA : Arctic Maritime Shipping Assessment
ARW : Average Route Width
BE : Basic Event
BHAA : Bulanık Hata Ağacı Analizi
CC : Consensus Coefficient
CCI : Centric Consistency Index
CFP : Crisp Failure Possibility
CS : Cut Set
DAMA : Database for Maritime Accidents
DM : Decision Maker
DP : Defuzzification Process
F-AHP : Fuzzy Analytical Hierarchy Process
FFTA : Fuzzy Fault Tree Analysis
FMA : Finnish Maritime Administration
FP : Failure Probability
FTA : Fault Tree Analysis
FV-I : Fussell-Vesely Importance
GB-AHS : Geliştirilmiş Bulanık Analitik Hiyerarşi Süreci
GF-AHP : Generic Fuzzy Analytical Hierarchy Process
IACS : International Association of Classification Societies
IC : Ice Concentration
IF-AHP : Improved Fuzzy Analytical Hierarchy Process
IM : Importance Measurement
IMO : International Maritime Organization
JB-AHS : Jenerik Bulanık Analitik Hiyerarşi Süreci
Max : Maximum width along with the track
MCS : Minimal Cut Set
Min : Minimum width along with the track
RA : Relative Agreement
RL : Route Length
RRW : Risk Reduction Worth
S : Slot Availability
SD : Sea Depth
SB : Sharp Bend
TDS : Top Decrease Sensitivity
TE : Top Event

LIST OF TABLES

Page

LIST OF FIGURES

RISK ASSESSMENT AND MARINE ACCIDENT ANALYSIS IN ICE-COVERED WATERS

SUMMARY

The crux of this thesis is to understand sea ship navigation in ice-covered waters. Arctic sea ice melts fast and soon the North Pole is foreseen to be open water. Besides several disadvantages of the global warming to the environment and ecology, it brings some opportunities to the transportation industry. For instance, the Northern Sea Route shortens the maritime distance approximately 7000 nautical miles comparing to the conventional Suez Canal route. This research examines three main topics that are tightly connected each other and may significantly affect polar navigation.

Before preparing the voyage plan, statistics and root causes of marine accidents are emerging issues for the polar regions. Secondly, all probable risks and their levels require attention. Finally, if it is decided to navigate through ice-covered waters, the route selection problem should be dealt with through a proper procedure. The mentioned issues are investigated as three chapters in the thesis and each chapters are summarized as follows.

In the third chapter, navigational risk factors of the ice navigation are defined and numerical weights of each risk are obtained by using Improved Fuzzy Analytical Hierarchy Process (IF-AHP) method after conducting expert consultations. Navigational routes of North Pole take a significant role of having economic and time advantage for global logistics. Its geographical position, presence of ice, heavy weather conditions, strong currents and winds are some risks for Polar transportation. There always have the possibility of unpredictable catastrophes (marine accidents) such as a collision, grounding, hull damage, etc. in ice-covered waters. Reflections of such unwanted incidents might be very costly for economic, political, environmental and safety concerns. However, there are limited researches regarding to analytic and systematical risk identification and determination of risk levels. The novelty of this chapter is that we consider the expert consultations in order to transform the linguistic expressions into numerical values. IF-AHP method including the expert aggregation and consistency check is used to analyze the data. The results and discussion are expected to guide the representatives understanding to minimize the probable risks before they occur.

The aim of the fourth chapter is to understand minimizing the vessel damages and marine accidents occurring in the Arctic region by using Fuzzy Fault Tree Analysis (FFTA) algorithm. Ice navigation has been conducted intensively in summer seasons of the year in the last five years. Therefore, navigation-oriented risk assessment is an emerging issue in the polar regions which are gained from the previous marine accidents in terms of safety. In this chapter, root causes of collision and grounding for the ice navigation are constructed. Risk levels of each factor are determined by expert consultations. Mitigation effectiveness of the precautions is also discussed to prevent the future incidents and provide an enhancement of the safe navigation.

The effects of global warming in the Arctic Ocean made the routes (tracks) more navigable. Therefore, especially after 2009, regular marine transportation through the Arctic, shipping and logistics operations on the ice navigation routes are emerging issues in the Arctic trading activities. Fifth chapter investigates the ice navigation problem and proposes an original decision making model for ice navigation operations in the ice-covered waters. The proposed approach deals with the existing and available navigational routes on a generic Arctic region and ensures the selection of optimum track based on navigational and ice-state factors. For the intended problem, an expert consultation is performed and the state of the problem is clarified. The Generic Fuzzy Analytic Hierarchy Process (GF-AHP) is used, as basis for the decision-making environment of ship master and its fuzzy set extension is preferred based on the uncertainty of expert responses. Finally, an illustration of optimal track selection is presented by using a simulated case in real terms.

The outcome of this work will be a guide regarding to ice navigation that aims to maximize opportunities and minimize challenges for the ice navigators, maritime organizations and so on. On the other hand, the methods, models and ideas given in this thesis that are likely to improve development for the researchers in the future.

BUZLU SULARDA RİSK DEĞERLENDİRMESİ VE DENİZ KAZA ANALİZİ

ÖZET

Bu tezin en önemli noktası, buzlu bölgelerdeki gemi seyrini anlamaktır. Son yıllarda Arktik deniz buzları hızlı şekilde erimektedir ve gelecekte Kuzey Kutbunun açık deniz olacağı öngörülmektedir. Küresel ısınmanın çevreye ve ekolojiye birçok dezavantajı olmasının yanısıra, taşımacılık endüstrisine bazı fırsatlar getirmektedir. Örneğin, Kuzey Deniz Rotası (Northern Sea Route), geleneksel Süveyş Kanalı rotasına kıyasla seyir rotasını yaklaşık 7000 deniz mili kısaltmaktadır. Bu araştırmada buzda gemi seyrini önemli şekilde etkileyen ve birbirine sıkı sıkıya bağlı üç ana başlık incelenmektedir.

Kutup bölgelerindeki bir suyolunun seyre elverişliliğine karar verilmeden önce, ilgili istatistiklerin ve deniz kazalarına neden olan kök sebeplerinin bilinmesi önem arzetmektedir. Daha sonra mevcut ve muhtemel tüm risklerin neler olduğu ve bu risklerin ne seviyede bulunduğu tespit edilmelidir. En son olarak da eğer buzlu bölgelerde seyir yapılmaya karar verildiyse, rota seçimi problemi incelenmelidir. Burada değinilen her bir konu, tezde üç bölüm halinde ele alınmış ve her bir bölüm aşağıda özetlenmiştir.

Üçüncü bölümde, buzda seyir emniyetine etki eden mevcut ve muhtemel tüm risk faktörleri kategorize edilmiş ve uzman görüşleri alındıktan sonra Geliştirilmiş Bulanık Analitik Hiyerarşi Süreci (GB-AHS) metodu yardımıyla herbir riske ait numerik ağırlıklar tespit edilmiştir. Küresel lojistikte ekonomik fayda ve süre avantajı sağlamak için kutup bölgelerindeki gemi seyir rotaları önemli bir rol üstlenmektedir. Bu bölgenin coğrafi pozisyonu, buzun mevcudiyeti, ağır hava şartları, kuvvetli akıntı ve rüzgarlar bu bölgede seyre etki eden risklerden bazılarıdır. Çatma, oturma ya da tekne hasarı gibi olumsuz durumlar bu bölgede her zaman meydana gelebilecek potansiyel deniz kazalarıdır. Böylesi durumların sonuçları, can ve mal emniyeti için büyük risk ve zorluk oluşturmaktadır ve bu olayların ekonomik, politik, çevresel etkileri çok masraflı olabilmektedir. Bununla birlikte bu çalışma, literatürde bu bölge için risk seviyelerinin analitik ve sistematik olarak ortaya konduğu ilk akademik çalışmadır.

Buzlu ortamlarda seyir için riskler yedi farklı kategoride toplanmıştır. Bunlar; (i) gemiyle doğrudan ilişkili olmayan dış faktörler, (ii) gemi yapısı ve gemi ekipmanların yeri, (iii) gemi ekipmanlarının teknik arızaları (iv) gemi operasyonları ve ekipmanların yerleştirilmesi ile ilgili riskler, (v) yük/yakıt ve bunları elleçleme ekipmanlarından kaynaklanan riskler, (vi) iletişim, organizasyon, operasyonel talimatlar ve rutin işlere ait riskler, (vii) insan faktörü, durum farkındalığı ve durum değerlendirmesine ilişkin riskler olarak saptanmıştır. Her bir risk faktörü kendi içerisinde alt kriterlere ayrılmaktadır. Toplamda 79 adet risk kriteri ele alınarak kutup bölgeleri için seyre etki eden kapsamlı bir risk değerlendirme çalışması yapılmıştır. Belirlenen bu risk faktörleri ve alt kriterleri ile GB-AHS metodunun ön şartı olan üç katmanlı hiyerarşi yapısı oluşturulmuş olmaktadır. Daha sonra ilgili bölümde geniş bir biçimde açıklanan

metodoloji adım adım uygulanmaktadır. Netice itibariyle uzmanların düşünceleri ve sözel ifadeleri sayısal değerlere dönüştürülerek GB-AHS metodu ile elde edilen veriler analiz edilmiştir. Bu bölgede seyir yapan gemiler ve idari yetkililere yol göstermesi amacıyla ortaya konan sonuçların, mevcut risklerin azaltılarak kaza sayısının minimize edilmesi amaçlanmaktadır.

Buzlu bölgelerdeki risklerin bilinmesi, ağırlıklandırılması ve önceliklendirilmesi deniz kazalarının önlenmesi için önemli bir öncüldür. Deniz kazalarına neden olan yada ileride olması muhtemel kök sebepler belirlenirken deniz kaza raporlarının ve uzman görüşlerinin yanısıra mevcut ve muhtemel tüm risklerin de incelenmesi gerekmektedir. Kutup bölgesinde herhangi bir kazaya neden olan tüm kök sebepler üçüncü bölümde belirlenen risk kriterleri içerisinde yer alması gerektiğinden hareketle çatma ve oturmaya sebep olan/olabilecek tüm kök sebepler ilgili risk kriterleriyle dördüncü bölümde eşleştirilmiştir.

Dördüncü bölümde, Bulanık Hata Ağacı Analizi (BHAA) algoritmasını kullanarak Arktik bölgesinde meydana gelen deniz kazalarının ve gemi hasarların nasıl minimize edileceğini anlamak amaçlanmıştır. Arktik bölgesinde buzlu ortamlarda seyir son beş yılın yaz aylarında yoğun bir şekilde gerçekleştirilmektedir. Bu yüzden, kutup bölgelerinde meydana gelmiş ve gelmesi muhtemel kazalardan elde edilen seyir odaklı risk değerlendirmesi emniyet açısından çalışılması gereken yeni bir konudur. Bu bölümde buzlu bölgelere özgü çatma ve oturmanın kök sebepleri belirlenmiştir. Herbir faktörün risk seviyesi uzman görüşleri alınarak tespit edilmiştir. Ayrıca, gelecekteki kazaların önüne geçmek için alınacak önlemlerin riski azaltmak için verimli olup olmadığı tartışılmış ve seyir emniyetini artırmanın yolları araştırılmıştır.

Günümüzde kuzey kutbundaki su yolları yalnızca yaz dönemleri seyre elverişli iken, küresel ısınmanın etkisiyle yakın gelecekte bölgenin daha uzun periyotlarda seyre elverişli olacağı öngörülmektedir. Bu yüzden, özellikle 2009'dan sonra Arktik bölgesinden geçerek yapılan düzenli deniz taşımacılığı artmaktadır. Buzda seyir rotaları üzerinden lojistik operasyonları Arktik bölgesindeki ticari faaliyetler konusunda akademik çalışmlarda artış gözlemlenmiştir. Beşinci bölüm, buzlu bölgelerdeki lojistik faaliyetler için buzda seyir problemini incelemekte ve buzlu sularda gemi operasyonları için orjinal bir karar verme modeli önermektedir. Amaçlanan bu yaklaşım, buzlu bölgelerdeki mevcut ve uygun seyir rotaları ile buza bağlı faktörler dikkate alınarak en optimum rotanın seçimi ile ilgilenmektedir. Ele alınan bu problemde, uzman görüşmeleri gerçekleştirilmiş ve problem net bir şekilde tanımlanmıştır. Jenerik Bulanık Analitik Hiyerarşi Süreci (JB-AHS) metodu kullanımında uzman yanıtlarının çalışmaya net yansıması için bulanık küme eklentisi tercih edilmiştir. Sonuç itibariyle, en optimal rotanın seçimi, belirlenen kriterlerin gerçeğe yakın değerleriyle ifadelerle hazırlanmış ve gösterilmiştir.

Rota seçiminde buz durumununa bağlı sekiz adet kriter belirlenmiştir. Bunlar, rota boyunca ortalama rota genişliği, rota uzunluğu, rotanın maksimum olduğu genişlik, rotanın minimum olduğu genişlik, buz konsantrasyonu, keskin manevra alanlarının sayısı ve rota boyunca geminin sığınabileceği slot sayısıdır. Bu kriterler hakkında yorum yapabilmek için bu kriterlere bağlı riskleri gözönünde bulundurmak gerekmektedir. Dolayısıyla buz durumuna bağlı riskler ve bu risklerle ilgili çatma ve oturmaya neden olabilecek kök sebepler, herbir rota seçim kriteri için tespit edilmiştir. Rota seçiminde sadece buz durumuna bağlı kriterler belirlendiği için diğer riskler sabit kabul edilmiştir. Örneğin; kötü hava şartları, akıntı rüzgar vs tüm rotalar için sabittir.

Bu çalışmanın çıktısı olarak; buzlu bölgelerde gemi seyrine ilişkin fırsatların maksimize edilmesi, risk ve zorlukların da minimize edilmesi amacıyla denizcilere, denizcilik organizasyonlarına ve diğer ilgililere alacağı kararlarda bir rehber sunması amaçlanmıştır. Diğer taraftan, tezde verilen metotlar, modeller ve fikirlerin geliştirilmesi için gelecekte araştırmacılara fırsatlar sunmaktadır.

1. INTRODUCTION

The transportation locations of economic world are on dramatic change with the emergence of new Arctic seaways [1]. Melt of sea-ice observed in the Northern Hemisphere sea ice cover that is considered with the greatest attention. As a result of both greenhouse effect and the seasonal fluctuations of long-term average temperatures, have brought a historical opportunity to extend maritime transport over the Arctic region. For instance, the Northern Sea Route shortens the Yokohama-London route via Suez Canal from approximately 11.000 nautical miles to 7.000 nautical miles. Figure 1.1 illustrates the Arctic Sea Routes that shorten the traditional routes (Courtesy of Wikipedia).

Figure 1.1: Comparison of conventional route and arctic route.

According to National Snow and Ice Data Center statistics, Arctic sea ice reaches the lowest extent in September 2014 (Figure 1.2) (Courtesy of national snow and ice data center, University of Colorado, Boulder). Therefore, traffic in the Arctic Ocean is increasing drastically based on the data of Northern Sea Route Information Office.

The decrease of multiyear ice in the North Pole forces the logistics and maritime companies to explore oil and gas as well as the shortest shipping routes. Although global warming has many negative effects on Arctic environment and habitat, newly

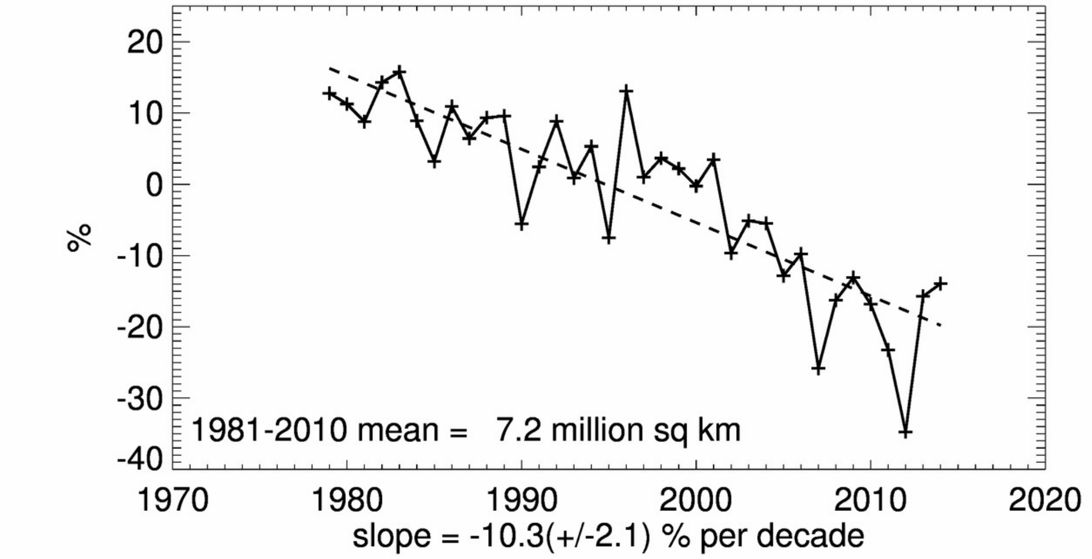


Figure 1.2: Northern hemisphere extent anomalies.

open routes might increase the economic activity in the region. Therefore, safe navigation of vessels operating in the Arctic region is highly significant for all relevant nations as well as other navigating vessels. Navigation in Arctic is risky because of the harsh and hazardous environment with heavy weather and severe ocean conditions [2].

Risks of Arctic navigation are defined in the third chapter. In the literature, there are limited academic researches on ice navigation and there exist no crisp data on the root causes of each unwanted events. The aim of third chapter is to find the numeric values of each risk levels by IF-AHP method. As a source of data several expert consultations are conducted for the intended problem. Quantitative approaches are inadequate for getting the bottom of the many incidents because of the intricate nature of risk factors. To overcome this inadequacy, qualitative (fuzzy) approach is preferred to apply for the risk assessment based on subjective experience [3].

Risk assessment is considered as a crucial process in almost all marine operations as well as Arctic navigation. Risk assessment for the vessels navigate in ice covered waters depends on (i)ice concentration in the framework of routes that ice floes allow/ traffic controls that is conducted by considering the ice forms (ii) whether or not the vessels are ice classed (ice class regulations) (iii) the assistance of ice breakers.

This is an inevitable reality that the risks for vessels navigating in ice covered waters are caused by not only increase in tanker traffic but also high frequency of vessel movements. Based on the definition of risk which is the multiplication of frequency and consequences, increase on number of tankers (Figure 1.3, Northern Sea Route

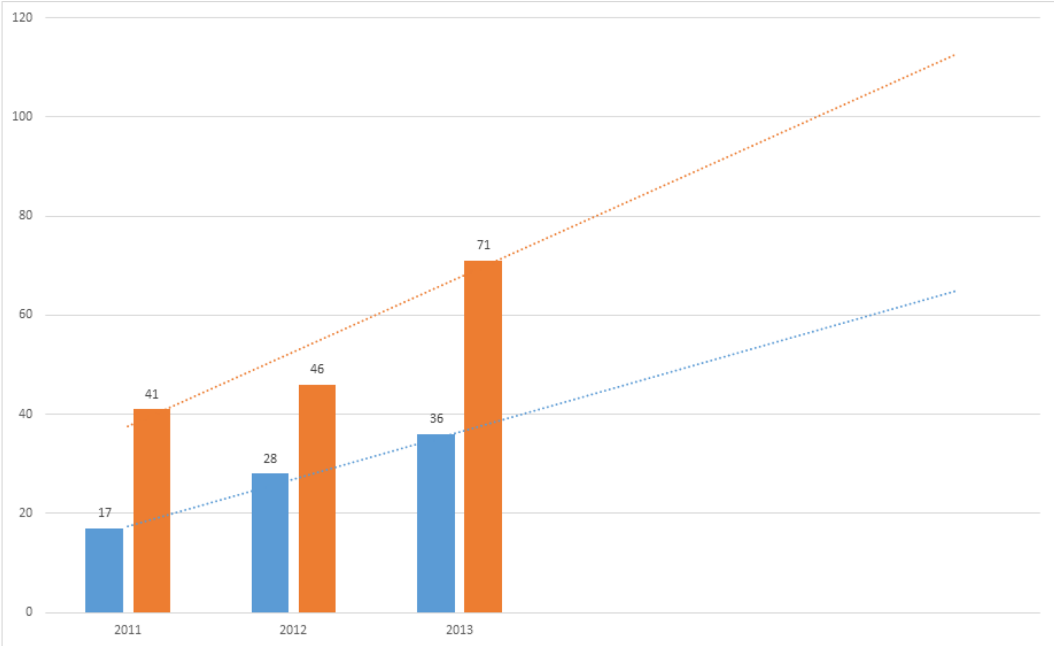


Figure 1.3: Number of tankers and total number of the vessels in the Arctic region.

Information Office) is crucial because of its massive and costly consequences if an accident occurs. Figure 1.3 depicts the increase of tankers and total number of vessels. Since the orange cloumn represents the total number of vessels, the blue ones point out the increase of tankers. The number of tankers is 17 out of 41 vessels in 2011, 28 out of 46 in 2012 and 36 out of 71 in 2013 [4].

It should be considered that a risk factor might involve/trigger different incidents due to marine accidents are composed of constant and unsteady parameters. Therefore, determining all probable risks are of significance in order to clarify the primary reasons. However, the reports, summaries and data related previous marine incidents are not solely enough to analyze navigational risks. Accordingly, experts are asked to discuss and define more probable risks, which they did not occur until now but might occur in the future.

According to Lloyd's Marine Intelligence Unit Sea Searcher Database, Canadian Transportation Safety Board (Marine) and Canadian Hydraulics Centre - Arctic Ice Regime System Database there exist 293 marine incidents occurred in the Arctic region between 1995-2004 (Arctic Marine Shipping Assessment 2009 Report, Arctic Council).

There exists a vast amount of literature on general marine accident analyses and reports considering the legal rules and marine pollution. Most of the studies involve the economic and political sides of the marine accidents. Also, the Arctic navigation is considered primarily difficulties of ice navigation and harms for the ecosystem in the literature. However, to our knowledge this is the first study that accounts for the existing and probable technical and navigational risk factors in the Arctic region. In the fourth chapter therefore, root causes of collision and grounding for the Arctic Region are constructed. Recommendations to reduce the occurrence probability of an unwanted event are proposed. Risk levels of each factor are determined by expert consultations. Mitigation effectiveness of the precautions is also discussed to prevent the future incidents and provide an enhancement of the safe navigation.

The Arctic navigation is a new concept and it has a short literature including track optimization among others [5,6]. Once a navigational route selected, above-mentioned studies improve the navigational quality in terms of time, structural stress, fuel consumption etc. However, the route selection is a prior problem, which is not discussed in earlier studies.

A possible shipping route on the Arctic region extremely improves loss of time and energy that are used in case of a long transportation over the regular basis. However, due to available shipping routes are still covered by floating ice (i.e. open ice, closed ice), the Arctic routing has a growing debate with its highly technical circumstances. Navigational track (route) optimization, entry to the ice field and route selection are some challenges in this field. Among these debates, optimal route selection is the main concern of fifth chapter and it depends on a number of factors such as the dimensions and the physical conditions of the route.

The route selection problem can be categorized as the static route selection and the dynamic one. The requirements for static route selection is based on instant inputs of indicators while assuming the ice field and weather conditions are stationary over the intended navigational sea field. In case of the dynamic problem, the ice field and weather may have variations over the region and the size and direction of vectors may change over the time.

As an introduction to the problem, fifth chapter deals with the static route selection problem with the perspective of subjective judgments of shipmasters. It is certain that these field experts have enough experience and knowledge on ice navigation operations and winterisation. The problem investigated by using Fuzzy Analytical Hierarchy Process (F-AHP) approach. The reasons behind the selection of FAHP are twofold: First, AHP is very useful for handling both quantitative and subjective matters and second, fuzzy extension facilitates the process for subjects in the survey by using linguistic representations. Decision makers' uncertainty is a common case and based on the drawbacks of uncertainty, fuzzy transformations help the moderator (i.e. researcher) to collect a data span rather than a crisp number without unknown uncertainty degree.

The experts are assured that they have the experience and knowledge on ice navigation and Arctic region. Majority of the experts are interest in experimental and numerical investigation of the model ice failure process, efficiency of ships in ice – shape optimization, the influence of ice loads on the propulsion machinery, environmental risk assessments of shipping in ice covered waters, consequence assessment of accidental ship and ice impact, consequence assessment following design relevant service actions in ice, first principal-based approaches for the identification and evaluation of ice induced actions, risk-based design methods and risk mitigation measures for arctic ships, performance of ships in ice, arctic field logistics and Trans-Arctic shipping.

The organization of this thesis in which the main objective is to understand Arctic sea ship navigation is as follows. Chapter 2 reviews relevant studies in the literature. Chapter 3 formally defines the risks in the Arctic region and conducts risk assessment for Arctic navigation. The levels of risks are computed by using Improved Fuzzy Analytical Hierarchy Process (IF-AHP) method. Chapter 4 provides the fault trees of collision and grounding, Fuzzy Fault Tree Analysis (FFTA) methodology and an application for the intended problem. Chapter 5 presents a route selection problem. Route selection criteria and alternatives are handled by Generic Fuzzy Analytical Hierarchy Process (GF-AHP) method. Finally, in chapter 6, the study is concluded with a summary, some comments and discussions.

2. LITERATURE REVIEW

There exist a vast amount of literature on various aspects of navigation in the Arctic region. A comprehensive review of previous research on this topic within Arctic shipping can be found in Schøyen (2011), Ho (2010) and Verny (2009). Economic aspects of Arctic transportation as well as its increase over the past decade were discussed in Lasserre (2014) and Hong (2012). These studies considered both Arctic routes and profitability. Existing navigation-oriented research on the Arctic region can broadly categorized into four groups: (1) Arctic shipping routes and profitability (2) environmental impacts and studies on Arctic meteorology and (3) Arctic politics (4) navigation. Previous research in these categories is briefly described below.

The problem of economic viability of using the Northen Sea Route was studied in Granberg (1998), Liu (2010) and Harsem (2011). The same problem was considered in Somanathan (2009) under simulating the Northwest Passage by comparing the alternate routes in terms of predefined constraits, whereas Lasserre (2011) presents interest of shipping companies in developing activities in the Arctic.

Risk analysis of the marine accidents are highly studied in the literature. For instance, Köse (1997) studied risk assessment of fishing vessels by using fault tree analysis and Uğurlu (2013) has conducted the same method in oil tanker accidents. However, the works of Kujala (2009) and Jalonen (2005) seem to be the only studies in the literature that considers the risk analysis of the ice navigation in the Baltic Sea from a navigator's point of view.

An overview of Arctic sea ice in global atmospheric circulation can be found in Budikova (2009). History of sea ice in the Arctic is given in Polyak (2010), Kellogg (1995). A comparison of the past rates of climate changes in the Arctic region was given in White (2010), glacial history of Arctic was studied in Jakobsson (2013). Yamanouchi (2011) proposed some explanations on early 20th century warming in the Arctic whereas Jakobbson (2014) introduced a program to review the Arctic quaternary environmental change. Models for snow depth and sea ice extent in the Arctic were proposed in Park (2013). Ford (2006) and Doel (2014) investigated vulnerability to climate change in the Arctic.

Studies of Arctic policy on the European Union is overviewed in Wegge (2011) and Offerdal (2008,2009). For the USA politics, National strategy for the Arctic region (2013) is declared. Blank (2011) and Padrtová (2012) conducted strategic studies regarding to Russian politics. Jensen (2010) compares the Norwegian and Russian policies by using the discourse analysis. Moreover, legal perspectives for the Arctic is studied in Stokke (2006).

Regarding the icebreaking service, Parsons (2011) discussed the operational infrastrusture and and effectiveness of the icebreakers in the Arctic region. Kotovirta (2009) studied route optimization ice covered waters. For optimal ship navigation, impacts of turn-radius constraints and safety distance were studied in Ari (2013). On the other hand, Snider (2012) and Buyssse (2007) describe challenges of polar ship operations and handling ships in ice. Satellite measurements and remote sensing technology regarding the both sea ice detection and ice navigation are studied in Parkinson (2008) and Alexandrov (2010).

3. RISK ASSESSMENT OF ICE NAVIGATION

Safety has been considered as the most significant attribute for all marine activities. Ice-covered waters set many risks not only to vessels and environment but also to human lives. For the risk management, all probable problems and risks are identified, required information are collected to support the decision-making process, the risks are assessed and prioritized and then action plans are prepared [43]. Maritime risk analysis is studied by many scholars to contribute the safety of maritime transportation based on diverse perspectives [44]. Some of these research are modeling for human error [45], risk assessment models combined with system simulation and expert judgment [46], Bayesian Belief Network [47], probabilistic risk analysis [19], collision estimation by geometrical probability, statistical and optimization methods [48].

In this chapter, risk assessment of ice navigation is conducted. The risks that the vessels might probably encounter in the polar regions are categorized below. Database for maritime accidents (DAMA of Det Norske Veritas) of which is previously used by Finnish Maritime Administration (FMA) is revised and adopted for constructing the hierarchical structural model of risk assessment for ice navigation in the polar regions [19, 20]. Due to the database is used only for the risk assessment of Finland Bay, after a literature review and expert consultation, it is modified for the polar regions as given below:

3.1 Navigational Risks In Ice-Covered Waters

B1-External risk factors

B1-1 Environmental conditions encountered such as fog, storms, compass anomalies,atmospheric effects and ice

B1-2 Drift of pack ice due to wind and surface currents and other ship-handling difficulties

B1-3 Colliding with floating obstacles (sharp corners of ice floes) or pressure to the vessel's hull, propellers, rudder

B1-4 Failure in establishment and maintenance of external aids to navigation

B1-5 Deficiencies in the reliability and detail of hydrographic and geographical information presented on polar navigation charts, coupled with a distinct lack of reliable bathymetry, current, and tidal data.

B1-6 Technical incapacitation of other vessels, ice-breakers, tugs leads to some,catastrophic outcomes

B1-7 Lack of operational efficiency and safety of other vessels.

B1-8 Technical equipment faults of external cargo loading/unloading or bunkering. Failures in quay, channel lock, or bridge structures

B1-9 Operational equipment faults in operation of cargo loading/unloading or bunkering. Operational faults in using port equipment or channel locks.

B1-10 Explosion or external conditions related to the oil drill.

B1-11 Ice restrictions which affect the vessel's movement and force to change of course and speed.

B1-12 Hazards of ice and snow accumulation on the superstructures.

B2-Risk factors related to structural design and arrangement of equipment locations

B2-1 Insufficiency of hull strength and horsepower of the vessel employed.

B2-2 Corrosion, welding for repair and for other works which weaken the strength of the ship

B2-3 Risk of stability caused from construction failures of hull scantlings.

B2-4 Insufficient maneuvering characteristics of vessel not specifically built for ice breaking or quick maneuvering for rapid change of ice conditions.

B2-5 Inappropriate design of the engine room/ arrangements of the places of the equipment have caused a danger of leakage or fire.

B2-6 Inappropriate design of the engine room/ arrangements of the cargo space or store.

B2-7 Inappropriate design of the engine room/ arrangements of other space, not bridge.

B2-8 Unusable design for maintenance, inspection, cleaning

B2-9 Other conditions (i.e. shell plating, frames, ice stringers, web frames, bow, stern, bilge keels) related to vessel construction or maintenance (i.e. rudder and steering arrangements, propeller, shafts and gears, miscellaneous machinery requirements)

B3-Risk factors related to technical faults in vessel equipment.

B3-1 Technical fault in sophisticated electronic navigation equipment (such as radar, sonar, and the visible, infrared, and microwave radiation sensors onboard satellites)
B3-2 Technical fault in maneuvering equipments (i.e. rudder and steering arrangements)
B3-3 Technical fault in propulsion machinery (i.e. propeller, shafts and gears,)
B3-4 Technical fault in auxiliary machinery (i.e. air compressors, cooling water system)
B3-5 Technical fault in berthing, (un)mooring, anchoring equipment / deck equipment
B3-6 Technical failures in remote and automatic control devices and emergency systems
B3-7 Cargo handling equipment technical faults
B3-8 Failures in safety devices /systems of redundant, inert gas and fire extinguish
B3-9 Technical errors in drilling equipment
B3-10 Other technical failures

B4-Risks based on the usage and arrangements of the equipment onboard for operation process

B4-1 Useless design of the bridge, misplacement, removed or no devices
B4-2 Faulty, useless or illogical design or misplacement of controls
B4-3 Inappropriate placement of device for usage
B4-4 Ill-equipped, ill-suited, ill-adapted, improper and hard usage of device
B4-5 Faults in ergonomics, design and operation of the device. Human-machine interface problems.

B5-Risks on cargo, fuel and related handling equipment

B5-1 Catching fire by itself of the cargo / fuel
B5-2 No or inadequate inert gas / fire or explosion prevention system

B5-3 Instability causes from the rules of faulty placement of cargo and imbalance causes from missing ballast etc.

B5-4 Poor cargo security

B5-5 Risks caused from liquid cargo leaks (barrels, containers, tanks, etc.)

B5-6 Leakages in cargo or fuel pipes/hoses

B5-7 Other factor related to cargo or fuel

B6-Communication, organizational, operational instruction faults and routine failures

B6-1 Inadequate or deficiencies for following the general instructions

B6-2 Unfamiliarity of general methods of operation or insufficient practice

B6-3 Deficiencies for following the safety instructions

B6-4 Familiarity with safety instructions, but no implementation

B6-5 Safety instructions related to the welding are not performed.

B6-6 Fire occurred during the welding process although safety precautions are taken.

B6-7 Tests and practices for lifesaving equipment not implemented

B6-8 No usage of equipment for protection.

B6-9 Poor knowledge of organization or instruction

B6-10 Rules for Inspection and maintenance not implemented

B6-11 No knowledge of stability or wrong calculations of stability.

B6-12 Leadership related and personal problems.

B6-13 Improper or insufficient look-out caused from manning. (i.e. missing helmsman)

B6-14 Directions of obligations or task area is not clear

B6-15 No or faulty bridge routines

B6-16 No implementation of Bridge routines.

B6-17 No up to-date sea charts or publications.

B6-18 Coordination faults during the process of service / procedures with tugs, shore organization etc.

B6-19 Other risks related to organization, safety regulation, periodical tasks or communication

B7-Human factors, interpretation, awareness & assessment of situation, etc.

B7-1 Duty incompetency of training or certifications etc.

B7-2 Practical incompetencies for duty such as experience, local knowledge of waters, usage of devices.

B7-3 Inappropriate design of task or operation such as cargo, night navigation, route planning, anchoring etc.

B7-4 Available warning mechanism is insufficiently developed and used.

B7-5 Alternative navigation systems is not used. Assessments of navigational lights, lighthouses etc. are wrongly or inadequate assessed

B7-6 The usage of available aids for navigation or publications is not sufficient.

B7-7 Failures of using the sea chart, Deficiencies regarding to positioning the own vessel

B7-8 Wrong of inadequate interpretation of other vessel's motions / intentions

B7-9 Wrong or inadequate interpretation of own vessel's motions (icebergs, current, wind etc.)

B7-10 Performing the task or operation under inconvenient and improper conditions

B7-11 Right side of the separation line is not used on the waterway, channel, track, crack, etc.

B7-12 Higher speed than expected.

B7-13 Sickness, fatigue, exhausting, overstrain etc.

B7-14 Falling asleep on the watch

B7-15 Usage of alcohol, drug or other intoxicating substance

B7-16 Other personnel related failures

3.2 Methodology: Improved Fuzzy AHP (IF-AHP) Method

IF-AHP transfers Reciprocal judgment matrix into the fuzzy consistent judgment matrix. Also, normalized aggregation, square root and eigenvector methods involve the process.

The steps of IF-AHP are shown below:

For IF-AHP method, $(0.1 \sim 0.9)$ scales are used. The scales and their meanings are given in the Table 4.5.

Table 3.1: Number scale: $(0.1 \sim 0.9)$ and its meaning

a$_{ij}$	The signification of a_{ij}	a_{ji}
0.5	a_i is as important as a_j	0.5
0.6	a_i is slight precedence over a_j	0.4
0.7	a_i is obvious precedence over a_j	0.3
0.8	a_i is forceful precedence over a_j	0.2
0.9	a_i is extreme precedence over a_j	0.1

Step 1: Comparative judgment matrix is set up as $F = (a_{ij})_{n \times n}$. The elements of matrix $F(a_{ij}, a_{ji})$ have these following properties: $0 < a_{ij} < 1, a_{ij} + a_{ji} = 1, a_{ii} = 0.5$.

Step 2: Fuzzy complementary judgment matrix is established. It is listed as fuzzy consistent matrix: $F = (r_{ij})_{nxn}$. r_i is the sum of rows as $r_i = \sum\limits_{j=1}^{n} r_{ij}$, r_j is the columns of judgment matrix F as $r_j = \sum\limits_{i=1}^{n} r_{ij}$ and $i, j = 1, 2, \ldots, n$ where

Step 3: Transformation formula $r_i = \frac{r_i - r_j}{2n} + 0.5$ is used to solve the row sum $r_i = \sum_{i=1}^{10} t_i$. The fuzzy consistent judgment matrix $R = (r_{ij})_{nxn}$ is converted from fuzzy judgment matrix $F = (f_{ij})_{nxn}$.

Step 4: Rank aggregation method (eq. 1) or Square root (eq. 2) method is used to get the ordering vector.

$$W^{(0)} = (w_1, w_2, \ldots, w_n)^T = \left[\frac{\sum\limits_{j=1}^{n} e_{1j}}{\sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} e_{ij}}, \frac{\sum\limits_{j=1}^{n} e_{2j}}{\sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} e_{ij}}, \ldots, \frac{\sum\limits_{j=1}^{n} e_{nj}}{\sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} e_{ij}} \right]^T \quad \textbf{(3.1)}$$

$$W^{(0)} = (w_1, w_2, \ldots, w_n)^T = \left[\frac{\sqrt[n]{\prod\limits_{j=1}^{n} e_{1j}}}{\sum\limits_{i=1}^{n} \sqrt[n]{\prod\limits_{j=1}^{n} e_{ij}}}, \frac{\sqrt[n]{\prod\limits_{j=1}^{n} e_{2j}}}{\sum\limits_{i=1}^{n} \sqrt[n]{\prod\limits_{j=1}^{n} e_{ij}}}, \ldots, \frac{\sqrt[n]{\prod\limits_{j=1}^{n} e_{nj}}}{\sum\limits_{i=1}^{n} \sqrt[n]{\prod\limits_{j=1}^{n} e_{ij}}} \right]^T \quad \textbf{(3.2)}$$

Step 5: Transformation formula of $e_i j = \frac{r_{ij}}{r_{ji}}$ is used to obtain reciprocal matrix $E = (e_{ij})_{nxn}$ that is transformed from the fuzzy complementary judgment matrix $R = (r_{ij})_{nxn}$. High accuracy of the ranking vector is solved by $W^{(0)}$

For the iterative initial value V_0, iteration formula $V_{k+1} = EV_k$ is used to find the eigenvector V_{k+1} and infinite norm $||V_{k+1}||_\infty$ of V_{k+1}. While $||V_{k+1}||_\infty - ||V_k||_\infty$ less than ε, $V_{k+1} = \lambda_{max}$ which is the largest eigenvalue. Then V_{k+1} is normalized and become the form of

$$V_{k+1} = \left[\frac{V_{k+1,1}}{\sum_{i=1}^{n} V_{k+1,i}}, \frac{V_{k+1,2}}{\sum_{i=1}^{n} V_{k+1,i}}, \ldots, \frac{V_{k+1,n}}{\sum_{i=1}^{n} V_{k+1,i}} \right]^T \tag{3.3}$$

Step 6:

$$V_k = \frac{V_{k+1}}{||V_{k+1}||_\infty} = \left[\frac{V_{k+1,1}}{||V_{k+1}||_\infty}, \frac{V_{k+1,2}}{||V_{k+1}||_\infty}, \ldots, \frac{V_{k+1,n}}{||V_{k+1}||_\infty} \right]^T \tag{3.4}$$

is taken and the ordering vector is $W^{(k)} = V_{i+1}$ and the calculation is completed. V_k becomes the new iterative initial value, which can be recalculated from the beginning.

3.3 Risk Assessment Model For IF-AHP Method

Statistics of marine accidents that occurred in the polar regions show that, there are several risk factors affect ice navigation (Table D.4). These can be attributed as (1) External risk factors (2) Ship structures and the location of equipment on-board (3) Technical failures in ship equipment (4) Issues related to the operation and placement of equipment on-board (5) Issues related to the cargo / fuel and cargo / fuel handling equipment (6) Issues related to communication, organization, operational instructions and routines (7) Human factors, awareness and assessment of situation, etc.

The hierarchical structure model of ice navigation is established in the Figure 3.1.

3.4 Application For The Risk Assessment Of Ice Navigation

The index of risk factors (as shown in Figure 3.1) and their criteria are determined based on the Database for maritime accidents (DAMA of Det Norske Veritas) of which is previously used by Finnish Maritime Administration (FMA) [19,20].

After an expert consultation, judgment matrices are obtained and the evaluation results are analyzed. Comparative judgement matrices and transformation of the complementary matrix into fuzzy consistent matrix are conducted. Then, complementary judgment matrix is transformed into the reciprocal matrix. Weight vector matrices are obtained. Then relative importance values are found.

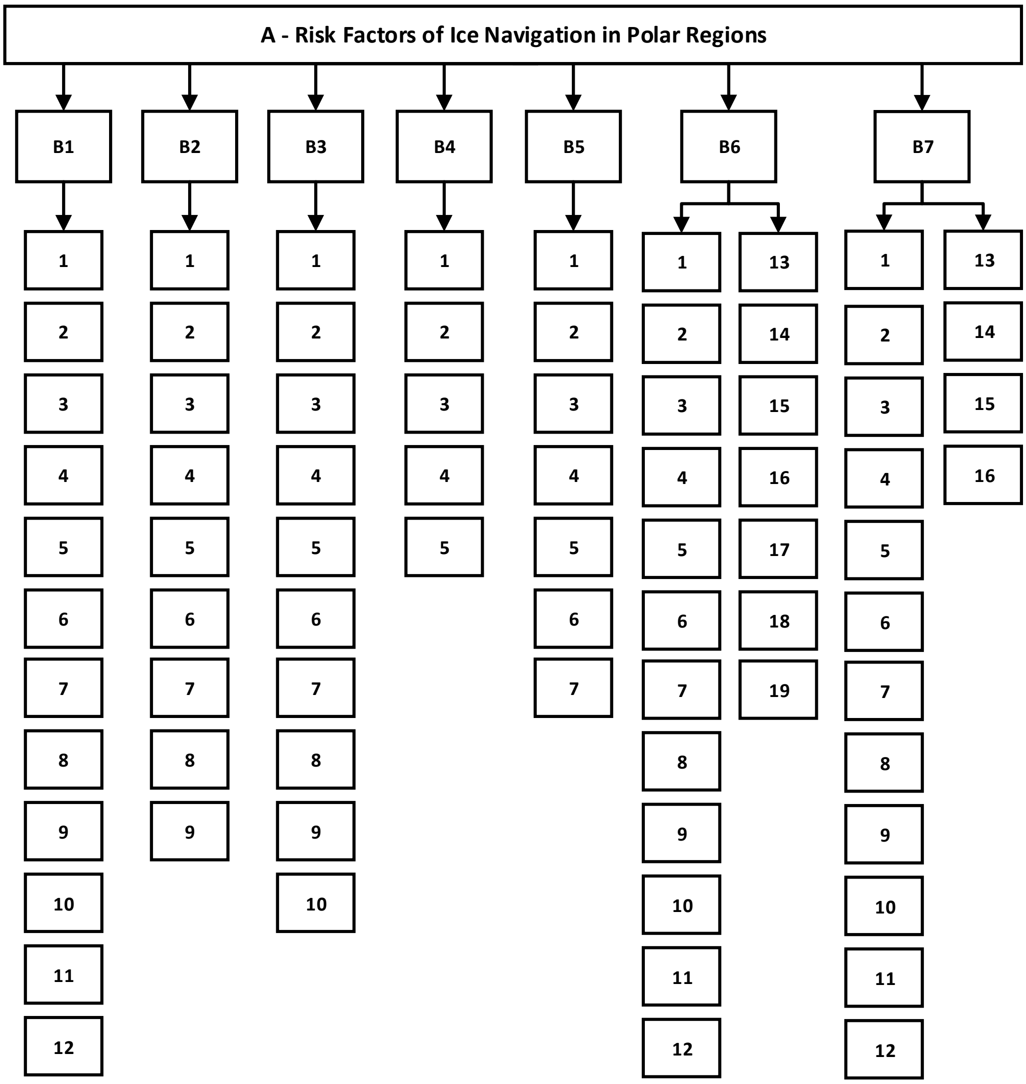


Figure 3.1: The hierarchical structure of risks factors for the ice navigation in the ice-covered waters

The above mentioned steps are performed by using the MATLAB software. The sample codes are provided in the Appendix A.

3.4.1 Judgment matrix construction and obtaining ordering vector

Priority judgment matrices based on the hierarchical structure model of risk assessment of ice navigation are shown below:

A-B judgment matrix:

	B1	B2	B3	B4	B5	B6	B7
B1	0,5	0,6	0,4	0,7	0,7	0,5	0,5
B2	0,4	0,5	0,8	0,6	0,4	0,6	0,6
B3	0,6	0,2	0,5	0,7	0,3	0,5	0,6
B4	0,3	0,4	0,3	0,5	0,5	0,7	0,6
B5	0,3	0,6	0,7	0,5	0,5	0,7	0,7
B6	0,5	0,4	0,5	0,3	0,3	0,5	0,7
B7	0,5	0,4	0,4	0,4	0,3	0,3	0,5

Fuzzy consistent judgment matrix is found as follows:

$$R_{ij} = (r_{ij})_{n\times n} = \begin{bmatrix} 0.5000 & 0.5000 & 0.5357 & 0.5429 & 0.4929 & 0.5500 & 0.5786 \\ 0.5000 & 0.5000 & 0.5357 & 0.5429 & 0.4929 & 0.5500 & 0.5786 \\ 0.4643 & 0.4643 & 0.5000 & 0.5071 & 0.4571 & 0.5143 & 0.5429 \\ 0.4571 & 0.4571 & 0.4929 & 0.5000 & 0.4500 & 0.5071 & 0.5357 \\ 0.5071 & 0.5071 & 0.5429 & 0.5500 & 0.5000 & 0.5571 & 0.5857 \\ 0.4500 & 0.4500 & 0.4857 & 0.4929 & 0.4429 & 0.5000 & 0.5286 \\ 0.4214 & 0.4214 & 0.4571 & 0.4643 & 0.4143 & 0.4714 & 0.5000 \end{bmatrix} \quad \textbf{(3.5)}$$

Normalized rank aggregation method is used and ordering vector is obtained as:

$$W_B^{(0)} = \{0.1510, 0.1510, 0.1408, 0.1388, 0.1531, 0.1367, 0.1286\}^T \quad \textbf{(3.6)}$$

The reciprocal matrix is given as:

$$R_{ij} = (r_{ij})_{n\times n} = \begin{bmatrix} 1.0000 & 1.0000 & 1.1538 & 1.1875 & 0.9718 & 1.2222 & 1.3729 \\ 1.0000 & 1.0000 & 1.1538 & 1.1875 & 0.9718 & 1.2222 & 1.3729 \\ 0.8667 & 0.8667 & 1.0000 & 1.0290 & 0.8421 & 1.0588 & 1.1875 \\ 0.8421 & 0.8421 & 0.9718 & 1.0000 & 0.8182 & 1.0290 & 1.1538 \\ 1.0290 & 1.0290 & 1.1875 & 1.2222 & 1.0000 & 1.2581 & 1.4138 \\ 0.8182 & 0.8182 & 0.9444 & 0.9718 & 0.7949 & 1.0000 & 1.1212 \\ 0.7284 & 0.7284 & 0.8421 & 0.8667 & 0.7073 & 0.8919 & 1.0000 \end{bmatrix} \quad \textbf{(3.7)}$$

Using the formulas in the second step to calculate the weight of the combination.

$$w_B^{(2)} = (0.1591, 0.1591, 0.1379, 0.1340, 0.1638, 0.1302, 0.1160) \quad \textbf{(3.8)}$$

Similar steps are carried out for other risk criteria as follows.

B1 judgment matrix:

	B1-1	B1-2	B1-3	B1-4	B1-5	B1-6	B1-7	B1-8	B1-9	B1-10	B1-11	B1-12
B1-1	0,5	0,6	0,5	0,4	0,5	0,3	0,5	0,6	0,6	0,4	0,4	0,5
B1-2	0,4	0,5	0,4	0,4	0,5	0,5	0,5	0,6	0,6	0,3	0,6	0,3
B1-3	0,5	0,4	0,5	0,5	0,5	0,5	0,4	0,5	0,5	0,5	0,5	0,6
B1-4	0,6	0,6	0,5	0,5	0,6	0,6	0,7	0,3	0,6	0,5	0,5	0,6
B1-5	0,5	0,5	0,5	0,4	0,5	0,5	0,4	0,5	0,6	0,3	0,5	0,4
B1-6	0,7	0,5	0,5	0,4	0,5	0,5	0,6	0,4	0,6	0,3	0,6	0,5
B1-7	0,5	0,5	0,6	0,3	0,6	0,4	0,5	0,5	0,7	0,2	0,5	0,4
B1-8	0,4	0,4	0,5	0,7	0,5	0,6	0,5	0,5	0,4	0,3	0,4	0,4
B1-9	0,4	0,4	0,5	0,4	0,4	0,4	0,3	0,6	0,5	0,3	0,4	0,3
B1-10	0,6	0,7	0,5	0,5	0,7	0,7	0,8	0,7	0,7	0,5	0,6	0,5
B1-11	0,6	0,4	0,5	0,5	0,5	0,4	0,5	0,6	0,6	0,4	0,5	0,3
B1-12	0,5	0,7	0,4	0,4	0,6	0,5	0,6	0,6	0,7	0,5	0,7	0,5

B2 judgment matrix:

	B2-1	B2-2	B2-3	B2-4	B2-5	B2-6	B2-7	B2-8	B2-9
B2-1	0,5	0,4	0,4	0,6	0,5	0,5	0,5	0,4	0,4
B2-2	0,6	0,5	0,4	0,6	0,6	0,5	0,7	0,5	0,5
B2-3	0,6	0,6	0,5	0,4	0,5	0,5	0,6	0,5	0,4
B2-4	0,4	0,4	0,6	0,5	0,3	0,5	0,4	0,4	0,6
B2-5	0,5	0,4	0,5	0,7	0,5	0,6	0,2	0,4	0,4
B2-6	0,5	0,5	0,5	0,5	0,4	0,5	0,4	0,6	0,4
B2-7	0,5	0,3	0,4	0,6	0,8	0,6	0,5	0,5	0,4
B2-8	0,6	0,5	0,5	0,6	0,6	0,4	0,5	0,5	0,2
B2-9	0,6	0,5	0,6	0,4	0,6	0,6	0,6	0,8	0,5

B3 judgment matrix:

	B3-1	B3-2	B3-3	B3-4	B3-5	B3-6	B3-7	B3-8	B3-9	B3-10
B3-1	0,5	0,3	0,5	0,6	0,6	0,5	0,7	0,7	0,6	0,6
B3-2	0,7	0,5	0,7	0,7	0,4	0,4	0,5	0,6	0,4	0,5
B3-3	0,5	0,3	0,5	0,5	0,5	0,4	0,4	0,4	0,5	0,4
B3-4	0,4	0,3	0,5	0,5	0,4	0,4	0,4	0,6	0,5	0,5
B3-5	0,4	0,6	0,5	0,6	0,5	0,5	0,5	0,6	0,6	0,5
B3-6	0,5	0,6	0,6	0,6	0,5	0,5	0,6	0,4	0,4	0,4
B3-7	0,3	0,5	0,6	0,6	0,5	0,4	0,5	0,7	0,6	0,4
B3-8	0,3	0,4	0,6	0,4	0,4	0,6	0,3	0,5	0,4	0,5
B3-9	0,4	0,6	0,5	0,5	0,4	0,6	0,4	0,6	0,5	0,5
B3-10	0,4	0,5	0,6	0,5	0,5	0,6	0,6	0,5	0,5	0,5

B4 judgment matrix:

	B4-1	B4-2	B4-3	B4-4	B4-5	B4-6
B4-1	0,5	0,5	0,3	0,6	0,4	0,4
B4-2	0,5	0,5	0,4	0,3	0,4	0,3
B4-3	0,7	0,6	0,5	0,4	0,4	0,3
B4-4	0,4	0,7	0,6	0,5	0,5	0,5
B4-5	0,6	0,6	0,6	0,5	0,5	0,5
B4-6	0,6	0,7	0,7	0,5	0,5	0,5

B5 judgment matrix:

	B5-1	B5-2	B5-3	B5-4	B5-5	B5-6	B5-7
B5-1	0,5	0,4	0,4	0,4	0,5	0,4	0,3
B5-2	0,6	0,5	0,3	0,4	0,4	0,3	0,3
B5-3	0,6	0,7	0,5	0,4	0,4	0,3	0,4
B5-4	0,6	0,6	0,6	0,5	0,4	0,4	0,3
B5-5	0,5	0,6	0,6	0,6	0,5	0,3	0,5
B5-6	0,6	0,7	0,7	0,6	0,7	0,5	0,5
B5-7	0,7	0,7	0,6	0,7	0,5	0,5	0,5

B6 judgment matrix:

	B6-1	B6-2	B6-3	B6-4	B6-5	B6-6	B6-7	B6-8	B6-9	B6-10	B6-11	B6-12	B6-13	B6-14	B6-15	B6-16	B6-17	B6-18	B6-19
B6-1	0,5	0,6	0,4	0,4	0,4	0,5	0,4	0,5	0,6	0,6	0,6	0,4	0,7	0,7	0,4	0,6	0,5	0,6	0,7
B6-2	0,4	0,5	0,7	0,4	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,7	0,7	0,4	0,4	0,4	0,4	0,3	0,3
B6-3	0,6	0,3	0,5	0,4	0,4	0,4	0,3	0,4	0,3	0,4	0,7	0,6	0,6	0,5	0,4	0,4	0,6	0,6	0,6
B6-4	0,6	0,6	0,6	0,5	0,5	0,6	0,6	0,7	0,7	0,5	0,5	0,5	0,6	0,7	0,5	0,5	0,6	0,7	0,7
B6-5	0,6	0,4	0,6	0,5	0,5	0,7	0,6	0,6	0,6	0,5	0,5	0,6	0,6	0,6	0,6	0,5	0,6	0,7	0,6
B6-6	0,5	0,4	0,6	0,4	0,3	0,5	0,7	0,6	0,7	0,7	0,5	0,6	0,6	0,6	0,6	0,5	0,7	0,5	0,5
B6-7	0,6	0,4	0,7	0,4	0,4	0,3	0,5	0,6	0,6	0,5	0,6	0,4	0,7	0,6	0,5	0,5	0,6	0,5	0,6
B6-8	0,5	0,4	0,6	0,3	0,4	0,4	0,4	0,5	0,3	0,4	0,3	0,4	0,3	0,4	0,5	0,5	0,6	0,5	0,7
B6-9	0,4	0,4	0,7	0,3	0,4	0,3	0,4	0,7	0,5	0,5	0,6	0,5	0,7	0,7	0,7	0,6	0,4	0,5	0,4
B6-10	0,4	0,4	0,6	0,4	0,5	0,3	0,5	0,6	0,5	0,5	0,4	0,4	0,4	0,3	0,3	0,7	0,7	0,6	0,4
B6-11	0,4	0,4	0,3	0,4	0,5	0,5	0,4	0,7	0,4	0,6	0,5	0,5	0,8	0,6	0,6	0,5	0,6	0,6	0,5
B6-12	0,6	0,3	0,4	0,4	0,4	0,4	0,6	0,6	0,5	0,6	0,5	0,5	0,6	0,6	0,5	0,7	0,6	0,7	0,6
B6-13	0,3	0,3	0,4	0,4	0,4	0,4	0,3	0,7	0,3	0,6	0,2	0,4	0,5	0,7	0,7	0,4	0,7	0,4	0,5
B6-14	0,3	0,6	0,5	0,3	0,4	0,4	0,4	0,6	0,3	0,7	0,4	0,4	0,3	0,5	0,6	0,6	0,4	0,5	0,7
B6-15	0,6	0,6	0,6	0,5	0,4	0,4	0,5	0,5	0,3	0,7	0,4	0,5	0,3	0,4	0,5	0,6	0,6	0,7	0,7
B6-16	0,4	0,6	0,6	0,5	0,5	0,5	0,5	0,5	0,4	0,3	0,5	0,3	0,6	0,4	0,4	0,5	0,7	0,7	0,7
B6-17	0,5	0,6	0,4	0,4	0,4	0,3	0,4	0,4	0,6	0,3	0,4	0,4	0,3	0,6	0,4	0,3	0,5	0,6	0,5
B6-18	0,4	0,7	0,4	0,3	0,3	0,5	0,5	0,5	0,5	0,4	0,4	0,3	0,6	0,5	0,3	0,3	0,4	0,5	0,6
B6-19	0,3	0,7	0,4	0,3	0,4	0,5	0,4	0,3	0,6	0,6	0,5	0,4	0,5	0,3	0,3	0,3	0,5	0,4	0,5

B7 judgment matrix:

	B7-1	B7-2	B7-3	B7-4	B7-5	B7-6	B7-7	B7-8	B7-9	B7-10	B7-11	B7-12	B7-13	B7-14	B7-15	B7-16
B7-1	0,5	0,6	0,7	0,7	0,4	0,6	0,6	0,4	0,5	0,5	0,4	0,6	0,7	0,6	0,6	0,6
B7-2	0,4	0,5	0,6	0,7	0,7	0,6	0,6	0,7	0,6	0,6	0,6	0,5	0,6	0,6	0,6	0,5
B7-3	0,3	0,4	0,5	0,7	0,6	0,6	0,6	0,7	0,7	0,6	0,7	0,7	0,7	0,7	0,7	0,7
B7-4	0,3	0,3	0,3	0,5	0,6	0,7	0,6	0,7	0,6	0,6	0,7	0,6	0,7	0,7	0,7	0,6
B7-5	0,6	0,3	0,4	0,4	0,5	0,4	0,5	0,4	0,6	0,5	0,6	0,4	0,4	0,4	0,4	0,4
B7-6	0,4	0,4	0,4	0,3	0,6	0,5	0,4	0,4	0,4	0,3	0,4	0,4	0,3	0,3	0,3	0,4
B7-7	0,4	0,4	0,4	0,4	0,5	0,6	0,5	0,4	0,4	0,4	0,3	0,5	0,5	0,4	0,4	0,4
B7-8	0,6	0,3	0,3	0,3	0,6	0,6	0,6	0,5	0,6	0,6	0,5	0,7	0,5	0,5	0,4	0,5
B7-9	0,5	0,4	0,3	0,4	0,4	0,6	0,6	0,4	0,5	0,3	0,5	0,4	0,4	0,6	0,6	0,3
B7-10	0,5	0,4	0,4	0,4	0,5	0,7	0,6	0,4	0,7	0,5	0,4	0,6	0,4	0,4	0,4	0,6
B7-11	0,6	0,4	0,3	0,3	0,4	0,6	0,7	0,5	0,5	0,6	0,5	0,5	0,5	0,4	0,5	0,4
B7-12	0,4	0,5	0,3	0,4	0,6	0,6	0,5	0,3	0,6	0,4	0,5	0,5	0,4	0,5	0,6	0,5
B7-13	0,3	0,4	0,3	0,3	0,6	0,7	0,5	0,5	0,6	0,6	0,5	0,6	0,5	0,5	0,5	0,5
B7-14	0,4	0,4	0,3	0,3	0,6	0,7	0,6	0,6	0,4	0,6	0,6	0,5	0,5	0,5	0,5	0,5
B7-15	0,4	0,4	0,3	0,3	0,6	0,7	0,6	0,6	0,4	0,6	0,5	0,4	0,5	0,5	0,5	0,4
B7-16	0,4	0,5	0,3	0,4	0,6	0,6	0,6	0,5	0,7	0,4	0,6	0,5	0,5	0,5	0,6	0,5

After gathering the judgment matrices the similar steps of IF-AHP method are employed. Each steps are given above as an example of risk factors (B).

The values for the risk criteria of risk factors B1, B2, B3, B4, B5, B6, B7 are found as respectively:

$$\begin{aligned} W_{B1}^{(2)} &= \{B1-1, B1-2, B1-3, B1-4, B1-5, B1-6, B1-7, B1-8, \\ &\qquad B1-9, B1-10, B1-11, B1-12\} \\ W_{B1}^{(2)} &= \{0.0803, 0.0777, 0.0817, 0.0918, 0.0777, 0.0845, 0.0790, 0.0777, \\ &\qquad 0.0691, 0.1069, 0.0803, 0.0934\} \end{aligned} \quad \textbf{(3.9)}$$

$$\begin{aligned} W_{B2}^{(2)} &= \{B2-1, B2-2, B2-3, B2-4, B2-5, B2-6, B2-7, B2-8, \\ &\qquad B2-9\} \\ W_{B2}^{(2)} &= \{0.1036, 0.1211, 0.1133, 0.1013, 0.1036, 0.1060, 0.1133, 0.1083 \\ &\qquad , 0.1295\} \end{aligned} \quad \textbf{(3.10)}$$

$$\begin{aligned} W_{B3}^{(2)} &= \{B3-1, B3-2, B3-3, B3-4, B3-5, B3-6, B3-7, B3-8, \\ &\qquad B3-9, B3-10\} \\ W_{B3}^{(2)} &= \{0.1124, 0.1080, 0.0884, 0.0902, 0.1059, 0.1017, 0.1017, 0.0884 \\ &\qquad , 0.0997, 0.1038\} \end{aligned} \quad \textbf{(3.11)}$$

$$\begin{aligned} W_{B4}^{(2)} &= \{B4-1, B4-2, B4-3, B4-4, B4-5, B4-6\} \\ W_{B4}^{(2)} &= \{0.1496, 0.1352, 0.1599, 0.1768, 0.1829, 0.1956\} \end{aligned} \quad \textbf{(3.12)}$$

$$\begin{aligned} W_{B5}^{(2)} &= \{B5-1, B5-2, B5-3, B5-4, B5-5, B5-6, B5-7\} \\ W_{B5}^{(3)} &= \{0.1187, 0.1153, 0.1332, 0.1371, 0.1452, 0.1778, 0.1727\} \end{aligned} \tag{3.13}$$

$$\begin{aligned} W_{B6}^{(2)} = \{&B6-1, B6-2, B6-3, B6-4, B6-5, B6-6, B6-7, B6-8, \\ &B6-9, B6-10, B6-11, B6-12, B6-13, B6-14, B6-15, B6-16, \\ &B6-17, B6-18, B6-19\} \\ W_{B6}^{(2)} = \{&0.0559, 0.0542, 0.0498, 0.0628, 0.0609, 0.0583, 0.0553, 0.0467, \\ &0.0536, 0.0493, 0.0542, 0.0559, 0.0477, 0.0493, 0.0542, 0.0531, 0.0462, \\ &0.0467, 0.0458\} \end{aligned} \tag{3.14}$$

$$\begin{aligned} W_{B7}^{(2)} = \{&B7-1, B7-2, B7-3, B7-4, B7-5, B7-6, B7-7, B7-8, \\ &B7-9, B7-10, B7-11, B7-12, B7-13, B7-14, B7-15, B7-16\} \\ W_{B7}^{(2)} = \{&0.0703, 0.0739, 0.0788, 0.0721, 0.0561, 0.0494, 0.0540, 0.0628, \\ &0.0561, 0.0612, 0.0597, 0.0590, 0.0612, 0.0620, 0.0597, 0.0636\} \end{aligned} \tag{3.15}$$

3.4.2 The results of application for risk assessment

The results of the calculations in section 3.4.1 indicate that fuzzy consistency judgment matrix is modified from the priority judgment matrix. Consistency condition is satisfied and iteration times is reduced. Convergence speed is improved under the accuracy condition of 0.0001. In the B layer, the value of external risk factors is 0.1591, risk factors related to structural design and arrangement of equipment locations is 0.1591, risk factors related to technical faults in vessel equipment is 0.1379, risks based on the usage and arrangements of the equipment on-board for operation process is 0.1340, risks on cargo, fuel and related handling equipment is 0.1638, communication, organizational, operational instruction faults and routine failures is 0.1302 and human factors, interpretation, awareness assessment of situation, etc is 0.1160. Thus they are in such sequence as risks on cargo, fuel and related handling equipment, external risk factors and risk factors related to structural design and arrangement of equipment locations with the same risk level, risk factors related to technical faults in vessel equipment, risks based on the usage and arrangements of the equipment on-board for operation process, communication, organizational, operational instruction faults and routine failures, human factors, interpretation, awareness assessment of situation, etc.

Three standard degree method is used to establish the priority judgment matrix. Marine accident statistical data agree well with this study. For third layer, Explosion or external conditions related to the oil drill (B1-10 = 0.1069), Other conditions (i.e. shell plating, frames, ice stringers, web frames, bow, stern, bilge keels) related to vessel construction or maintenance (i.e. rudder and steering arrangements, propeller, shafts and gears, miscellaneous machinery requirements) (B2-9 = 0.1295), Technical fault in sophisticated electronic navigation equipment (such as radar, sonar, and the visible, infrared, and microwave radiation sensors onboard satellites) (B3-1 = 0.1124), Faults in Ergonomics, design and operation of the device. Human-machine interface problems (B4-5 = 0.1956), Leakages in cargo or fuel pipes/hoses (B5-7 = 0.1778), Familiarity with safety instructions, but no implementation (B6-4 = 0.0628), Inappropriate design of task or operation such as cargo, night navigation, route planning, anchoring etc.(B7-3 = 0.0788) have more heavily weight. These results indicate that more regulations or enforcement for the existing polar code and related codes are required to eliminate the risks. For instance, the result of B3-1 proves the significance of polar class, The International Association of Classification Societies (IACS) published a set of Unified Requirements for Polar Class Ships which is not mandatory. Arctic Maritime Shipping Assessment (AMSA) has suggested qualifications and training for crew and ice navigators as need for the example of B7-3. In a conclusion, the results can accurately present the levels of the risks under their domain. This provides the theoretic basis for representatives, ship-owners and navigators on the focus on managing the ice navigation operations safely in ice-covered waters.

In this chapter, 79 risk criteria are studied in a comprehensive perspective. These risks are significant for analyzing the marine accidents. In the following chapter, root causes of collision and grounding are determined by considering the risk criteria mentioned in this chapter. Moreover, these risk criteria should be considered during the route selection process. Then, a route selection problem for ice-covered waters is introduced. The Figure 3.2 shows the relationships of each chapters based on the risks considered.

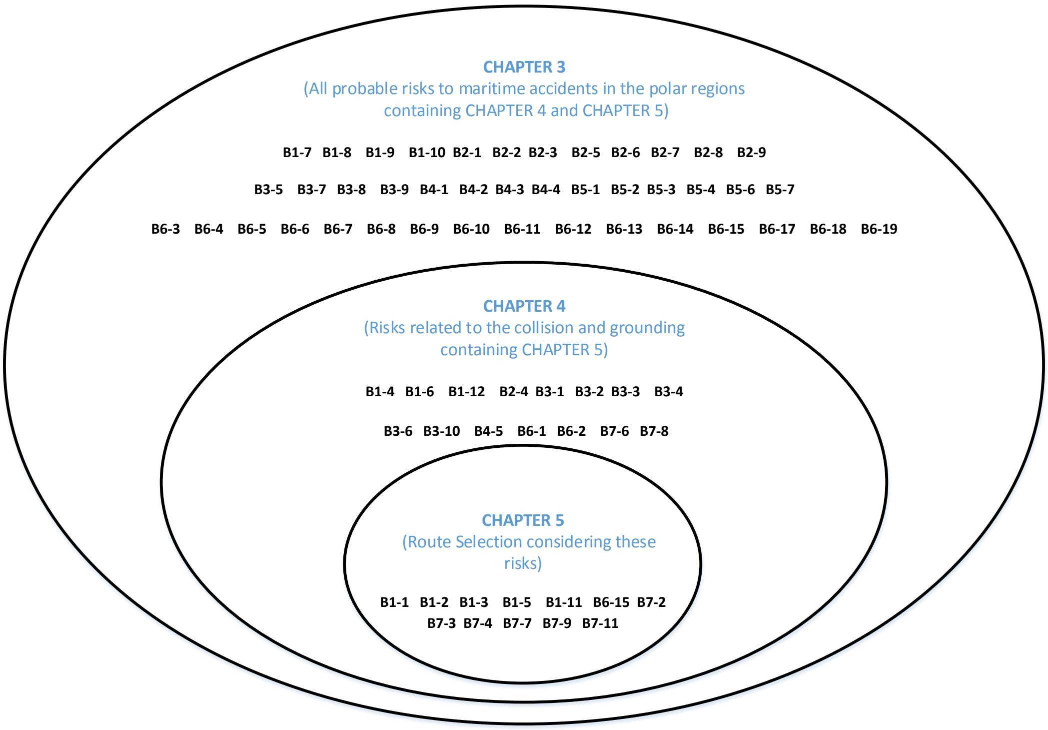


Figure 3.2: Contributing risk criteria to chapters

Risk identification, determination of risk levels and priorities are some prerequisites for prevention of marine accidents in the polar regions. Therefore, during the identification of basic events for marine accidents, alongside the marine accident reports and expert thoughts, all existing and probable risk criteria are required to be considered. Based on the key concept which declares that the index of risk criteria should include all basic events, the basic events of collision and grounding are matched with the related risks in the fourth chapter.

For the route selection problem, eight criteria are determined considering the ice-state factors. These are average route width alongside the route, route length, maximum width of the route, minimum width of the route, ice concentration, sharp bend, slot availability and sea depth. In order to make any comment on these criteria, related risks should be take into account. Therefore, related risk criteria are considered for intended route selection problem.

4. A FUZZY FAULT TREE ANALYSIS (FFTA) OF MARINE ACCIDENTS OCCURRING IN ICE-COVERED WATERS

In this chapter, marine accidents occurring in ice-covered waters is considered and the generic hazards that the vessels encounter in this region are defined. Chapter 3 deals with all probable risks in ice-covered waters in a comprehensive perspective. After specifically analysis of both criteria of risks and previous marine accidents, fault trees for grounding and collision are structured. Tables 4.1 and 4.2 show the relationship between the risk criteria and the related root causes. The tables clarify the type of marine accidents whether it is a collision (C) or grounding (G). In other words, all basic events (BEs) of the fault trees are determined after considering all probable risk criteria. Furthermore, the risk criteria are investigated for grounding and collision accidents based on the MAIB report. The relationship between the root causes of the real cases and risks is established as time occurrence.

Table 4.1: Relationship between risk criteria and related basic events.

Risk Criteria	Related Basic Events	Type	Occurrence
B1-1 Environmental conditions encountered such as fog, storms, compass anomalies, atmospheric effects and ice	X23 Bad weather Conditions	G	3
	X24 Environmental Restrictions	G	
B1-2 Drift of pack ice due to wind and surface currents and other ship-handling difficulties	X4 Ice drifting	G	
B1-3 Colliding with floating obstacles (sharp corners of ice floes) or pressure to the vessel's hull, propellers, rudder	X11 Stuck by ice floe	G	
	X1 Stuck in ice	G	
B1-4 Failure in establishment and maintenance of external aids to navigation	X45 Failures during other assistance work	C	
	X46 Improper salvage operation of IB during ice breaking/cutting	C	
B1-5 Deficiencies in the reliability and detail of hydrographic and geographical information presented on polar navigation charts, coupled with a distinct lack of reliable bathymetry, current, and tidal data	X12 Grounding as ice floes stuck between the bottoms	G	
	X14 Inadequate depth	G	
B1-6 Technical incapacitation of other vessels, ice-breakers, tugs leads to some, catastrophic outcomes	X2 Insufficient power of IB, tugboat	G	
	X3 Insufficient number of IB, tugboat	G	
	X41 Maneuver failures of IB	C	
	X42 Wrong directions of IB	C	
B1-11 Ice restrictions which affect the vessel's movement and force to change of course and speed.	X11 Stuck by ice floe	G	
	X37 Crossing ship cannot get out of the channel	C	
B1-12 Hazards of ice and snow accumulation on the superstructures.	X36 Direct impact of other ships	C	
B2-4 Insufficient maneuvering characteristics of vessel not specifically built for ice breaking or quick maneuvering for rapid change of ice conditions.	X5 Trend of the ship is towards the shallowness	G	
	X6 The ship is close to the shallowness	G	
B3-1 Technical fault in sophisticated electronic navigation equipment (such as radar, sonar, and the visible, infrared, and microwave radiation sensors onboard satellites)	X25 GPS Failure	G	
	X26 Echo Sounder failure	G	
	X27 Inactivated ECDIS shallowness alert	G	
	X34 Anti-collision system failure	C	
	X35 Communication equipment failure	C	
B3-2 Technical fault in maneuvering equipment (i.e. rudder and steering arrangements)	X18 Bow thruster Failure	G	
	X20 Machinery Failure	G	
	X28 Steering gear Failure	C	
	X7 Interpretation Failures of officers	G	
B3-3 Technical fault in propulsion machinery (i.e. propeller, shafts and gears)	X19 Machinery Failure	G	
	X29 Engine Failure	C	
B3-4 Technical fault in auxiliary machinery (i.e. air compressors, cooling water system)	X19 Machinery Failure	G	
B3-6 Technical failures in remote and automatic control devices and emergency systems	X5 Trend of the ship is towards the shallowness	G	
	X6 The ship is close to the shallowness	G	
B3-10 Other technical failures	X7 Interpretation failures of equipment	G	
B4-5 Faults in ergonomics, design and operation of the device. Human-machine interface problems	X8 Interpretation failures of officers	G	

Table 4.2: (Continued):Relationship between risk criteria and related basic events.

Risk Criteria	Related Basic Events	Type	Occurence
B6-1 Inadequate or deficiencies for following the general instructions	X9 Lack of internal communication	G	1
	X10 Lack of external Communication	G	
	X16 Lack of communication	C	
	X33 Communication failure (Bridge Team)	C	
	X38 Communication Failure (Vessel to IB or tugboat)	C	
	X39 External Communication (Vessel to IB)	C	
	X40 Internal Communication (Bridge Team)	C	
B6-2 Unfamiliarity of general methods of operation or insufficient practice	X35 Communication equipment Failure	C	2
B6-15 No or faulty bridge routines	X12 Grounding as ice floes stuck between the bottoms	G	3
	X13 Inadequate preventive action	G	
	X14 Inadequate depth	G	
	X15 Devaiton from suggested course	G	
B7-2 Practical incompetency for duty such as experience, local knowledge of waters, usage of devices.	X13 Inadequate preventive action	G	6
	X14 Inadequate depth	G	
	X17 Improper evasive maneuver	G	
	X30 Lack of situational awareness	C	
	X44 Incorrect towage operation	C	
B7-3 Inappropriate design of task or operation such as cargo,night navigation, route planning, anchoring etc.	X21 Improper voyage plan	G	1
	X22 UKC & Squat Calculation Fault	G	
	X32 Improper route selection	C	
	X43 Improper preparedness for the towage	C	
B7-4 Available warning mechanism is insufficiently developed and used.	X12 Grounding as ice floes stuck between the bottoms	G	
B7-6 The usage of available aids for navigation or publications is not sufficient.	X16 Lack of communication	G	1
B7-7 Failures of using the sea chart, Deficiencies regarding to positioning the own vessel	X5 Trend of the ship is towards the shallowness	G	3
	X6 The ship is close to the shallowness	G	
	X14 Inadequate depth	G	
	X31 Deviation from suggested route	C	
	X15 Deviation from suggested course	G	
B7-8 Wrong of inadequate interpretation of other vessel's motions / intentions	X8 Interpretation failures of officers	G	1
B7-9 Wrong or inadequate interpretation of own vessel's motions (icebergs, current, wind etc.)	X8 Interpretation failures of officers	G	1
	X15 Deviation from suggested course	G	
	X31 Deviation from suggested route	C	
	X5 Trend of the ship is towards the shallowness	G	
	X6 The ship is close to the shallowness	G	
B7-11 Right side of the separation line is not used on the waterway, channel, track, crack, etc.	X5 Trend of the ship is towards the shallowness	G	
	X6 The ship is close to the shallowness	G	
	X14 Inadequate depth	G	

The causes of each accidents are identified and occurrence probability is determined. It is aimed that the results will help to understand mitigating the risks of ice navigation in the polar regions. Our methodology involves the fault tree analysis (FTA) of the marine accidents occurring in the ice covered waters. Due to there exist limited data on this specific subject, fuzzy approach is utilized.

A novel aspect of our approach is that the causes of each accidents occur in the polar regions are classified and logical relation is established. Stepwise risk identification for the vessels navigating in ice-covered waters is conducted in this chapter. OpenFTA software is used which is an open source FTA program developed by Auvation (http://www.openfta.com). FTA is a systematic approach to estimate the frequency of the failure rates for dangerous events. In this research, numerical risk levels of each causes for grounding (27) and collision (19) are determined by face to face and online expert consultations. Significance of primary events and minimal cut sets are calculated. In addition, occurrence probabilities of collision and grounding are obtained. The fuzzy extended methodology (Fuzzy FTA) illustrates collision and grounding cases to identify an appropriate management tool to minimize the risk of the marine accidents. FFTA method accurately reduces the uncertainty where the data of occurrence probability are limited or insufficient.

4.1 Marine Accidents Occurring In Ice-Covered Waters

Failure determination is the primary step for the risk assessments, if the aim and method of the analysis are predefined. Risk identification is therefore, conducted for the applicability of assessment on similar failures for several marine accidents. The data and statistics from the previous years should be used for the fault detection (Appendices A.3 and A.4). However, due to the cumulative characteristics of this process, it should allow for the users to generate the creative features. In this chapter, marine accident data and statistics are gathered from the several databases and history of the accidents are considered by the help of expert consultations.

As it is known, navigation has been experienced for a long time. Therefore, risks related to the navigation is very well known and there exists the categories related to each type of accident. Types of marine casualties and incidents are listed by IMO code [49] as follows:

1. Collision: To strike or one vessel is struck by another ship in the cases of whether under way, anchored or moored.
2. Stranding or grounding: Hitting or touching shore, sea bottom or underwater objects such as wrecks etc.
3. Contact: Striking any fixed or floating object other than those included in collision and stranding.
4. Fire or explosion
5. Hull failure or failure of doors or ports, etc.: Failures which are not caused by collision and fire or explosion.
6. Machinery damage: The damages which requires towage or shore assistance not caused by collision and hull failure.
7. Damages to ship or equipment: Not caused or covered by collision and machinery damage.
8. Capsizing or listing: Others than mentioned in collision and damages to ship or equipment.
9. Missing: Lost vessels.
10. Other: All other types of casualties, which are not covered by collision and missing.

Causes of accidents in polar regions might differentiate both nature and consequences of the casualties in various forms because of the severe winter conditions and ice existence in the environment. These are exclusive type of casualties which occur in icy waters. General observed accidents and incidents in the ice covered waters are shown in the Table 4.3.

Risk of any marine accidents has a potential to threaten the human lives, cargo and as well as the environment. There are many contributory factors (Figure 4.1) of the incidents regarding to the ice navigation which is defined in this chapter.

For each type of marine accidents occurring in the polar regions based on the available data are requested and derived from the databases given in the Appendix B section. Although there exists some recent changes on technical and technological developments over vessels and navigation, at the same time however, variations of

Table 4.3: General accidents in the polar regions.

Direct Damage of Ice to the Vessel
Inner and outer hull plates, stiffeners, other parts of hull, appendages, rudder, propeller, machinery damage, damage to ship systems and equipment
Hazards of Icing
Loss of stability, freeboard or visibility
Grounding
Drifting with ice or power driven
Collision
Assistance: Icebreaker or other vessels
Independent: Head to head, head to tail, side to side, head to side
Fire or Explosion

environmental conditions, nature of human and organizational errors are constant for involving in all types of marine accidents. In fact, occurrence time of an accident is not so significant for a fault tree analysis; differently, the root causes of a casualty are considered universally. Countermeasures to the earlier failures might be referred to overcome the similar accidents will occur in the future. The fault trees are not designed and established upon the previous accidents in contrast, risk identification is determined based on the possibility of each causes. The fault tree is a branched form of the hazards occurring/might occur during the whole process of ice navigation. In the following sections, typical marine accidents are discussed.

4.1.1 The physical ice damage to outer plates of vessel

Diverse ice formations might contort the hull of a vessel as a result of a permanent change. Any type or size of physical ice damages (i.e. fractures, ruptures, cracks, etc.) are placed under this category. Interaction with ice might cause dents after a pressure of an ice block, destruction on welded connections and deformation of the plates with a physical change of the structure. Ice also have a characteristics to stick the hull surface which increases the corrosion after it removes the paint as a protection. If the vessel's resistance to the ice pressure does not compensate the friction caused from the removal of coatings, the vessel becomes fatigue and it stops [50]. Thus, for the vessels stuck in ice, the risk increases by time because of the environmental unfavorable effects. Non pre-definable nature of ice loads and vagueness of the ice trajectories are the major risk factors for the ice navigation. Ice-class and ice-strengthened vessels might

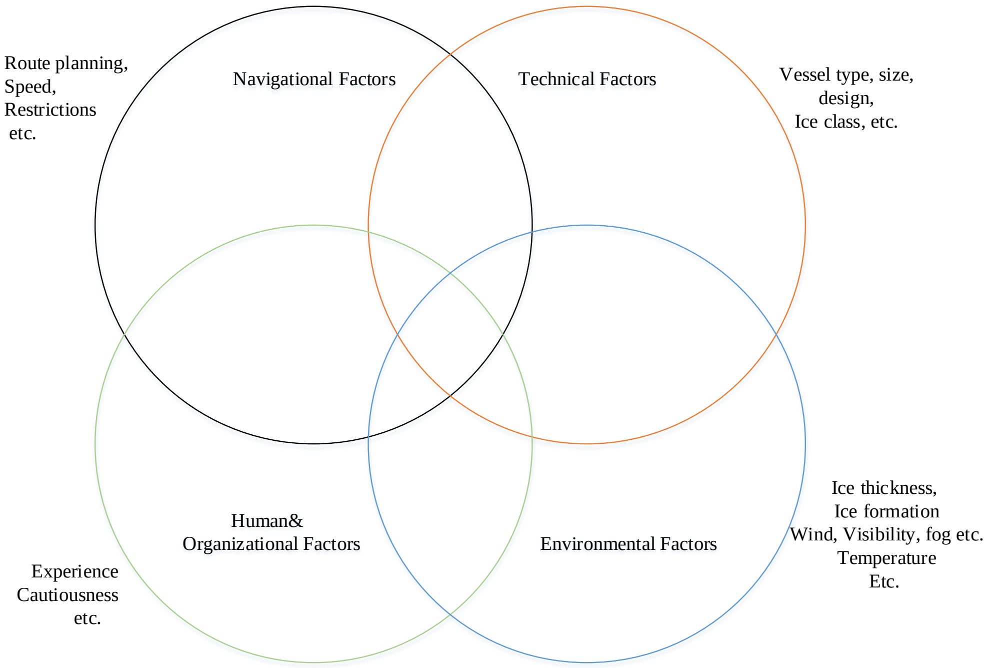


Figure 4.1: General factors for marine casualties.

operate smoothly, and withstand against the harsh ice conditions. Ice damage is such a serious risk which might cause the loss of whole vessel. Normally, there is always a trade-off between finance of both strengthening the outer plates of the vessel and safety concerns. As a result of icing, extra weight decreases the cargo capacity because of draught limit of the vessel.

4.1.2 Ice impact

As it is seen on the Figure 4.2, multiyear ice has 30% of Arctic sea ice (Courtesy of NSIDC). Besides, even one-year ice might damage the vessels in a large scale. Especially, when approaching the ice edge, if speed of the vessel is high, ice impact might exceed the force of the strength of the vessel.

4.1.3 Ice compression

Ice compression mostly damages the midships of the vessel. If a drifting ice block encounters a vessel and touches the hull, motion and course of the vessel alter under the effect of that obstacle. Wind, current and waves are the main environmental factors to direct and accelerate the ice field as well as a broken ice pack. Bounds for the acceleration of ice might be approximately between the % 2-3 of the wind speed. If

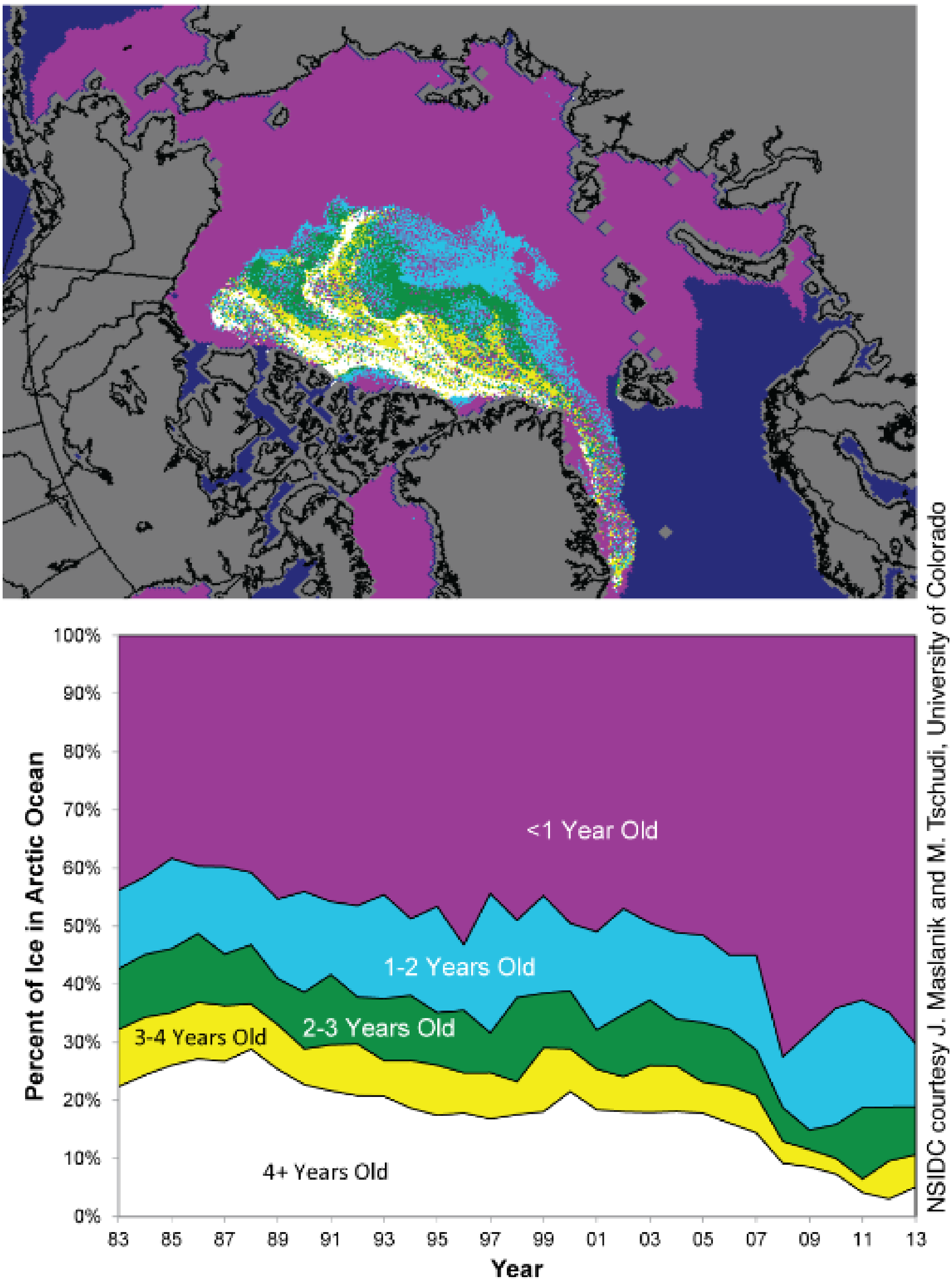


Figure 4.2: Ice conditions in the arctic region.

the wind speed is 11-12 m/s, the ice acceleration is observed as 0.35 m/s. [51]. If free-board of the vessel is low and the machinery power is limited, ice blocks can easily move and collapse to deck which might cause the vessel being beset.

4.1.4 Rudder damage

A failure of a rudder is either the failure of machinery of the rudder or any part of itself. Directed ice loads might result as rudder error, as well as it forces to damage the rudder. The worst scenario of rudder damage is the bend of the rudder stoke [52]. Therefore, requirements for the ice-class vessels mainly focus on strengthening the navigational equipment of the vessel such as rudder, propeller etc.

To keep the operability of the vessels in ice-infested areas, rudder stoppers are recommended for ice navigation which might limit the turn angles of the vessel or stop it. The first countermeasure for the rudder damage, operational risk control is implemented for vessels of deep trim by the astern. Rudder generally gets damaged by the cause of operational errors. If a vessel in ice field cannot increase its speed or navigates in a constant acceleration, it stops soon. Vessels have to turn astern and move in a straight direction to avoid being stuck. Otherwise, rudder might be damaged by the effect of suction as well as the floating ice blocks.

4.1.5 Propeller damage

Propellers are the critical mechanisms of the vessels in terms of interaction with the ice loads. Damages to the propeller blades are caused by the condense ice loads during the icebreaker towage, maneuvering, fixing the regime of the controllable pitch propeller or even stopping. During the maneuvering process or for the fixed pitch propellers. Blades may be damaged however, if the fractures are small or some parts are missed, it might be repaired without removing whole propeller system. The worst scenario is the loss of the propeller. If the propulsion system is inappropriately designed, ice loads and heavy vibrations might damage the main machinery. Similarly, it is not a desirable case for the propulsion, if components of the propeller are metal fatigue as well as the vibration of the ill-designed main machinery. The propeller of the single propeller vessel is placed centerline of the vessel. Each propellers of two-propeller vessels are not as safe as the propeller of single propeller vessels [53]. In order to prevent the suction of the ice blocks to the propeller during the maneuvers, the distance between the sea surface and propeller should be minimized. Deep aft trim should be used to avoid the ambiguity directions of pieces of ice loads broken by the hull. If the vessel is in ballast condition, propeller blades might hit the ice floes thus, risk of propeller damage increases. If the propeller does not function properly or lost, the vessel might expose to uncontrollable grounding or icing which might damage human lives, cargo and as well as environment.

4.1.6 Machinery damage

Machinery damage is not a usual hazard. If there exists a hazard caused from ice or icing, this is because of wrong design principles of the propeller structure. Large amount of cargo, high vibration, the usage of design which does not to serve to its design purpose. Laakso (1984) describes the checklist regarding to the propulsion machinery as given below [54]:

1. A propulsion machinery should be able to have full propulsion power in a particular time for the vessel which navigates at the different speeds.
2. A propulsion machinery should be able to control the continuous power in the cases of astern and ahead.
3. A propulsion machinery should have the possibility to reverse the power of propeller thrust.
4. Even under the heavy loads, the stability of the propeller should be able to be controlled.
5. The main machinery should be kept from the extra cargoes.
6. Dimensions of the shaft elements should be able to burden the ice loads.
7. The propulsion system should be able to allow the process of ice-propeller interaction.
8. The machinery should be able to process the cold air and sea water.
9. For the cooling of machinery, sea water should be able to be utilized in a careful manner.
10. It should be able to operate with little water under the vessel.

The above items regard to the machinery of a vessel which navigates in ice covered waters are expected for the reliability of the operations. The machinery failures might not be directly related to the damages however, in the critical situations, the vessel should be ready with a full-functional machinery mechanism for self-operation. Otherwise, same consequences are determined as propeller failures. Even tugboats and icebreakers might also suffer from the machinery damage. The number of icebreakers in a particular field is another concern in terms of assistance for the safe and secure navigation.

4.1.7 Damage to hull appendages

Besides hull, ruder or propeller of a vessel might suffer from ice damage, other appendages might be damaged such as bilge keels and stabilizer fins etc. Those structures should be bent or removed before navigating in ice due to those subsequent parts might get damaged. Ice class regulations dictate designing the hull appendages as well as the hull. The same principles as such in design of a propeller structure and strengthen of the hull should be applied to the hull appendages.

4.1.8 Hazards of icing

The amount of ice on the superstructures and deck equipment might increase because of the low temperature and the spray ice. The cumulative accumulation of instant frozen sea water might affect the course of the vessel in terms of stability. This might cause for human errors and prevent operational routines. Because of the listing, cargoes might shift. Moreover, icing might prevent the usage of radars, communication devices, emergency equipment, lifeboats and even pilot ladder.

Several parameters effect the rate of icing such as temperature(both air and sea water), salinity, wind, sea state, course and speed of the vessel as well as the design of the vessel (Figure 4.3,reproduced from Lundqvist & Udin). Avoidance of icing is possible by sheltering on a lee of land for a predefined time. Furthermore, an effective and operational alter of the course and speed might prevent icing of the vessel. Sometimes longer routes might be more convenient rather than getting rid of the negative effects of icing in a shorter route in terms of financial cost.

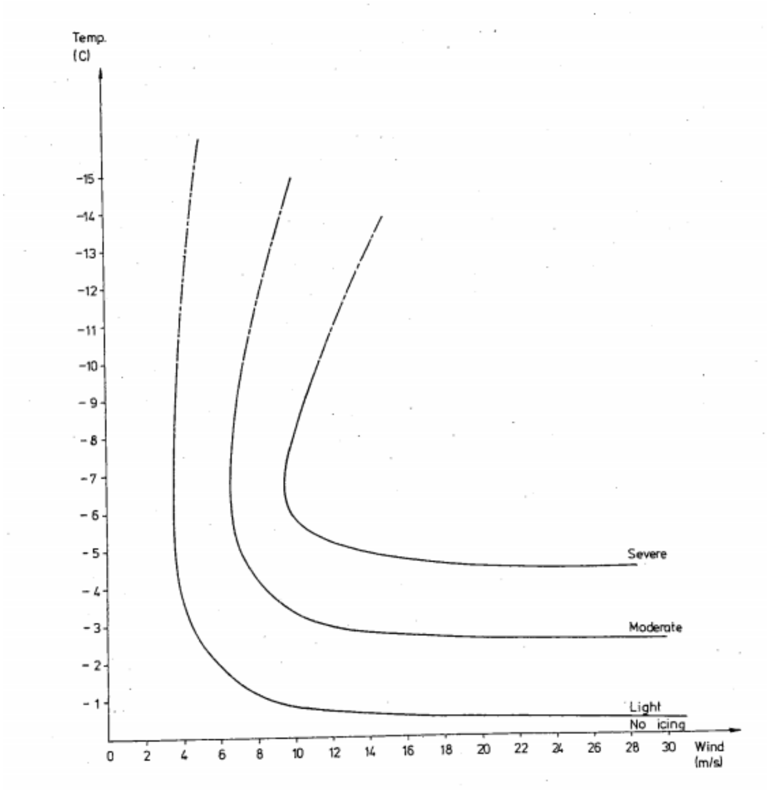


Figure 4.3: Relation of wind and temperature.

4.1.9 Grounding

Ship grounding is a type of marine accident that involves the impact of a ship on seabed, waterway side or an ice block [55]. Grounding during the ice navigation can be separated into two types: uncontrollable grounding which environmental effects such as wind, ice pressure, current and waves cause the vessel to get grounded, and other is controllable or mechanized grounding since the vessel's machinery and propeller works, another factors cause the vessel to get grounded.

Avoidance of the grounding is almost impossible for a vessel stuck inside an ice field which drifts through submerged rocks or a land. There are several such cases that icebreakers assist. In these cases, vessels might avoid grounding and might be unstuck by the appropriate maneuvers on time to keep the intended course. Ice blocks might affect the vessel with unexpected and sudden changes on the course. If an ice behaves like a fender and to avoid it prevents the safe navigation thus, grounding becomes inevitable.

Grounding might occur when approaching such ice ridges which have a deep ice and shallow water. Snowfall as well as fog and icing not only effect the visibility but also electronic devices such as radars, antennas and etc. Low temperature limits the usage of navigation aids. Ice blocks might obstruct the radar signals. Some previous channels might direct the vessel to the undesired locations. Especially in the environment which has a low visibility, vessels might easily get beset in the fracture.

4.1.10 Collision

Collision in ice differs from the open sea collision by following cases.

The vessels either navigate by the help of an icebreaker or in a convoy navigation, the distance is so close. In the above cases of the visibility is very low. The vessels which navigate in a channel, the edges might be too hard.

However, fortunately, because of the short distance and ice itself as a damper, the consequences of these types of collisions mostly do not result in undesirable ends. Collisions might be categorized as:

1. Bow to aft (head to tail) collision
2. Bow to side (head to side) collision
3. Head to rear end collision
4. Side to side collision

Head to rear end collisions are generally observed as vessel to icebreaker collision or convoy collisions in case of the distance is short and speed is high [50].

Since an ice breaker encounters an ice ridge, it might stop abruptly, the following vessel might not keep the distance or might not take an action to avoid colliding. The most significant reason for the collision in ice field is existence of ice in the environment which does not let to avoid collision. Maneuvering in the ice is quite hard for the vessels comparing to the open sea navigation because of the unexpected stochastic motions of the vessels even since the rudder control is not problematic. In order not to contact with a stuck vessel, icebreaker keeps the distance loose during the ice breaking process. Operational experience, foresight of the future events, prediction of the speed and its response to commands of the vessel, existence of propeller thrust and rudder force, special care for the instant changes should be considered to avoid the collisions in ice navigation. In the following section, the methodology used for the collision and grounding is described.

4.2 Methodology: Fault Tree Analysis (FTA)

Fault tree analysis is a risk assessment tool that identify the root causes of unwanted incidents [56]. Marine accidents involve lots of possible qualitative or/and quantitative combinations of factors such as human errors, normal events and component events. The probability that the occurrence of an undesired event or frequency of an event in a given period of time is determined.

A fault tree schematics starts with an "Top Event" (TE) which is shown with a rectangular and as a branch of a tree, other related logical events are drawn below [57]. Mostly, critical events such are chosen as a TE. The causes for each occurence of events are divided into the branches in a stepwise approach. The assessment maintains at each level, until the root causes or assessment boundary conditions are reached. The basic root causes are not required a further development. Root causes are shown with symbol of a circle. If the data of a root cause is unavailable, this is called an "undeveloped event" and shown as a diamond. A triangle symbol represents "transfer" in FTA which means the tree is developed to display further other trees [58].

Principally, "OR" and "AND" gates are used as logical operators in the fault tree schematics. The output of the AND gate depends on any of the input events occur. This means AND gate is an intersection of sets containing all input events. One of the input event directly influence the output of the OR gate. This means OR gate is an union of the sets containing all input events [58]. Figure 4.4 shows the logic symbols of the fault tree analysis below.

Fault Tree Analysis is developed into six steps [59]:
Step 1. Defining the problem and boundary conditions. Explaining the criticality of the TE with the physical borders, beginning conditions and limitation of external loads.
Step 2. Constructing the Fault Tree Analysis model. Description and assessment of the failure events.
Step 3. Establishment of the minimal cut sets (MCSs) and path sets.
Step 4. Qualitative analysis of the fault tree.

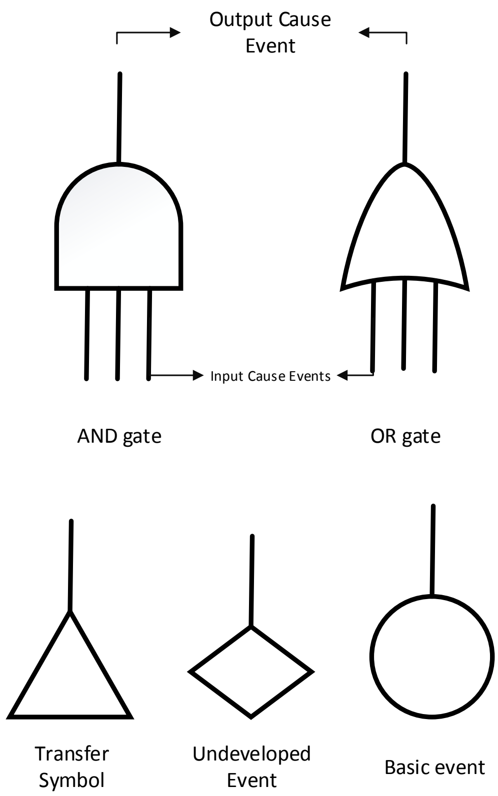


Figure 4.4: The symbols of a fault tree.

Step 5. Quantitative evaluation of the logic model. Probability of the TE and reliability of the BEs.
Step 6. Reporting the results.

4.2.1 Notation and quantification of the probability of the logic gates

Let $Q_0(t)$ is the probability of the TE occurs at time t, $q_i(t)$ probability of the BE i occurs at time t. $Q_0(t)$ is the probability of the minimal cut set j fails at time t. Let stands for the BE i occurs at time t.

4.2.1.1 AND gate

Let $q_1(t) = P(E_i(t))$ for i=1,2. Top event probability $Q_0(t)$ is

$$Q_0(t) = P(E_1(t) \cap E_2(t)) = P(E_1(t) \cdot E_2(t)) = q_1(t) \cdot q_2(t) \qquad \textbf{(4.1)}$$

If there is a single AND gate with n events;

$$Q_0(t) = \prod_{j=1}^{n} q_j(t) \qquad \textbf{(4.2)}$$

4.2.1.2 OR gate

Let $q_1(t) = P(E_i(t))$ for i=1,2. Top event probability $Q_0(t)$ is

$\mathrm{Q}_0(t) = P(E_1(t) \cup E_2(t)) = P(E_1(t) + E_2(t) - E_1(t) \cap E_2(t)) = q_1(t) - q_2(t) - q_1(t) \cdot q_2(t) = 1 - (1 - q_1(t)) \cdot (1 - q_2(t))$ **(4.3)**

If there is a single AND gate with n events;

$$Q_0(t) = 1 - \prod_{j=1}^{n} (1 - q_j(t)) \quad \textbf{(4.4)}$$

4.2.1.3 Cut set assessment

A minimal cut set fails if all r BEs fails simultaneously. The probability of the cut set j fails at time t is

$$\phi_j(t) = \prod_{i=1}^{n} q_{j,i}(t) \quad \textbf{(4.5)}$$

4.2.1.4 Top event probability

Minimal cut sets related to the TE by an OR gate. Therefore, at least one of the minimal cut sets fail the TOP event occurs. The probability of TOP event is:

$$Q_0(t) \leq 1 - \prod_{j=1}^{k} (1 - \phi_j(t)) \quad \textbf{(4.6)}$$

4.2.2 FFTA model for marine accidents in the polar regions

In the conventional FTA, crisp data for each BEs are applied as fault probabilities. However, it is too difficult to find the absolute probabilities and quantitative analysis for perfect components in the multiple systems. On the other hand, crisp approach has a dilemma to express the nature of inaccuracy and vagueness for computing the rate of faults in the imprecision of a system model. For the statistical inferences, this generally occurs in a dynamic environment or a system which has inadequate or no data. Therefore, due to this shortage, working with approximate estimation of the probabilities for these faults becomes necessary. Conventional FTA may not be convenient for implementing it especially for calculation the probabilities of faults under these circumstances [60]. Thus, a novel form is required, which includes the subjectivity, individuality and rate of faults for handling vagueness to embed into the conventional FTA. It is more acceptable that the usage of possibility rather than the probability of a fault [61].

Probability values of the components are expressed as fuzzy numbers. There are lots of studies to overcome the shortage of the conventional FTA by using the fuzzy set theory. Tanaka et. al, (1983) has developed the FTA by applying the probabilities as trapezoid numbers and has studied on determining the probability of TE by a fuzzy extension method [61].

4.2.2.1 Rating scale

In this phase, experts express their subjective opinions for each BE. There sometimes might be an ambiguity because of insuffcent or no data which is caused from the physical constraints or lack of sources. This imprecision might be handled after combining the expert opinions to realize the expert elicitation [62]. Expertization is a methodology of scientific consensus and used for infrequent events. Usage of parameters is allowed in the process of expert elicitation. In that respect, each topic is directly related to the field of each experts. Elicitation process might also be called as an "Educated estimation" which is completed to express the linguistic vague values as numeric crisp style. This technique is studied in a diverse disciplines. For instance, it contributes the decision and risk analyses, statistics, probability estimations, in the field of philosophy and mathematics etc. Measurement of subjective probability is achieved in an environment of multiple conditions [63].

1. While lacking of evidence due to it is obtained not in a reasonable style.
2. It is available only for similar situations. Similar data values might be used as the probability for the intended case.
3. In the case of conflicting models and data resources.
4. The usage of data obtained from the experiments to target physical processes indirect way. Approximate value scaling is sometimes more simpler than re-scaling.

According to Ford and Sterman (1998), expert knowledge is biased from his/her own perspectives and aims. Therefore, an expert knowledge impossibly be objective [64].

Expert selection should be managed in a careful manner whether the academic research will be conducted in a heterogeneous expert group or homogeneous expert group. Since heterogeneous expert group include scientists and workers, homogeneous expert group include only scientists. Based on the expert judgments, effect of homogeneous expert group is fewer comparing to the heterogeneous expert group. In a heterogeneous expert group, there are various experts from diverse fields. Due to they will revise all probable opinions, heterogeneous expert group has an advantage. In summary, expert selection should be based on following criteria: (1) Learning period of an expert depends on the knowledge and specific experience on the field. Then the experts reflect their proficiencies to judgments, assessments and analytic behaviors. (2) The experienced cases might be theoretical or/and practical.

In this chapter, a heterogeneous expert group is preferred for estimating the fuzzy probabilities of vague events. Table 4.4 shows the weight factors of selected experts. Opinions of each expert are expressed as linguistic terms to determine the experts' opinions on all BEs. Usage of linguistic terms is more capable for the quantitative cases whether they defined as wrong or too complex [65].

Table 4.4: Criteria for determining the expert weights.

Parameters	Classification	Score
Professional Position	Academician	5
	Company operations manager	4
	Company deck inspector	3
	Master	2
	Chief officer	1
Sea service time (year)	16	5
	11 - 15	4
	6 - 10	3
	3 – 5	2
	2	1
Shore service time (year)	26	5
	16 - 25	4
	11 - 15	3
	6 - 10	2
	5	1
Educational level	PhD	5
	Master	4
	Bachelor	3
	HND	2
	School Level	1

4.2.2.2 Aggregating stage

Experts might have different opinions regarding to their knowledge, experience and expertise. The important factor here is the provision of consensus after an aggregation process of all experts' opinions and viewpoints. An algorithm has been developed by Hsu and Chen (1994) to aggregate the linguistic opinions of experts in a homogeneous or heterogeneous group [66]. Here, it is preferred to use the score scale mentioned in [67].

Suppose that experts $E_k(k = 1,2,\ldots,M)$ express their opinions on a particular subject. In relation to this, there is a context which is previously defined as linguistic variables. These linguistic terms can be converted into fuzzy numbers. Detailed algorithm is defined as follows:

1- Calculating the degree of similarity or consensus for $\widetilde{R}_u$ and $\widetilde{R}_v$ opinions of experts where $S_{uv}(\widetilde{R}_u,\widetilde{R}_v) \in [0,1]$. According to this approach, $\widetilde{A} = (a_1,a_2,a_3,a_4)$ and $\widetilde{B} = (a_1,a_2,a_3,a_4)$ are two trapezoid numbers. Then, degree of similarity between these two fuzzy numbers is obtained by the similarity function which is expressed as follows:

$$S(\widetilde{A},\widetilde{B}) = 1 - \frac{1}{4}\sum_{i=1}^{4} |a_i - b_i| \tag{4.7}$$

where $S(\widetilde{A},\widetilde{B}) \in [0,1]$. The more $S(\widetilde{A},\widetilde{B})$ means the more similarity between $\widetilde{A}$ and $\widetilde{B}$.
2- Average Agreement (AA) degree $AA(E_u)$ of the experts,

$$AA(E_u) = \frac{1}{M-1}\sum_{\substack{u\neq v\\ v=1}}^{M} S(\widetilde{R}_u,\widetilde{R}_v) \tag{4.8}$$

3- Relative Agreement degree calculation, $RA(E_u)$ of the experts, $E_u(u = 1,2,\ldots,M)$ as

$$RA(E_u) = \frac{A(E_u)}{\sum_{u=1}^{M} A(E_u)} \tag{4.9}$$

4- Consensus Coefficient (CC) degree estimation, $CC(E_u)$ of expert, $E_u(u = 1,2,\ldots,M)$, $CC(E_u) = \beta \cdot w(E_u) + (1-\beta)\cdot RA(E_u)$ where β is a relaxation factor and $0 \leq \beta \leq 1$. This declares the importance of $w(E_u)$ over $RA(E_u)$. If $\beta = 0$, weight of expertize is not considerable, and it means the group is homogeneous. If $\beta = 1$, consensus degree of an expert becomes equal to importance weight. CC degree is a good tool to measure the relative values of each experts. This is a responsibility for the decision maker to assign the appropriate value of β. As a result, aggregated result of expert judgments $\widetilde{R}_{AG}$ is expressed as follows:

$$\widetilde{R}_{AG} = C(E_1) \times \widetilde{R}_1 + C(E_2) \times \widetilde{R}_2 + \cdots + C(E_M) \times \widetilde{R}_M \qquad (\mathbf{4.10})$$

4.2.2.3 Defuzzification process (DP)

DP produces measurable results by fuzzy logic. DP has widely been used in a various fields from fuzzy control applications to industrial processes. DP is a significant measurement for decision making processes in a fuzzy environment. For DP, center of area technique which is developed by Sunego (1999) is used [68]. This method is expressed as:

$$X^* = \frac{\int \mu_i(x) x \mathrm{d}x}{\mu_i(x)} \qquad (\mathbf{4.11})$$

where X^* is the defuzzified output $\mu_i(x)$ is the aggregated membership function, x is the output variable.

The formula given above can state the triangular or trapezoid numbers. DP of a triangular fuzzy number is denoted as:

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x-a}{a_2-a_1} x\mathrm{d}x + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} x\mathrm{d}x}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1}\mathrm{d}x + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2}\mathrm{d}x} = \frac{1}{3}(a_1 + a_2 + a_3) \qquad (\mathbf{4.12})$$

DP of a trapezoidal fuzzy number $\widetilde{A} = (a_1, a_2, a_3, a_4)$ is denoted as:

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x-a}{a_2-a_1} x\mathrm{d}x + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} x\mathrm{d}x + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} x\mathrm{d}x}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1}\mathrm{d}x + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2}\mathrm{d}x + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3}\mathrm{d}x} = \frac{1}{3}\frac{(a_4+a_3)^2 - a_4 a_3 - (a_1+a_2)^2 + a_1 a_2}{a_4 + a_3 - a_2 - a_1} \qquad (\mathbf{4.13})$$

4.2.2.4 Transformation of CFP of BEs into FP

As mentioned earlier, there might have some data regarding to the fault rates of some events and some data might have vagueness. This problem can be solved only by the transformation of fuzzy numbers from crisp failure possibility (CFP) to fault probability. This is completed by the equality below:

$$FP = \begin{cases} \frac{1}{10^K}, & \text{if } CFP \neq 0 \\ 0, & \text{if } CFP = 0 \end{cases}, K = \left[\left(\frac{1-CFP}{CFP}\right)\right]^{\frac{1}{3}} \times 2.301 \qquad (\mathbf{4.14})$$

Onsiawa (1998) has developed a function to use it by converting CFP into failure probability (FP). This function is gathered by addressing some properties. For instance, the probability rate of human sensations and it is gathered from the proportionateness of the possibility to probability [69–72].

4.2.2.5 Calculation of all MCSs and TE occurrence

A TE is directed by MCS which a cut set (CS) is defined as combination or intersection of BEs. This is the minimal combination and all faults are required for occurrence of TE. Based on this combination, if one of the faults does not occur, MCS and thus, TE will not occur.

Fault trees include minimum numbers of MCS which they are unique. If MCS is composed of only one element, that fault triggers occurrence of TE. If MCS is composed of two elements, this situation proves that there are two problems. Both problems trigger occurrence of TE. TE occurs by the combination of MCS which the equality is given below:

$$\mathrm{P(T) = P(MCS_1} \bigcup MCS_2 \bigcup \cdots \bigcup MCS_N)$$
$$= P(MCS_1) + P(MCS_2) + \cdots + P(MCS_N) - (P(MCS_1 \bigcap MCS_2) + P(MCS_1 \bigcap MCS_3) +$$
$$\cdots + P(MCS_i \bigcap MCS_j \dots) \cdots + (-1)^{N-1} P(MCS_1 \bigcap MCS_2 \bigcap \dots MCS_N) \quad \mathbf{(4.15)}$$

where $P(MCS_i)$ is the occurence probability of MCS_i and N is the number of MCS

4.2.2.6 Ranking of minimal cut sets

One of the significant outputs of the FTA is importance measurement (IM) set which is calculated for TE. IMs are significant for all MCS. For each MCS in the fault tree, prioritization process can be conducted both based on the contribution to the probability of TE and importance level at the MCS. By calculation of IMs, sensitivity of TE's probability can be calculated whether it is increasing or decreasing. There are two types of IM calculations for different applications. IM is calculated for each MCS and described as Fussell-Vesely Importance (FV-I). FV-I is the contribution of MCSs to the probability of TE. FV-I is determined for each cut set which is modelled in the fault tree. This quantitative importance provides quantitative importance in all fault elements and allows for prioritization. TE is calculated by addition of MCSs. Therefore, FV-I is calculated by the sum of all MCSs. This measurement is applied for all MCSs to determine the importance of an individual MSC. The fault of system $Q_i(t)$ is a contribution of MCS which gives the system error. Importance measurement is computed as follows:

$$I_i^{FV}(t) = \frac{Q_i(t)}{Q_s(t)} \quad \textbf{(4.16)}$$

where $Q_i(t)$ is the probability of failure of MCS_i and $Q_s(t)$ of TE due to all MCSs.

4.2.2.7 Risk reduction worth (RRW)

RRW calculates the decrease of the probability of TE at a possibility. If it is convinced for not to be given a MCS, it gives the decreasing probability of TE. This type of IM is called as Top Decrease Sensitivity (TDS). For a MCS, RRW shows the decrease of TE's probability which is obtained since MCS is not occurred. Therefore, RRW is recalculated in the fault tree by assigning 0 to the MCS and as a result it calculates the maximum decrease and maximum reduction for the probability of TE. RRW value is determined for all MC.

4.2.3 FFTA model for marine accidents occurring in the polar regions

For the risk related research, expert consultations should be carried out since the situations have insufficient or no data. A framework based on fuzzy set theory and FTA is aimed for the experts who express their opinions qualitative manner. This framework is capable for assessment of the judgments. The model is shown on the figure 4.5 [73]. Firstly, BEs are seperated as fault rate is known and fault rate is unknown. At the second phase, the probability of known BEs' fault rate is obtained. Third phase, expert consultation is conducted for the probability of unknown BEs' fault tree. Then judgment values are assigned to the each unknown BEs. This evaluation is generally as fuzzy number format. Fourth step is an aggregation procedure. For all vague BEs, this phase is completed by aggregating of expert opinions which are expressed in a linguistic manner. After an appropriate algorithm application, the fuzzification process is handled by the conversion of fuzzy possibilites of expert judgments into crisp expressions. At the sixth phase, crisp possibilities are converted as fault probabilities. Then MCS and TE estimations are ended. Lastly, MCSs are ranged.

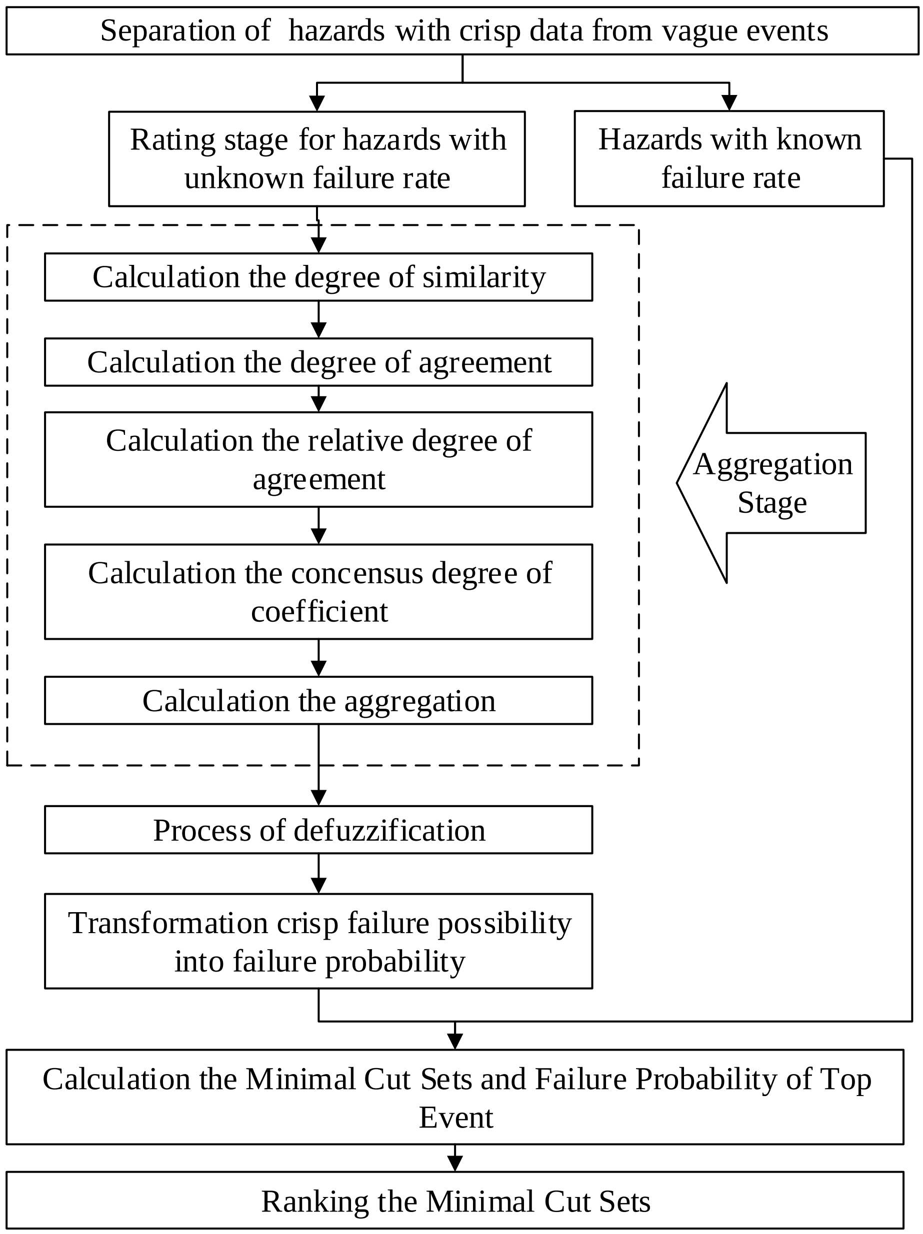


Figure 4.5: Structure of the proposed methodology.

1-Seperation of the hazards

As mentioned in the first phase of the methodology, separation process is operated for the BEs which have known fault rates and BEs which have unknown fault rates. Some fault probabilities are given in these sources. Thus, BEs which have known fault rates and BEs which have unknown fault rates are required to be separated. However, for collision and grounding in the intended region, there exists no known data regarding the BEs.

2-Provision of fault probabilities for BEs which have known fault rates

Construction of a perfect analysis is only possible by assigning either the fault rates or data of BEs' possibilities. After a proper work, the most accurate fault rates should be obtained based on the available facilities. Inaccuracy of the fault rates depends on applicability of huge amount of these data. A fault rate should be applied to a particular application of a component, operating or non-operating environment of a component. Fault rate data hierarchy is stated as follows [73]:

- Updated working data of an element
- Updated working data of similar design element
- Life test or accelerated data test on an element
- Life test or accelerated data test on a similar design element
- Field or test data from Supplier of element
- Specialization databases or in-house databases
- Standart manuals for trusted data

According to Preyssl (1995) three methods are generally used to determine the probability of an event [74]:

1. Statistical method
2. Extrapolation method
3. Expert judgment method

Statistical method is used for the direct test application based on the experienced data to calculate the probability. Extrapolation method includes model estimations, the data contain similar situations and standard reliability manuals. Expert judgment method depends on direct estimations from the individuals.

The interval τ of an element in a system is regularly tested. A fault may occur in any time during the test process however, faults are only determined on the test process. After a test process, the element is accepted as its new one. This is typical situation for many safety-critical elements such as sensors and valves. The fault probability of an inspected event is calculated as follows [75, 76].

$$P(t) = \frac{1}{2}\lambda\tau \qquad \textbf{(4.17)}$$

where λ is the component failure rate, τ is the inspection interval.

Table 4.5: The scale of fuzzy sets.

Linguistic Expressions	Fuzzy numbers
Very Low (VL)	(0,0,0.1,0.2)
Low (L)	(0.1,0.2,0.2,0.3)
Mildly Low (ML)	(0.2,0.3,0.4,0.5)
Medium (M)	(0.4,0.5,0.5,0.6)
Mildly High (MH)	(0.5,0.6,0.7,0.8)
High (H)	(0.7,0.8,0.8,0.9)
Very High (HV)	(0.8,0.9,1,1)

If the element is a kind of non-inspected, fault rate P, which is also called as unreliability is obtained as follows:

$$P(t) = 1 - e^{-\lambda\tau} \quad \textbf{(4.18)}$$

where λ is the component failure rate. τ is the relevant time interval.

Based on Maclaurin Series, if $\lambda t < 1$, for P, the equality given above is obtained as follows:

$$P(t) = 1 - (1 + \frac{-\lambda t}{1!} + \frac{\lambda^2 t^2}{2!} + \frac{-\lambda^3 t^3}{3!} + \cdots + \frac{\lambda^n t^n}{n!}) \cong \lambda t \quad \textbf{(4.19)}$$

4.3 Case Study: FFTA Of Marine Accidents

Deaths and injuries is the top adverse event, however, in this chapter, grounding (Figure C.1 and Figure C.2) and collision are considered (Figure C.3 and Figure C.4) separately as two different top events as shown in the Appendix C.

In this chapter, faults of collision and grounding in the polar regions are searched as an case study. Due to ice navigation is a new concept, there are very limited data to determine the probability of each BE. Therefore, hazard separation and calculation with failure rate stages are ignored. To overcome this, expert consultation is conducted.

4.3.1 Rating scale

Chen and Hwang (1992) have developed an appropriate numerical approximation method which transforms the linguistic expressions into fuzzy numbers [77]. The linguistic scale is defined in the Table 4.5.

According to Miller (1956) and Norris (1998), for an appropriate judgement for the linguistic term selection is between 5 to 9 [78, 79]. Therefore, 7 fuzzy linguistic scale

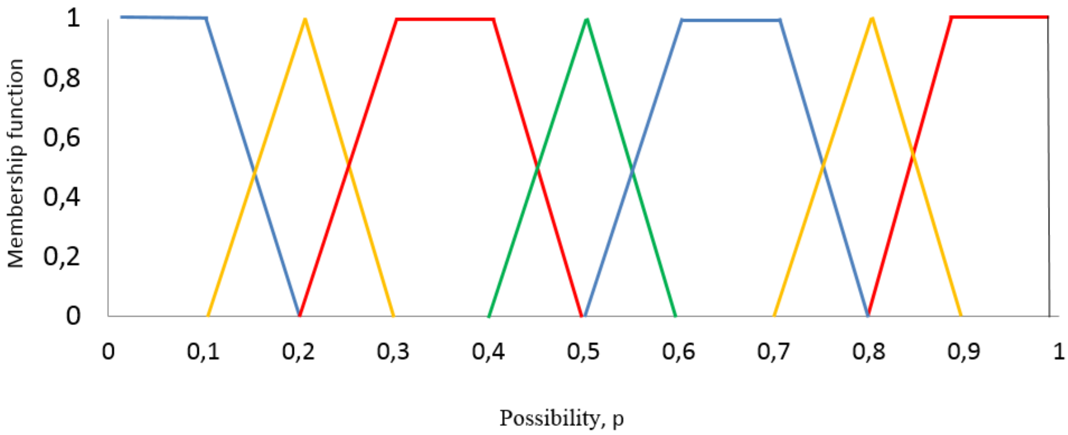


Figure 4.6: Equivalence of linguistic values represent trapezoidal fuzzy numbers.

Table 4.6: Professions and experience of the experts.

No of experts	Professional position	Sea service time (year)	Shore service time (year)	Educational level	Weighting factor	w
1	Academician	3-5	11-15	PhD	15	0,13
2	Academician	3-5	5	PhD	13	0,11
3	Academician	3	5	PhD	12	0,10
4	Academician	3	5	PhD	12	0,10
5	Academician	11-15	11-15	MSc	16	0,13
6	Master	16	16-25	PhD	16	0,13
7	Master	6-10	5	MSc	10	0,08
8	Master	6-10	5	BS	9	0,08
9	Chief Officer	3-5	6-10	PhD	10	0,08
10	Chief Officer	6-10	5	BS	7	0,08

is determined for this chapter. Trapezoidal fuzzy numbers are given in the Figure 4.6 [67].

A heterogeneous expert group is preferred for the expert consultation. As they have rich backgrounds and different experiences on particular subjects of polar region, they are not assigned equal weights which is given on the Table 4.6.

4.3.2 Aggregation stage

The aggregation process is completed in this stage after all experts' decisions. Consensus coefficient is obtained after the β value is set as 0.5 for each experts. To clarify the aggregation process, BE 40 *Internal Communication Failure* for the collision when assisted as an example, is given in the Table 4.7, Table 4.8, Table 4.9, Table 4.10, Table 4.11.

Table 4.7: $\tilde{R}_u = (r_{u1}, r_{u2}, r_{u3}, r_{u4})$ experts' opinions for BE X40.

Experts	Opinions of experts			
	r_{u1}	r_{u2}	r_{u3}	r_{u4}
E1	0,0	0,0	0,1	0,2
E2	0,0	0,0	0,1	0,2
E3	0,2	0,3	0,4	0,5
E4	0,2	0,3	0,4	0,5
E5	0,0	0,0	0,1	0,2
E6	0,0	0,0	0,1	0,2
E7	0,1	0,2	0,2	0,3
E8	0,7	0,8	0,8	0,9
E9	0,8	0,9	1,0	1,0
E10	0,5	0,6	0,7	0,8

Table 4.8: Similarity functions.

No	Similarity function	Similarity function value	No	Similarity function	Similarity function value	No	Similarity function	Similarity function value
1	S(E1&E2)	1	16	S(E2&E9)	0,15	31	S(E5&E6)	1
2	S(E1&E3)	0,725	17	S(E2&E10)	0,425	32	S(E5&E7)	0,875
3	S(E1&E4)	0,725	18	S(E3&E4)	1	33	S(E5&E8)	0,275
4	S(E1&E5)	1	19	S(E3&E5)	0,725	34	S(E5&E9)	0,15
5	S(E1&E6)	1	20	S(E3&E6)	0,725	35	S(E5&E10)	0,425
6	S(E1&E7)	0,875	21	S(E3&E7)	0,85	36	S(E6&E7)	0,275
7	S(E1&E8)	0,275	22	S(E3&E8)	0,55	37	S(E6&E8)	0,275
8	S(E1&E9)	0,15	23	S(E3&E9)	0,425	38	S(E6&E9)	0,15
9	S(E1&E10)	0,425	24	S(E3&E10)	0,7	39	S(E6&E10)	0,425
10	S(E2&E3)	0,725	25	S(E4&E5)	0,725	40	S(E7&E8)	0,4
11	S(E2&E4)	0,725	26	S(E4&E6)	0,725	41	S(E7&E9)	0,275
12	S(E2&E5)	1	27	S(E4&E7)	0,85	42	S(E7&E10)	0,55
13	S(E2&E6)	1	28	S(E4&E8)	0,85	43	S(E8&E9)	0,875
14	S(E2&E7)	0,875	29	S(E4&E9)	0,425	44	S(E8&E10)	0,85
15	S(E2&E8)	0,275	30	S(E4&E10)	0,7	45	S(E9&E10)	0,725

Table 4.9: Average and relative agreement of experts.

Average agreement of experts (AA)		Relative agreement of experts (RA)	
E1	0,686	E1	0,11
E2	0,686	E2	0,11
E3	0,713	E3	0,12
E4	0,713	E4	0,12
E5	0,686	E5	0,11
E6	0,619	E6	0,10
E7	0,647	E7	0,10
E8	0,480	E8	0,08
E9	0,369	E9	0,06
E10	0,580	E10	0,09

Table 4.10: Consensus coefficient.

Consensus coefficient (CC)	
CC1	0,1206
CC2	0,1076
CC3	0,1012
CC4	0,1012
CC5	0,1250
CC6	0,1196
CC7	0,0958
CC8	0,0779
CC9	0,0733
CC10	0,0773

Table 4.11: Aggregation of BE X40.

Aggregation of BE X40			
0,2020	0,2547	0,3373	0,4300

4.3.3 Defuzzification of subjective BEs

For this chapter, center of area defuzzification method is applied to the problem. Defuzzification results of all BEs are indicated in the Table 4.12.

4.3.4 Conversion of CFPs to failure probability

Equation 4.14 is applied to convert the CFP into FP, which is shown in the Table 4.13.

Failure probability is calculated after obtaining all failure probabilities of all BEs. Between the Equations 4.1 to 4.6 is applied to the calculation by considering the logic gates. Then, the failure probability of TE is calculated.

Table 4.12: Defuzzification.

BEs	Defuzzification of BEs (CFP)	BEs	Defuzzification of BEs (CFP)
X01	0,625	X24	0,672
X02	0,789	X25	0,585
X03	0,679	X26	0,569
X04	0,841	X27	0,505
X05	0,841	X28	0,178
X06	0,870	X29	0,211
X07	0,861	X30	0,228
X08	0,843	X31	0,161
X09	0,861	X32	0,171
X10	0,880	X33	0,225
X11	0,420	X34	0,254
X12	0,617	X35	0,226
X13	0,813	X36	0,265
X14	0,766	X37	0,265
X15	0,819	X38	0,301
X16	0,679	X39	0,380
X17	0,742	X40	0,307
X18	0,695	X41	0,380
X19	0,663	X42	0,290
X20	0,824	X43	0,303
X21	0,500	X44	0,301
X22	0,845	X45	0,324
X23	0,848	X46	0,338

Table 4.13: Conversion of CFP into failure probability.

BEs	FP of BEs	BEs	FP of BEs	BEs	FP of BEs
X01	0,01147	X17	0,02417	X33	0,00017
X02	0,03293	X18	0,01785	X34	0,00050
X03	0,01620	X19	0,01459	X35	0,00034
X04	0,04789	X20	0,04221	X36	0,00059
X05	0,04789	X21	0,00500	X37	0,00060
X06	0,06045	X22	0,04939	X38	0,00090
X07	0,05586	X23	0,05056	X39	0,00197
X08	0,04884	X24	0,01549	X40	0,00092
X09	0,05614	X25	0,00889	X41	0,00200
X10	0,06567	X26	0,00800	X42	0,00080
X11	0,00275	X27	0,00850	X43	0,00092
X12	0,01094	X28	0,00014	X44	0,00090
X13	0,03895	X29	0,00026	X45	0,00114
X14	0,02837	X30	0,00035	X46	0,00132
X15	0,04072	X31	0,00010		
X16	0,01622	X32	0,00012		

Table 4.14: Occurrence probabilities of MCSs.

MCSs	Probability	MCSs	Probability	MCSs	Probability
X38	9,029E-04	X13X20X7	9,187E-05	X13X26X8	1,523E-05
X10X12	7,187E-04	X13X20X8	8,032E-05	X10X13X21	1,279E-05
X12X9	6,144E-04	X10X13X17	6,185E-05	X13X21X9	1,093E-05
X12X7	6,114E-04	X13X17X9	5,287E-05	X13X21X7	1,088E-05
X36	5,906E-04	X13X17X7	5,262E-05	X13X21X8	9,514E-06
X37	5,906E-04	X13X17X8	4,600E-05	X39X41	3,886E-06
X12X8	5,346E-04	X10X13X18	4,566E-05	X39X46	2,620E-06
X34	5,089E-04	X10X13X24	3,963E-05	X39X45	2,266E-06
X30	3,529E-04	X13X18X9	3,904E-05	X40X41	1,826E-06
X35	3,396E-04	X13X18X7	3,885E-05	X39X43	1,826E-06
X29	2,690E-04	X10X13X19	3,734E-05	X39X44	1,775E-06
X10X11	1,808E-04	X13X24X9	3,388E-05	X39X42	1,577E-06
X33	1,721E-04	X13X18X8	3,396E-05	X40X46	1,231E-06
X11X9	1,546E-04	X13X24X7	3,371E-05	X10X14X15X16	1,231E-06
X11X7	1,538E-04	X13X19X9	3,192E-05	X40X45	1,064E-06
X28	1,438E-04	X13X19X7	3,176E-05	X14X15X16X9	1,052E-06
X11X8	1,345E-04	X13X24X8	2,948E-05	X14X15X16X7	1,047E-06
X32	1,297E-04	X13X19X8	2,777E-05	X14X15X16X8	9,155E-07
X10X13X23	1,294E-04	X10X13X25	2,277E-05	X40X43	8,578E-07
X10X13X22	1,264E-04	X10X13X27	2,189E-05	X40X44	8,341E-07
X13X23X9	1,106E-04	X10X13X26	2,048E-05	X40X42	7,413E-07
X13X23X7	1,100E-04	X13X25X9	1,947E-05	X1X10X2X4X5X6	3,440E-09
X13X22X9	1,080E-04	X13X25X7	1,937E-05	X1X2X4X5X6X9	2,941E-09
X10X13X20	1,080E-04	X13X27X9	1,871E-05	X1X2X4X5X6X7	2,926E-09
X13X22X7	1,075E-04	X13X27X7	1,862E-05	X1X2X4X5X6X8	2,559E-09
X31	1,028E-04	X13X26X9	1,750E-05	X1X10X3X4X5X6	1,692E-09
X13X23X8	9,621E-05	X13X26X7	1,742E-05	X1X3X4X5X6X9	1,446E-09
X13X22X8	9,399E-05	X13X25X8	1,694E-05	X1X3X4X5X6X7	1,439E-09
X13X20X9	9,232E-05	X13X27X8	1,628E-05	X1X3X4X5X6X8	1,259E-09

Table 4.15: Numbers of marine accidents between 1995-2004.

Year	#
1995	35
1996	53
1997	23
1998	19
1999	21
2000	19
2001	31
2002	30
2003	28
2004	34

Table 4.16: Numbers of marine accidents based on months of the year.

Month	#
JAN	16
FEB	35
MAR	30
APR	6
MAY	15
JUN	18
JUL	39
AUG	22
SEP	31
OCT	35
NOV	23
DEC	23

Table 4.17: Numbers of marine accidents based on vessel type.

Vessel Type	#
Bulk Carrier	37
Container Ship	8
Fishing Vessel	108
General Cargo Ship	72
Government Vessel	11
Oil/Gas Service & Supply	1
Passenger Ship	27
Pleasure Craft	0
Tanker Ship	12
Tug/Barge	15
Unknown	2

Table 4.18: Numbers of marine accidents based on primary reason.

Primary Reason	#
Collision	22
Damage to Vessel	54
Fire/Explosion	25
Grounded	68
Machinery Damage/Failure	71
Sunk/Submerged	43
Miscellaneous	10

Table 4.19: Sensitivity analysis of first 30 MCSs.

TE for collision = 0,00411489; TE for grounding = 0, 007525782		
No of MCS	Occurrence probability of MCS	F-VIM
X38	9,028E-04	21,94
X36	5,906E-04	14,35
X37	5,906E-04	14,35
X34	5,088E-04	12,37
X10X12	7,187E-04	9,55
X30	3,529E-04	8,58
X35	3,395E-04	8,25
X12X9	6,144E-04	8,12
X10X13X17	6,185E-05	7,10
X29	2,680E-04	6,51
X33	1,720E-04	4,18
X28	1,437E-04	3,49
X32	1,269E-04	3,15
X31	1,027E-04	2,50
X10X11	1,808E-04	2,40
X11X9	8,341E-06	2,05
X11X7	7,413E-06	2,04
X11X8	1,345E-04	1,79
X10X13X23	1,294E-04	1,72
X10X13X22	1,264E-04	1,68
X13X23X9	1,106E-04	1,47
X13X23X7	1,100E-04	1,46
X13X22X9	1,106E-04	1,44
X13X22X7	1,075E-04	1,43
X10X13X20	1,080E-04	1,43
X13X23X8	9,621E-05	1,28
X13X22X8	9,399E-05	1,25
X13X20X9	9,232E-05	1,23
X13X20X7	9,187E-05	1,22
X13X20X8	8,032E-05	1,07

4.3.5 Calculation failure probability of TE

In this stage, after the application of Generic FTA, the failure probabilities of all BEs are determined. By using the Equation 4.15 the probability of TE is calculated. List of MCSs is provided in the Table 4.19.

Failure probability of TE is calculated as for collision 4.114890E-003 (~ 0.004) for grounding 7.525782E-003 (~ 0.008) after all calculations. MCSs and list of F-VIM are shown in the Table 4.14 and 4.19. The data of arctic marine shipping assessment (AMSA) are derived from various databases such as Lloyd's Marine Intelligence Unit Sea Searcher Database, Canadian Transportation Safety Board (Marine) and Canadian Hydraulics Centre - Arctic Ice Regime System Database. According to the AMSA report, the approximate number of vessels in the Arctic marine area during 2004, including the North Pacific Great Circle Route is 6000 [80]. Numbers of marine accidents between 1995-2004 are provided in Table 4.15, numbers of marine accidents based on months of the year in Table 4.16 and numbers of marine accidents based on vessel type are given in Table 4.17. The number of collision and grounding between the years 1995 to 2004 are given in the Table 4.18.

Accordingly, total number of collision is 22 and grounding is 68. The number of the vessels involved to the collision an grounding are not more than these numbers. Therefore, if it is divided by 6000 which is the approximate number of vessels in the Arctic marine area during 2004, including the North Pacific Great Circle Route. The results for collision is obtained as (~ 0.0036) and for grounding is found as (~ 0.0113). These results indicate that the findings are directly proportional for the real cases.

5. ROUTE SELECTION PROBLEM IN ICE-COVERED WATERS

Table 5.1 shows the relationship between the risk criteria (Chapter 1), the related root causes (Chapter 2) and the route selection criteria. In order to make a judgment over a predefined criterion for route selection problem, all probable risks should be considered. Therefore, all probable ice-state risk factors and BEs (root causes) for marine accidents should be taken into account. The first column of the Table 5.1 represents all probable ice-state risk criteria, second column points out root causes of grounding and collision and third column shows the relation for the criteria of route selection problem. The definitions of criteria for route selection are described in the next section. Due to the criteria of route selection problem are determined based on only ice-state factors, rest of risk criteria are assumed identical for all alternatives. For instance, external factors such as sea and weather conditions are assumed as same for all tracks.

Table 5.1: Criteria of route selection considering the risk criteria and related basic events.

Risk Criteria	Related Basic Events	Criteria of Route Selection Problem
B1-1 Environmental conditions encountered such as fog, storms, compass anomalies, atmospheric effects and ice	X23 Bad weather conditions	
	X24 Environmental restrictions	ARW, SD, Max, Min, IC
B1-2 Drift of pack ice due to wind and surface currents and other ship-handling difficulties	X4 Ice drifting	ARW
B1-3 Colliding with floating obstacles (sharp corners of ice floes) or pressure to the vessel's hull, propellers, rudder	X11 Stuck by ice floe	ARW
	X1 Stuck in ice	
B1-5 Deficiencies in the reliability and detail of hydrographic and geographical information presented on polar navigation charts, coupled with a distinct lack of reliable bathymetry, current, and tidal data	X12 Grounding as ice floes stuck between the bottoms	SD
	X14 Inadequate depth	SD
B1-11 Ice restrictions which affect the vessel's movement and force to change of course and speed.	X11 Stuck by ice floe	ARW
	X37 Crossing ship cannot get out of the channel	S
B6-15 No or faulty bridge routines	X12 Grounding as ice floes stuck between the bottoms	SD
	X13 Inadequate preventive action	
	X14 Inadequate depth	SD
	X15 Deviation from suggested Course	ARW, S, SD, Max, Min, IC, SB, RL
B7-2 Practical incompetency for duty such as experience, local knowledge of waters, usage of devices.	X13 Inadequate preventive action	
	X14 Inadequate depth	SD
	X17 Improper evasive maneuver	
	X30 Lack of situational awareness	
	X44 Incorrect towage operation	
B7-3 Inappropriate design of task or operation such as cargo, night navigation, route planning, anchoring etc.	X21 Improper voyage plan	ARW, S, SD, Max, Min, IC, SB, RL
	X22 UKC & Squat Calculation Fault	SD
	X32 Improper route selection	
	X43 Improper preparedness for the towage	
B7-4 Available warning mechanism is insufficiently developed and used.	X12 Grounding as ice floes stuck between the bottoms	SD
B7-7 Failures of using the sea chart, Deficiencies regarding to positioning the own vessel	X5 Trend of the ship is towards the shallowness	SB, IC
	X6 The ship is close to the shallowness	
	X14 Inadequate depth	SD
	X31 Deviation from suggested route	SB
	X15 Deviation from suggested course	ARW, S, SD, Max, Min, IC, SB, RL
B7-9 Wrong or inadequate interpretation of own vessel's motions (icebergs, current, wind etc.)	X8 Interpretation failures of officers	
	X15 Deviation from suggested course	ARW, S, SD, Max, Min, IC, SB, RL
	X31 Deviation from suggested route	SB
	X5 Trend of the ship is towards the shallowness	SB,IC
	X6 The ship is close to the shallowness	SB,IC
B7-11 Right side of the separation line is not used on the waterway, channel, track, crack, etc.	X5 Trend of the ship is towards the shallowness	SB,IC
	X6 The ship is close to the shallowness	SB,IC
	X14 Inadequate depth	SD

Logistics activities in the polar regions are regularly conducted by ferries, big RO-ROs, ice-breaker convoys in these areas. These powerful vessels make routes (tracks). Therefore, recent tracks are preferably for navigation in ice-covered sea regions. Figure 5.1 presents an objective vessel and previous tracks opened by ice breakers or other vessels. The particulars of the objective ship is given in the Table 5.2. Ice navigation process becomes hard in such an environment and route selection management requires field experience.

Figure 5.1: A ship prepares to navigate in ice-covered sea regions.

Table 5.2: Particulars of the objective ship.

Particulars	Value
Gross Tonnage:	41053
Deadweight (t):	76503
Length x Breadth (m):	220 x 33
Year Built:	2012
Draught (m)	14

The vessels traveling from one point to another in ice, it is significant detecting the optimal routes that reduce the travel time, fuel consumption and as well as getting stuck in ice. For seafarers, the route information is gathered from various sources such as radar/ARPA, satellite images, infrared cameras, visual recognition and charts. After continuous observations, there exist three accessible routes as indicated in Figure 5.2. There are three different possible routes defined as T1, T2 and T3 that connect beginning point to the end destination.

The average route width (ARW), slot availability (S), maximum width along with the track (Max), minimum width along with the track (Min), ice concentration (IC), Route

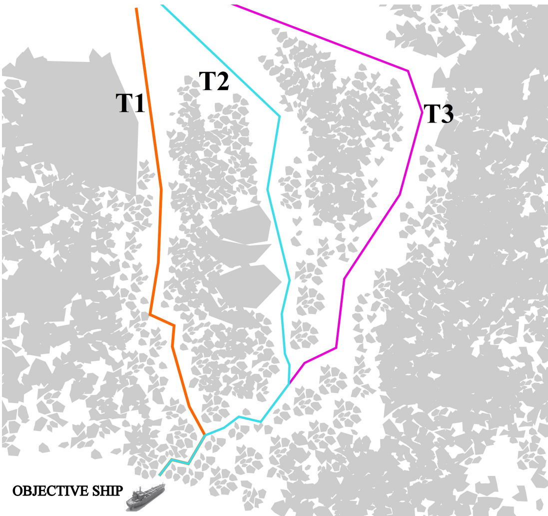


Figure 5.2: Routes for the ship navigation in ice-covered sea regions.

Length (RL), sea depth (SD) and sharp bend (SB) are the eight selective parameters which affect the ice navigation based on time, oil consumption, expenditures and safety. Characteristics of tracks are given in the Table 5.3.

Table 5.3: Characteristics of Tracks.

	T1	T2	T3
ARW (m)	63	75	115
S	2	2	5
Max (m)	82	70	140
Min (m)	54	62	62
IC (1/10 to 1)	4/10	5/10	2/10
RL (nm)	25	29	44
SD (m)	18	17.5	21
SB	4	2	4

It is assumed that this platform is static and floes are constant. Due to this approach, IC (Figure 5.3) which is a ratio in tenths roughly corresponds to an average ice concentration along with the selected tracks.

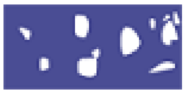
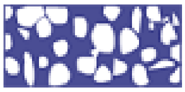
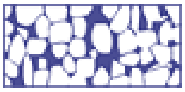
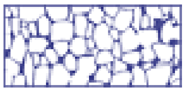
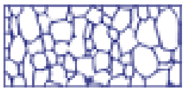
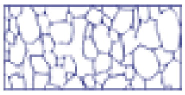
Ice Concentration		
Open Water	< 1/10	
Very open drift	1-3/10	
Open drift	4-6/10	
Close pack	7-8/10	
Very close pack	9/10	
Very close pack	9+/10	
Compact / Consolidated ice	10/10	

Figure 5.3: Ice concentration diagram.

In a narrow and straight track, if a ship meets a big piece of fast ice which is broken off and acts like a fender, there is a great risk of collision. In this case study, all floes are static and it is assumed there are no obstacles in the tracks. However, when two vessels are in crossing situation, the safest way is to stop just outside the track, which I called is a "slot" (Figure 5.4). If there is an available slot, the safer method is the use of slot for clearing the track and the vessel drifts in slot till the track is cleared. Once the vessel has passed, one can easily get unstuck by an astern maneuver.

Figure 5.4: Track meet of two vessels ans slot availability.

Sea depth is crucial for the vessels' keels, hulls and as well as the propellers. Hard ice may damage the vessel physically and stop the manoeuvrability of the vessel. Engaging a sharp bend is another navigational challenge in ice covered waters. This manoeuvring requires a special skill and experience (see Figure 5.5) Speed of the vessel should be reduced to half ahead while 5 cables left (185x5 meters) and should be steered to left then given the command of full astern.

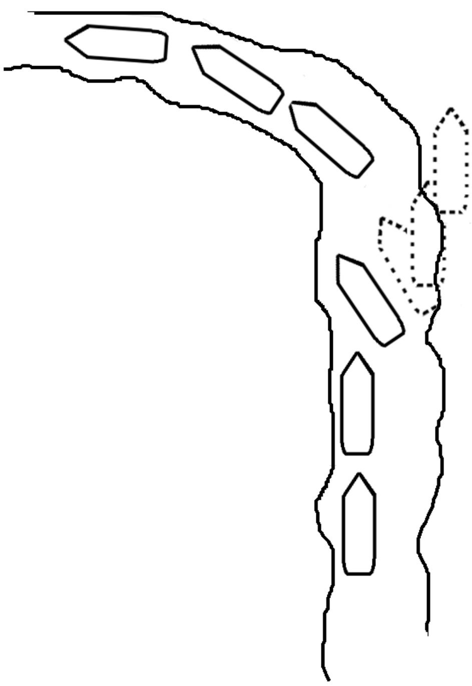


Figure 5.5: Engaging a sharp bend.

5.1 Methodology: Generic Fuzzy Analytical Hierarchy Process (GF-AHP)

5.1.1 Linguistic variable

In a natural or artificial language, a linguistic variable is that such a variable as weather, the values are expressed as fuzzy words or sentences such as hot, very hot, cold, very cold instead of numbers [81].

A linguistic variable has an approximation character, which is either too complex or unclear describing to quantitative terms. Linguistic variables are commonly applied in humanistic systems such as human decision processes, artificial intelligence, pattern recognition, law, medical realms, economy and related areas [82].

5.1.2 Fuzzy sets and triangular fuzzy numbers

Fuzzy set is firstly developed and introduced by Zadeh [83]. A triangular fuzzy number is a convex and normalized fuzzy set $\tilde{A}$ and $\mu_{\tilde{A}}(x)$ is the continuous linear function, which is membership function of $\tilde{A}$.

Definition of a triangular fuzzy number $\tilde{A} = (l, m, u)$ is basically,

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & x \geq l \\ (x-l)/(m-l) & l \leq x < m \\ 1 & x = m \\ (u-x)/(u-m) & m < x \leq u \\ 0 & u < x \end{cases} \tag{5.1}$$

where l and u are the upper (most promising value) and lower (smallest possible value) bounds of fuzzy number $\tilde{A}$ and m is the midpoint. A triangular fuzzy number is shown in Figure 5.6.

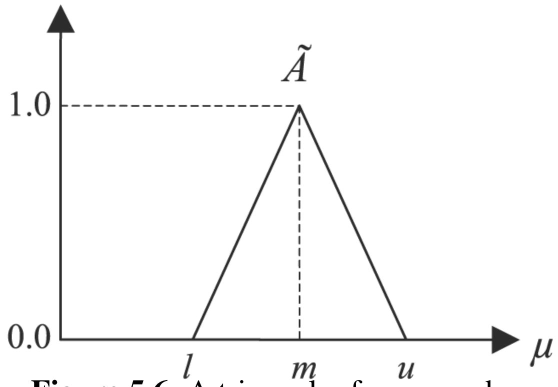


Figure 5.6: A triangular fuzzy number.

The intersection between M_1 and M_2 given in the Figure 5.7.

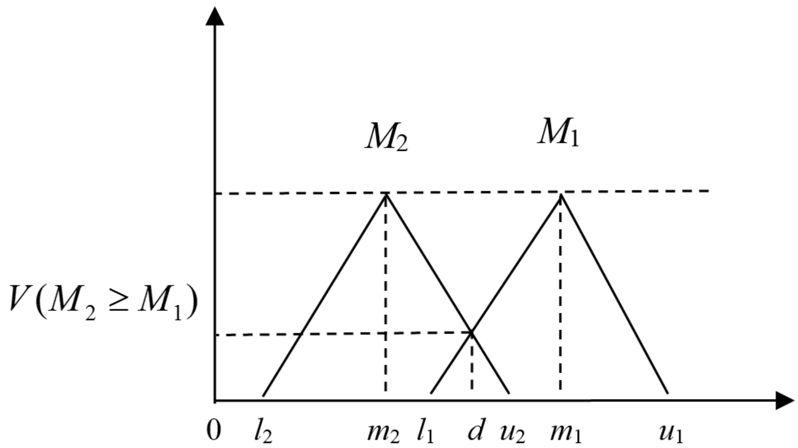


Figure 5.7: The intersection between M_1 and M_2.

Two positive triangular fuzzy numbers (l_1, m_1, u_1) and (l_2, m_2, u_2) then:

$$(l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$$
$$(l_1, m_1, u_1) \cdot (l_2, m_2, u_2) = (l_1 \cdot l_2, m_1 \cdot m_2, u_1 \cdot u_2)$$
$$(l_1, m_1, u_1)^{-1} \approx (\tfrac{1}{u_1}, \tfrac{1}{m_1}, \tfrac{1}{l_1})$$
$$(l_1, m_1, u_1) \cdot k = (l_1 \cdot k, m_1 \cdot k, u_1 \cdot k)$$

where k is a positive number.

Vertex method is used to calculate the distance of two triangular fuzzy numbers [84].

$$d_v(\tilde{m},\tilde{n}) = \sqrt{\frac{1}{3}[(l_1-l_2)^2+(m_1-m_2)^2+(u_1-u_2)^2]}$$

5.1.3 Fuzzy analytical hierarchy process (F-AHP)

Thomas L. Saaty proposed the AHP firstly which is a decision making tool [85]. This method is widely used by researchers [86–88]. The main purpose of AHP is to use the experts' knowledge however; the classical AHP does not reflect the human thinking style because it uses the exact values when comparing the criteria or alternative [89]. Also, there are lots of criticisms regarding the classical AHP based on its unbalanced scale, uncertainty and imprecision of pairwise comparisons. Fuzzy AHP is more accurate and it is developed to handle these shortcomings. Learhoven and Pedrycz proposed the F-AHP first by the comparisons of fuzzy ratios [90]. Buckley worked on trapezoidal fuzzy numbers to evaluate the alternatives in respect to the criteria [91]. For the pairwise comparisons Chang used extent analysis method for the synthetic extent values [92].

The steps of extent synthesis method are: Let $X = \{x_1,x_2,\dots,x_n\}$ as an object set and $G = \{g_1,g_2,\dots,g_n\}$ be a goal set. Each object is taken and extent analysis is performed for each goal. Therefore, m extent analysis values for each object can be obtained.

$$M^1_{g_i},M^2_{g_i},\dots,M^m_{g_i}, i = 1,2,\dots,n \quad \textbf{(5.2)}$$

where all $M^j_g (j = 1,2,\dots,m)$ are the triangular fuzzy numbers.

Step 1. Regarding the ith object, the value of fuzzy synthetic extent is defined as:

$$S_i \sum_{j=1}^{m} M^j_{g_i} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M^j_{g_i}\right]^{-1} \quad \textbf{(5.3)}$$

Obtaining $\sum\limits_{j=1}^{m} M^j_{g_i}$ the fuzzy addition operation of m extent analysis values for particular matrix is performed such as:

$$\sum_{j=1}^{m} M^j_{g_i} = \sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \quad \textbf{(5.4)}$$

The fuzzy addition operation of $M_g^j (j = 1, 2, \ldots, m)$ values is performed such as:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} = \sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \tag{5.5}$$

The inverse of the vector in Equation **5.3** is computed as;

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{5.6}$$

Step 2. The height of a fuzzy set $hgt(A)$ is the maximum of membership grades of A, $hgt(A) = \sup_{x \in X} \mu_A(x)$

The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as:

$$V(M_2 \geq M_1) = sup_{y \geq x}[min(\mu_{M_1}(x), \mu_{M_2}(y))]$$

and can be expressed as follows:

$$\text{V}(\text{M}_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1 & \text{if } m_2 \geq m_1, \\ 0 & \text{if } l_1 \geq u_2, \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise.} \end{cases}$$

Figure 5.8 illustrates d is the y-axis value of the highest intersection point D between μ_{M_1} and μ_{M_2}. Both $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ should be known for the comparison of M_1 and M_2.

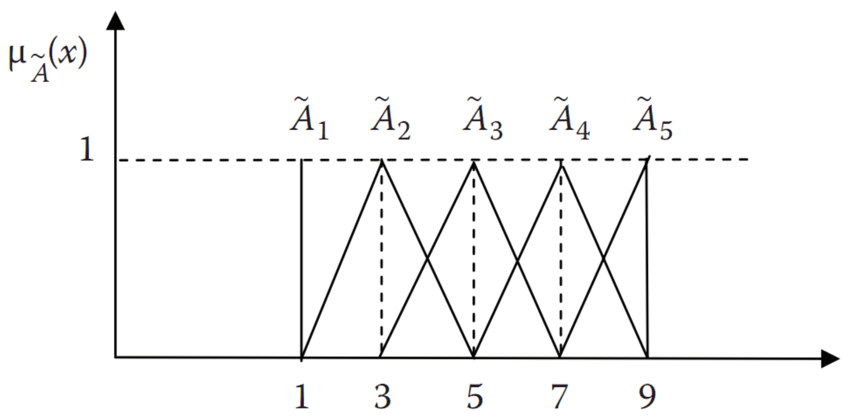


Figure 5.8: Fuzzy number of linguistic variable set.

Step 3. The degree possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i (i = 1, 2, \ldots, k)$ can be defined by

V(M $\geq M_1, M_2, \ldots, M_k) = V[M \geq M_1 and (M \geq M_2) and \ldots and (M \geq M_k)] = minV(M \geq M_i)$

Assume that $d'(A_i) = minV(S_i \geq S_k)$ for $k = 1,2,\ldots,n; k \neq i$.Then the weight vector is given by

$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T$

where $A_i(i = 1,2,\ldots,n)$ are n elements.

Step 4. Normalization and normalized weight vectors are:

$W = (d(A_1), d(A_2), \ldots, d(A_n))^T$

where W is a non-fuzzy number.

The non-numerical expressions as fuzzy linguistic variables, which help the decision maker to describe his/her pair-wise comparison of each criterion and alternatives, reflect the Saaty (1977)'s nine-point fundamental scale (Figure 5.8) [93].

Assign the linguistic comparison term and their equivalent fuzzy numbers considered in this chapter are shown in Table 5.4 [89, 94–97].

For the intended problem, individual aggregation matrix is conducted by expert prioritization, which is called lambda coefficient.

Let $A = (a_{ij})_{n\times n}$, where $a_{ij} > 0$ and $a_{ij} \times a_{ji} = 1$, be a judgment matrix. The prioritization method denotes to the process of acquiring a priority vector $w = (w_1, w_2, \ldots, w_n)^T$ where $w_i \geq 0$ and $\sum\limits_{i=1}^{n} w_i = 1$, from the judgment matrix A.

Let $D = \{d_1, d_2, \ldots, d_m\}$ be the set of experts, and $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_m\}$ be the weight vector of decision makers, where $\lambda_k > 0, k = 1,2,\ldots,m$ and $\sum\limits_{k=1}^{m} \lambda_k = 1$.

Let $E = e_1, e_2, \ldots, e_m$ be the set of the experience in professional career (in years for this chapter) for each expert, and λ_k for each expert is defined by

$$\lambda_k = \frac{e_k}{\sum\limits_{k=1}^{m} e_k} \tag{5.7}$$

Let $A(k) = (a_{ij}^{(k)})_{n\times n}$ be the judgment matrix which is gathered by the decision maker d_k. $w_i^{(w)}$ is the priority vector of criteria for each expert calculated by

$$w_i^{(k)} = \frac{(\prod_{j=1}^{n} a_{ij})^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} \quad \textbf{(5.8)}$$

The individual priority aggregation is defined by

$$w_i^{(w)} = \frac{(\prod_{k=1}^{m} (w_i^{(k)})^{\lambda_k}}{\sum_{i=1}^{n}\prod_{k=1}^{m}} \left(w_i^{(k)}\right)^{\lambda_k} \quad \textbf{(5.9)}$$

where $w_i^{(w)}$ is the aggregated weight vector. Then extent synthesis method is applied for consequent selection [92]. A pairwise comparison between alternatives i and j on criterion C is defined by

$$a_{ij}^{c} = \frac{A_r^i}{A_r^j} \quad \textbf{(5.10)}$$

Where A_r^i is the rank valuation set of alternative i. By the final consistency control, the procedure of GF-AHP is achieved. Consistency control and CCI for fuzzy-AHP applications are completed in the following section.

5.1.4 Centric consistency index (CCI)

According to the Saaty's approach, all decision makers' matrix should be consistent to analyse the selection problem [98]. For the consistency control of F-AHP method, centric consistency index (CCI) is used, which is based on geometric consistency index [99, 100]. The calculation of CCI algorithm is as follows;

$$CCI(A) = \frac{2}{(n-1)\cdot(n-2)}\sum_{i<j}\Big(\log(\frac{a_{Lij}+a_{Mij}+a_{Uij}}{3}) \\ -\log(\frac{w_{Li}+w_{Mi}+w_{Ui}}{3})+\log(\frac{w_{Lj}+w_{Mj}+w_{Uj}}{3})\Big)^2 \quad \textbf{(5.11)}$$

When CCI(A) is 0, A is fully consistent. Aguarón expresses the thresholds as $(\overline{GCI} = 0.31)$ for $n = 3$; $(\overline{GCI} = 0.35)$ for $n = 4$ and $(\overline{GCI} = 0.37)$ for $n > 4$. When $CCI < (\overline{GCI})$ that means this matrix is sufficiently consistent [100].

5.2 Case Study: Design Of The Model And Application For Track Selection

GF-AHP is a novel extended form of conventional methods of FAHP [101]. GF-AHP is applied to our intended problem because of its many novel contributions over traditional AHP methods. First, GF-AHP is able to execute uncertain consultations. Second, GF-AHP proposes a decision maker weighting algorithm to combine with the FAHP. Third, GF-AHP is improved for direct numerical inputs. Fourth, GF-AHP proposes a consistency check index method. GF-AHP procedure consists of these superiorities. Arrangement of the hierarchy is important in using GF-AHP. The determination of the objectives, criteria and alternatives are placed in a hierarchical structure (Figure 5.9).

By a pre-survey method, all criteria are determined. The main criteria such as the average route width (ARW), slot availability (S), maximum width along with the track (Max), minimum width along with the track (Min), ice concentration (IC), Route Length (RL), sea depth (SD) and sharp bend (SB) are decided concerning to analyse their impact on alternatives. Then the survey is applied to twelve decision makers (DM). Seven of them are master mariners, three of them are company representatives and two of them are academicians. Figure 5.10 shows the corresponding hierarchical design of the track selection problem.FAHP approach is employed in the determination of the weights of criteria and alternatives components of the decision hierarchies. In the application of the AHP approach, a pair-wise comparison table is formed.

As a first step in the application of the F-AHP approach, for the each criterion, weights and priorities are compared pair-wise using a fuzzy extension of Saaty's 1–9 scale (Table 5.4).

The F-AHP approach is applied to calculate weights of alternatives for each criterion (Table 5.5).

Table 5.6 shows the alternatives for the track selection and their symbols.

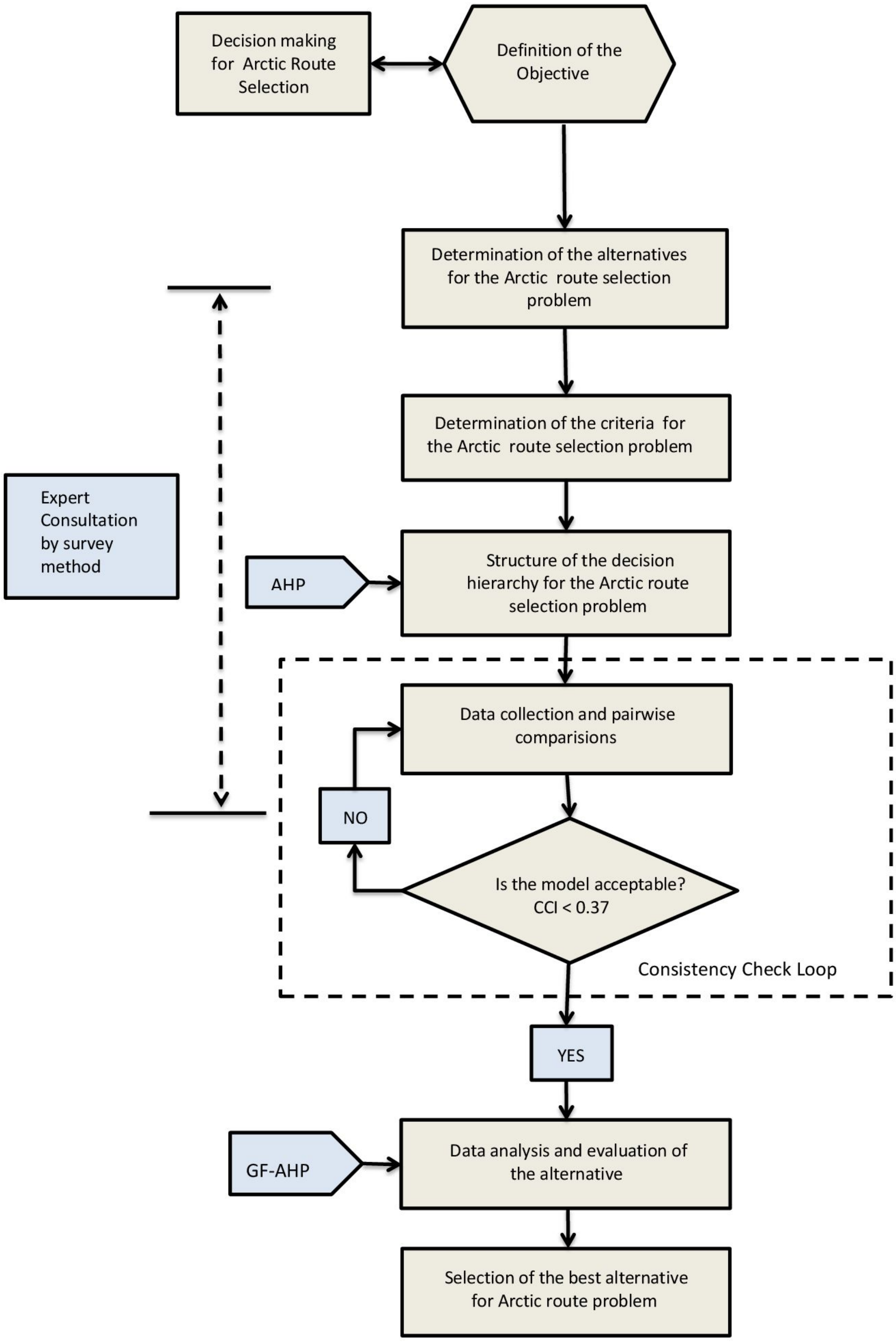


Figure 5.9: GF-AHP procedure.

For the decision process, pairwise comparison survey was conducted and reported as follows. The individual fuzzy judgment matrices, which assess criteria-to-criteria comparison, are presented in Table 5.7 and Table 5.8. Lambda (λ) is the expertise priority of the decision maker based on the time spent for this industry.

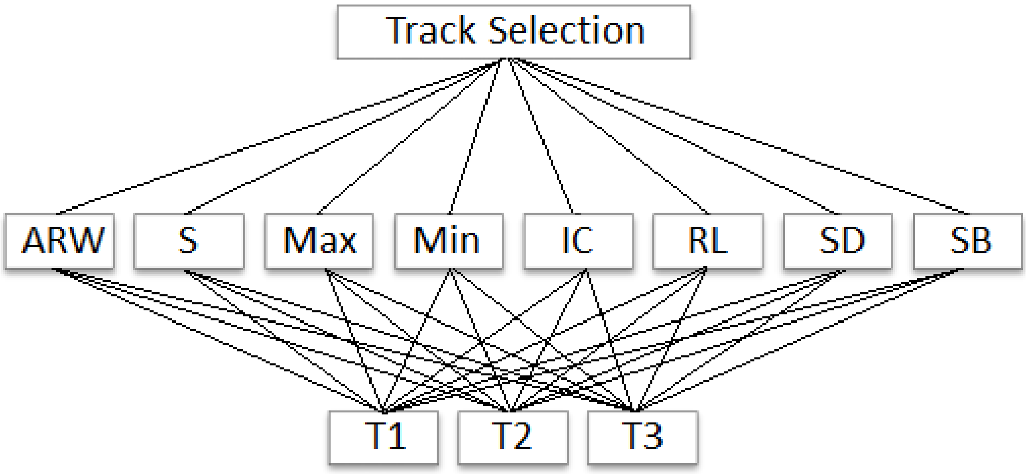


Figure 5.10: The hierarchy of the track selection process.

Table 5.4: Membership function of linguistic scale.

Fuzzy number	Linguistic scales	Membership function	Inverse
$\tilde{A}_1$	Equally Important	(1,1,1)	(1,1,1)
$\tilde{A}_2$	Moderately important	(1,3,5)	(1/5,1/3,1)
$\tilde{A}_3$	More Important	(3,5,7)	(1/7, 1/5, 1/5)
$\tilde{A}_4$	Strongly Important	(5,7,9)	(1/9, 1/7, 1/5)
$\tilde{A}_5$	Extremely Important	(7,9,9)	(1/9, 1/9, 1/7)

Table 5.5: The criteria for the model of track selection and their symbols.

Criteria	The symbols of each criterion
Average Route Width	*ARW*
SlotAvailability	*S*
MaximumWidth alongside the track	*Max*
MinimumWidth alongside the track	*Min*
IceConcentration	*IC*
TheRoute Length	*RL*
SeaDepth	*SD*
SharpBend	*SB*

Table 5.6: The alternatives for the model of track selection and their symbols.

Alternatives	The symbols of each alternatives
Track 1	*T1*
Track 2	*T2*
Track 3	*T3*

Table 5.9 shows the individual fuzzy priority vector and aggregated weight vector. Each DM usually finds that Average Route width (ARW) is the most important

Table 5.7: The individual fuzzy judgment matrix for criteria of track selection.

DM1	=0.04		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(3,5,7)	(5,7,9)	(3,5,7)	(1,3,5)	(1/5,1/3,1)	(1,3,5)	(1,3,5)
		S	(1/7,1/5,1/3)	(1,1,1)	(3,5,7)	(1,3,5)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		Max	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,3,5)	(1,3,5)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(1,3,5)	(1,3,5)
		RL	(1,3,5)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)
DM2	=0.16		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)	(1,1,1)	(1,1,1)	(1,3,5)
		S	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,1)	(1,1,1)	(1,3,5)
		Max	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1,1,1)	(1,3,5)	(1,1,1)	(1,1,1)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)
		RL	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)
		SD	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)
DM3	=0.08		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,3,5)	(3,5,7)	(5,7,9)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		S	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		Max	(1/7,1/5,1/3)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		Min	(1/9,1/7,1/5)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)
		RL	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)
DM4	=0.09		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,3,5)	(3,5,7)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		S	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(3,5,7)	(1,3,5)	(1,3,5)
		Max	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)
		RL	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)
DM5	=0.09		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(3,5,7)	(1,3,5)	(1,3,5)
		S	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		Max	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)
		RL	(1/7,1/5,1/3)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)
DM6	=0.05		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(3,5,7)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		S	(1/7,1/5,1/3)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		Max	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
		RL	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)

factor with its 0.34 value (midpoint) and the Slot availability (S) is the second crucial indicator (0.27). Other aggregated weight coefficients contribute the final outcome are 0.18, 0.17, 0.11, 0.10, 0.07 The mean aggregated weight (MAW) is calculated for each criterion as 0.27, 0.22, 0.09, 0.16, 0.10, 0.15, 0.10 and 0.07 respectively (Table 5.10). The aggregated weight vector is computed by the expert priority vector of DMs (λ) and the individual priority vector of each DM. The result is consistent since the CCI is 0.01 less than the threshold of 0.37. The extent synthesis is performed for the route selection problem as follows:

Table 5.8: (Continued) The individual fuzzy judgment matrix for criteria of track selection.

DM7	=0.09		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(3,5,7)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		S	(1/7,1/5,1/3)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		Max	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
		RL	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)
DM8	=0.08		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		S	(1,1,1)	(1,1,1)	(3,5,7)	(1,3,5)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		Max	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1,1,1)	(1,1,1)
		RL	(1,1,1)	(1,1,1)	(3,5,7)	(1,1,1)	(3,5,7)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)
DM9	=0.08		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(3,5,7)	(1,3,5)	(1,3,5)
		S	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		Max	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/7,1/5,1/3)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)
		RL	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)
DM10	=0.08		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		S	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(3,5,7)
		Max	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)
		RL	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(7,9,9)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(1/5,1/3,1)	(1,3,5)	(1/9,1/9,1)	(1/5,1/3,1)	(1,1,1)
DM11	=0.08		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		S	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		Max	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,1,1)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)
		RL	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)
DM12	=0.08		ARW	S	Max	Min	IC	RL	SD	SB
		ARW	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,1)
		S	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,1)
		Max	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,1,1)
		Min	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
		IC	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)
		RL	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1,3,5)
		SD	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1,3,5)
		SB	(1,1,1)	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)

Table 5.9: The individual fuzzy priority vector of decision-makers and aggregated weight vector for criteria of track selection.

	ARW	S	Max	Min	IC	RL	SD	SB
DM1	(0.24,0.25,0.25)	(0.17,0.18,0.16)	(0.06,0.05,0.06)	(0.12,0.11,0.10)	(0.12,0.11,0.12)	(0.18,0.20,0.17)	(0.07,0.06,0.08)	(0.05,0.04,0.06)
DM2	(0.16,0.20,0.19)	(0.13,0.17,0.19)	(0.11,0.09,0.09)	(0.13,0.14,0.16)	(0.09,0.09,0.10)	(0.16,0.13,0.10)	(0.16,0.12,0.08)	(0.05,0.05,0.08)
DM3	(0.26,0.32,0.30)	(0.15,0.13,0.12)	(0.15,0.14,0.13)	(0.14,0.14,0.12)	(0.08,0.08,0.10)	(0.10,0.09,0.10)	(0.07,0.06,0.08)	(0.05,0.04,0.06)
DM4	(0.23,0.28,0.26)	(0.19,0.21,0.21)	(0.13,0.12,0.12)	(0.11,0.10,0.11)	(0.09,0.08,0.09)	(0.13,0.09,0.08)	(0.06,0.07,0.07)	(0.05,0.04,0.06)
DM5	(0.22,0.30,0.29)	(0.16,0.18,0.18)	(0.13,0.08,0.07)	(0.13,0.12,0.12)	(0.07,0.05,0.07)	(0.15,0.13,0.11)	(0.08,0.07,0.08)	(0.07,0.06,0.08)
DM6	(0.22,0.29,0.29)	(0.15,0.20,0.20)	(0.13,0.08,0.07)	(0.13,0.12,0.12)	(0.10,0.07,0.07)	(0.13,0.11,0.10)	(0.07,0.08,0.08)	(0.07,0.05,0.07)
DM7	(0.23,0.29,0.27)	(0.16,0.19,0.18)	(0.05,0.03,0.05)	(0.15,0.14,0.15)	(0.13,0.08,0.08)	(0.14,0.12,0.12)	(0.07,0.08,0.08)	(0.07,0.06,0.08)
DM8	(0.18,0.21,0.19)	(0.20,0.22,0.20)	(0.04,0.03,0.05)	(0.12,0.14,0.15)	(0.09,0.07,0.08)	(0.23,0.20,0.17)	(0.08,0.07,0.08)	(0.06,0.06,0.08)
DM9	(0.23,0.25,0.22)	(0.20,0.23,0.21)	(0.04,0.03,0.05)	(0.15,0.14,0.15)	(0.09,0.07,0.08)	(0.23,0.20,0.17)	(0.08,0.07,0.08)	(0.06,0.06,0.08)
DM10	(0.19,0.24,0.23)	(0.21,0.25,0.24)	(0.12,0.08,0.07)	(0.12,0.12,0.13)	(0.07,0.05,0.07)	(0.16,0.12,0.11)	(0.07,0.09,0.10)	(0.06,0.05,0.06)
DM11	(0.20,0.25,0.22)	(0.20,0.21,0.18)	(0.13,0.11,0.10)	(0.13,0.12,0.12)	(0.09,0.09,0.12)	(0.13,0.11,0.10)	(0.07,0.06,0.08)	(0.06,0.05,0.07)
DM12	(0.21,0.21,0.18)	(0.21,0.21,0.18)	(0.07,0.05,0.06)	(0.16,0.17,0.18)	(0.11,0.12,0.14)	(0.09,0.09,0.12)	(0.06,0.07,0.08)	(0.09,0.06,0.06)
Agg. Weight	(0.21,0.34,0.32)	(0.18,0.27,0.26)	(0.09,0.10,0.10)	(0.14,0.18,0.19)	(0.09,0.11,0.13)	(0.14,0.17,0.15)	(0.08,0.11,0.11)	(0.06,0.07,0.10)

Table 5.10: The aggregated fuzzy judgment matrix for criteria of track selection.

	ARW	S	Max	Min	IC	RL	SD	SB	MAW
ARW	(1.00,1.00,1.00)	(0.22,2.14,2.82)	(1.29,2.85,4.20)	(1.19,3.27,5.31)	(1.00,3.00,5.00)	(1.13,2.31,3.39)	(1.00,2.52,3.88)	(1.00,2.75,4.40)	0.27
S	(0.35,0.47,0.82)	(1.00,1.00,1.00)	(0.14,2.92,4.58)	(1.00,2.75,4.40)	(1.00,3.00,5.00)	(1.11,1.76,2.21)	(1.00,2.52,3.88)	(1.09,2.86,4.52)	0.22
Max	(0.24,0.35,0.78)	(0.22,0.34,0.88)	(1.00,1.00,1.00)	(0.37,0.50,0.74)	(0.51,0.79,1.19)	(0.54,0.70,1.04)	(0.67,1.04,1.59)	(0.65,1.09,1.66)	0.09
Min	(0.19,0.31,0.84)	(0.23,0.36,1.00)	(1.35,1.98,2.68)	(1.00,1.00,1.00)	(1.00,2.87,4.69)	(1.00,1.19,1.29)	(1.00,2.52,3.88)	(1.00,3.00,5.00)	0.16
IC	(0.20,0.33,1.00)	(0.20,0.33,1.00)	(0.84,1.27,1.94)	(0.21,0.35,1.00)	(1.00,1.00,1.00)	(0.61,0.83,1.18)	(0.88,1.37,1.81)	(0.76,1.48,2.33)	0.10
RL	(0.29,0.43,0.88)	(0.45,0.57,0.90)	(0.96,1.43,1.86)	(0.78,0.84,1.00)	(0.85,1.20,1.64)	(1.00,1.00,1.00)	(1.00,2.52,3.88)	(1.17,3.27,5.24)	0.15
SD	(0.26,0.40,1.00)	(0.26,0.40,1.00)	(0.45,1.76,0.90)	(0.26,0.40,1.00)	(0.55,0.73,1.14)	(0.26,0.40,1.00)	(1.00,1.00,1.00)	(1.00,2.52,3.88)	0.10
SB	(0.23,0.36,1.00)	(0.22,0.35,0.92)	(0.60,0.91,1.54)	(0.20,0.33,1.00)	(0.43,0.68,1.32)	(0.19,0.31,0.86)	(0.26,0.40,1.00)	(1.00,1.00,1.00)	0.07

CCI=0.01

$S_{ARW} = (8.81, 19.81, 30.01) \otimes (1/45.84, 1/86.31, 1/132.89) = (0.07, 0.23, 0.65)$

$S_S = (7.68, 17.28, 26.41) \otimes (1/52.64, 1/100.22, 1/153.81) = (0.06, 0.20, 0.58)$

$S_{MAX} = (4.20, 5.82, 8.88) \otimes (1/52.64, 1/100.22, 1/153.81) = (0.03, 0.07, 0.19)$

$S_{MIN} = (6.77, 13.24, 20.38) \otimes (1/52.64, 1/100.22, 1/153.81) = (0.05, 0.15, 0.44)$

$S_{IC} = (4.71, 6.97, 11.27) \otimes (1/52.64, 1/100.22, 1/153.81) = (0.04, 0.08, 0.25)$

$S_{RL} = (6.49, 11.26, 16.40) \otimes (1/52.64, 1/100.22, 1/153.81) = (0.05, 0.13, 0.36)$

$S_{SD} = (4.04, 7.59, 10.93) \otimes (1/52.64, 1/100.22, 1/153.81) = (0.03, 0.09, 0.24)$

$S_B = (3.13, 4.34, 8.63) \otimes (1/52.64, 1/100.22, 1/153.81) = (0.02, 0.05, 0.19)$

$V(S_{ARW} \geq S_S) = V(S_{ARW} \geq S_{MAX}) = V(S_{ARW} \geq S_{MIN}) = V(S_{ARW} \geq S_{IC}) = V(S_{ARW} \geq S_{RL}) = V(S_{ARW} \geq S_{SD}) = V(S_{ARW} \geq S_B) = 1$

$V(S_S \geq S_{ARW}) = V(S_S \geq S_{MIN}) = V(S_S \geq S_{IC}) = V(S_S \geq S_{RL}) = V(S_S \geq S_{SD}) = V(S_S \geq S_B) = 1$

$V(S_S \geq S_{MAX}) = (0.07 - 0.23)/(0.20 - 0.58) - (0.23 - 0.07) = 0.95$

$V(S_{MAX} \geq S_{ARW}) = 0.47, V(S_{MAX} \geq S_S) = 0.52, V(S_{MAX} \geq S_{MIN}) = 0.63, V(S_{MAX} \geq S_{IC}) = 0.92$

$V(S_{MAX} \geq S_{RL}) = 0.69, V(S_{MAX} \geq S_{SD}) = 0.91, V(S_{MAX} \geq S_B) = 1$

$V(S_{MIN} \geq S_{ARW}) = 0.86, V(S_{MIN} \geq S_S) = 0.91, V(S_{MIN} \geq S_{MAX}) = V(S_{MIN} \geq S_{IC}) = V(S_{MIN} \geq S_{RL}) = V(S_{MIN} \geq S_{SD}) = V(SS \geq S_B) = 1$

$V(S_{IC} \geq S_{ARW}) = 0.57, V(S_{IC} \geq S_S) = 0.63, V(S_{IC} \geq S_{MAX}) = 0.73, V(S_{IC} \geq S_{MIN}) = 0.73, V(S_{IC} \geq S_{RL}) = 0.79, V(S_{IC} \geq S_{SD}) = 0.99, V(S_{IC} \geq S_B) = 1$

$V(S_{RL} \geq S_{ARW}) = 0.79, V(S_{RL} \geq S_S) = 0.85, V(S_{RL} \geq S_{MAX}) = 0.94, V(S_{RL} \geq S_{MIN}) = 0.94, V(S_{RL} \geq S_{IC}) = V(S_{RL} \geq S_{SD}) = V(S_{RL} \geq S_B) = 1$

$V(S_{SD} \geq S_{ARW}) = 0.54, V(S_{SD} \geq S_S) = 0.60, V(S_{SD} \geq S_{MAX}) = 0.71, V(S_{SD} \geq S_{MIN}) = 0.71, V(S_{SD} \geq S_{IC}) = 1, V(SSD \geq S_{RL}) = 0.77, V(S_{SD} \geq S_B) = 1$

$V(S_B \geq S_{ARW}) = 0.40, V(S_B \geq S_S) = 0.46, V(S_B \geq S_{MAX}) = 0.55, V(S_B \geq S_{MIN}) = 0.55, V(S_B \geq S_{IC}) = 0.80, V(S_B \geq S_{RL}) = 0.60, V(S_B \geq S_{SD}) = 0.80$

Calculation of the priority weights for criteria is completed by using Eq. 7:

$d'(ARW) = min(1,1,1,1,1,1,1) = 1$

$d'(S) = min(0.95,1,1,1,1,1,1) = 0.95$

$d'(Max) = min(0.47,0.52,0.63,0.92,0.69,0.91,1) = 0.47$

$d'(Min) = min(0.86,0.91,1,1,1,1,1) = 0.86$

$d'(IC) = min(0.57,0.63,0.73,0.73,0.79,0.99,1) = 0.79$

$d'(RL) = min(0.79,0.85,0.94,0.94,1,1,1) = 0.79$

$d'(SD) = min(0.54,0.60,0.71,0.71,1,0.77,1) = 0.54$

$d'(B) = min(0.40,0.46,0.55,0.55,0.80,0.60,0.80) = 0.40$

If it is normalized, the priority weight is computed as

$d(C) = (0.18,0.17,0.08,0.15,0.10,0.14,0.10,0.07)$

Table 5.11: The aggregated fuzzy judgment matrix for alternatives of track selection under each criterion.

Criteria			T1	T2	T3	MAW
	ARW	T1	(1, 1, 1)	(0.34,0.69,1.70)	(0.18,0.25,0.39)	0.14
		T2	(0.59,1.46,2.94)	(1, 1, 1)	(0.19,0.31,0.88)	0.27
		T3	(2.56,4.04,5.56)	(1.14,3.21,5.24)	(1, 1, 1)	0.59
GCI=0.31						
			T1	T2	T3	MAW
	Slot	T1	(1, 1, 1)	(1,1,1)	(0.23,0.39,1.06)	0.22
		T2	(1,1,1)	(1, 1, 1)	(0.33,0.47,1)	0.22
		T3	(0.94,2.55,4.43)	(1,2.12,3.01)	(1,1,1)	0.56
GCI=0.13						
			T1	T2	T3	MAW
	Max	T1	(1, 1, 1)	(0.94,0.96, 1)	(0.30,0.49,0.98)	0.18
		T2	(1,1.04,1.07)	(1,1,1)	(0.32,0.43,0.66)	0.13
		T3	(1.02,2.06,3.29)	(1.53,2.33,3.15)	(1,1,1)	0.69
GCI=0.18						
			T1	T2	T3	MAW
	Min	T1	(1,1,1)	(0.39,0.52,0.82)	(0.40,0.70,1.10)	0.20
		T2	(1.22,1.91,2.59)	(1,1,1)	(0.65,0.79,0.98)	0.40
		T3	(0.91,1.44,2.50)	(1.03,1.27,1.54)	(1,1,1)	0.40
GCI=0.09						
			T1	T2	T3	MAW
	IC	T1	(1,1,1)	(0.59,1.46,2.33)	(0.19,0.31,0.46)	0.21
		T2	(0.43,0.69,1.68)	(1,1,1)	(0.22,0.37,0.55)	0.13
		T3	(2.15,3.23,5.14)	(1.81,2.68,4.50)	(1,1,1)	0.65
GCI=0.07						
			T1	T2	T3	MAW
	RL	T1	(1,1,1)	(1,3,5)	(1.75,3.62,5.22)	0.47
		T2	(1.22,1.91,2.59)	(1,1,1)	(1,1.09,1.14)	0.26
		T3	(0.91,1.44,2.50)	(1.03,1.27,1.54)	(1,1,1)	0.27
GCI=0.08						
			T1	T2	T3	MAW
	SD	T1	(1,1,1)	(0.41,0.61,1.04)	(0.39,0.51,0.77)	0.18
		T2	(0.97,1.64,2.43)	(1,1,1)	(0.59,0.92,1.28)	0.39
		T3	(1.30,1.95,2.59)	(0.78,1.09,1.68)	(1,1,1)	0.44
GCI=0.04						
			T1	T2	T3	MAW
	SB	T1	(1,1,1)	(0.31,0.51,1.36)	(1,1,1)	0.26
		T2	(0.74,1.96,3.26)	(1,1,1)	(1,1.11,1.16)	0.48
		T3	(1,1,1)	(0.86,0.90,1.00)	(1,1,1)	0.26
GCI=0.33						

Table 5.12: Final assessment of alternatives of track selection.

	ARW	S	Max	Min	IC	RL	SD	SB	Alternative priority weight
Weight	0.18	0.17	0.08	0.15	0.10	0.14	0.10	0.07	
T1	0.14	0.22	0.18	0.20	0.21	0.47	0.18	0.26	0.23
T2	0.27	0.22	0.13	0.40	0.13	0.26	0.39	0.48	0.28
T3	0.59	0.56	0.69	0.40	0.65	0.27	0.44	0.26	0.49*

*selected alternative

Then, similar steps are followed for alternatives. Table 5.11 indicates the aggregated fuzzy judgment matrix under each criterion, which is calculated from the decision makers' individual fuzzy judgment matrices.

Table 5.12 presents the final outputs of the route selection problem. Track 3 is found to be the most feasible route by the AHP expert consultation. Superiority of the selected route is quite explicit since the difference between the first and second selection is 0.26. The results exposed an opposite ranking rather than the traditional expectations. The shortest sea route (track 1) is the last optimum while the longest route (track 3) is the best among three alternatives. It is clear that the shortest navigational route does not guarantee the safety of navigation.

6. CONCLUSIONS

Logistics and oil/gas companies interest Arctic region because of its shorter routes comparing to the conventional Suez Canal route. Accordingly, marine traffic (especially number of tankers) increases in this region. Therefore, a comprehensive risk assessment for ice navigation in the Arctic region is examined. The novelty of first chapter is that the risk levels of ice navigation in the polar regions are determined by using improved fuzzy analytical hierarchy process (IF-AHP) approach. In order to get the numerical risk levels of each risk factors, expert consultations are conducted. Total number of 79 risk criteria under 6 risk factors are asked to field experts in order to find relative weights of each criterion. By using the MATLAB software, the algorithm of IF-AHP is performed.

As a result of this application, the risk levels for the B layer is obtained as follows: Risks on cargo, fuel and related handling equipment (B5-0.1638), external risk factors (B1-0.1591) and risk factors related to structural design and arrangement of equipment locations (B2-0.1591), risk factors related to technical faults in vessel equipment (B3-0.1379), risks based on the usage and arrangements of the equipment on-board for operation process (B4-0.1340), communication, organizational, operational instruction faults and routine failures (B6-0.1302), human factors, interpretation, awareness assessment of situation, etc. (B7-0.1160). The risk levels for the third layer is obtained as for B1, explosion or external conditions related to the oil drill, for B2, other conditions (i.e. shell plating, frames, ice stringers, web frames, bow, stern, bilge keels) related to vessel construction or maintenance (i.e. rudder and steering arrangements, propeller, shafts and gears, miscellaneous machinery requirements), for B3, Technical fault in sophisticated electronic navigation equipment (such as radar, sonar, and the visible, infrared, and microwave radiation sensors onboard satellites) for B4, faults in ergonomics, design and operation of the device, human-machine interface problems for B5, leakages in cargo or fuel pipes/hoses for B6, familiarity with safety instructions, but no implementation and for B7, inappropriate design of task or operation such as cargo, night navigation, route planning, anchoring etc. are found as they have more heavily weight. These results indicate that more regulations or enforcement for the existing codes are required to eliminate the risks. Risk assessment for the polar regions is aimed to provide a guide for representatives to take corresponding measures to avoid such risks.

Due to the marine accidents can lead unwanted consequences, analyses to understand root causes must begin by understanding the risks. The risk analysis presents a perspective for both marine accidents and route selection problem. By considering the risks in a holistic perspective, a marine accident analysis for polar regions is carried out in the fourth chapter. The related risks and hazards that cause collision and grounding are determined then the relationships are established. A fuzzy fault tree approach is conducted for collision and grounding occurring in the polar regions wherein the objective is to minimize the risk of re-occurrence by identifying the critical minimal cut sets in the system. Novelty of the fourth chapter is that classification of the causes for each accidents occur in the polar regions is conducted after logical relations are established. The structures of fault trees for grounding and collision are constructed, by using linguistic variables, the ambiguities are handled and occurrence probabilities of hazards are determined. In order to remove the vagueness nature of the system, instead of using crisp failure possibilities, failure probability is preferred to determine the numerical risk levels of each causes after completing several expert consultations. Safety performance of a system can be improved by using the importance measure therefore, fussell vesely measure index is determined to identify the critical minimal cut sets in order to reduce the occurrence likelihood of a top event. Failure probability for collision and grounding are 0.004 and 0.008 respectively. According to data of AMSA database, the results are convenient comparing to real cases.

The fifth chapter deals with a route selection problem in ice-covered waters, which is carried out in an uncertain environment. There might always have trade-offs between the route selection criteria. Ice-state risks for the route selection problem are identified by considering the all probable risks and the risks related to collision and grounding. In the traditional approach, the shortest sea route is usually preferred since the cost aversion drives decision makers especially for the ice navigation because of less time spending in ice. On the other hand, safety of route is a subjective factor which cannot be directly measured and evaluated. By using the generic fuzzy analytical hierarchy method, the safety risk is indirectly embedded into the decision making process by consulting with experts. Navigational safety in the polar regions is mostly related with the dimensional limitations of route. The results indicate that the safety is more significant than length of the route. Therefore, a shorter route does not guarantee that the route is safer.

All vessels in ice-covered waters should be equipped adequately. Especially characteristics of pipelines and hoses are required to be strong enough and elastic in order to stand for probable minimum temperatures. Polar class vessels should be revised based the risks given in this study. Marine threat monitoring systems and forecast models for potential obstacles should be developed for ice-covered waters. By considering the risks of cargo, fuel and related handling equipment and B2-9 new design vessels should be constructed. Only polar class ships, based on IACS Unified Requirements for Polar Class Ships, should operate in polar waters or another similar alternative standard. Satellite integrated alternative route selection problems should be dealt with in a dynamic environment including weather conditions. Probabilistic models considering the future traffic congestion should be studied for analysing the probable marine accidents. Infrastructure problems such as inadequate numbers of icebreakers, etc. should be solved. New vessel traffic services are required for ice-covered waters. A new chapter based on ice navigation might be added to COLREGs.

For further studies, risk management tools for the polar regions can be generated by considering the results of this thesis. Fault Tree Analysis for the other ice-navigation-related failures such as icing, stuck in ice, machinery failures and similar accidents are the research gaps to be developed for the polar regions. Finally, optimization of route selection problem in ice-covered waters can be generated in a dynamic environment.

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APPENDICES

APPENDIX A : The sample MATLAB codes for IF-AHP algorithm.

APPENDIX B : The Main Data Sources For Marine Accidents.

APPENDIX C : Fault Trees of Collision and Grounding.

APPENDIX D : Statistics of Marine Accidents based on MAIB report.

APPENDIX E : Incidents recorded by MAIB as occurring North of 66° 33’ 1993 to 2011: A two page sample report of MAIB and statistical data of Arctic marine accidents based on MAIB report.

APPENDIX A

Algorithm of IFAHP Method

```
function iahp
clear ; clc ;
e=0.0001
Max=20
F=[0.5 0.6 0.4 0.7 0.7 0.5 0.5
   0.4 0.5 0.8 0.6 0.4 0.6 0.6
   0.6 0.2 0.5 0.7 0.3 0.5 0.6
   0.3 0.4 0.3 0.5 0.5 0.7 0.6
   0.3 0.6 0.7 0.5 0.5 0.7 0.7
   0.5 0.4 0.5 0.3 0.3 0.5 0.7
   0.5 0.4 0.4 0.4 0.3 0.3 0.5 ]
% To compute the fuzzy consistent matrix
N= size( F ) %  nxn matrix
r=sum(F') % sum of transpose
for i=1:N(1)
    for j=1:N(2)
R(i , j)=(r(i)-r(j))/(2*N(1))+0.5
end
end

E = R./R'

% To compute the initial vector
U=sum(R') / sum(sum(R) )
V(: ,1)=U'/max( abs (U) )

for i=1:Max

V(: , i+1)=E*V(: , i )
V(:,i+1)=V(:,i+1)/max(abs(V(:,i+1)))
if max( abs (V(: , i+1)-V( : , i ))) <e
k=i
W=V(: , i +1)./sum(V(: , i +1))
break
else
end
end
end
```

APPENDIX B

The Main Data Sources For Marine Accidents

Global Integrated Shipping Information System (GISIS)
IMO MSC-MEPC.3/Circ.3
IMO FSI 20/INF.17
FSI and IMO Council documents on IMODOCS
IMO Performance Indicators
International Shipping Facts and Figures - Information Resources on Trade, Safety, Security and the Environment
Lloyd's Casualty Returns available from Lloyd's Register Library
LMIU Casualty Reports
IHS Fairplay World Casualty Statistics
International Union of Marine Insurers (IUMI)
European Maritime Safety Agency: Annual Maritime Accident Review
ShipPax Information
Marine Casualty Profiles International Maritime Statistics Forum
Wally Mandryk Lloyd's List Intelligence
Australian Transport Safety Bureau (ATSB)
Transportation Safety Board of Canada (TSBC)
BEAmer- The Bureau d'enquêtes sur les événements de mer
Dutch Transport Safety Board
Transport Accident Investigation Commission (TAIC)
Swedish Accident Investigation Board (SHK)
UK Marine Accident Investigation Branch (MAIB)
Marine Accident Reporting Scheme (MARS)
US National Transportation Safety Board (NTSB)

APPENDIX C

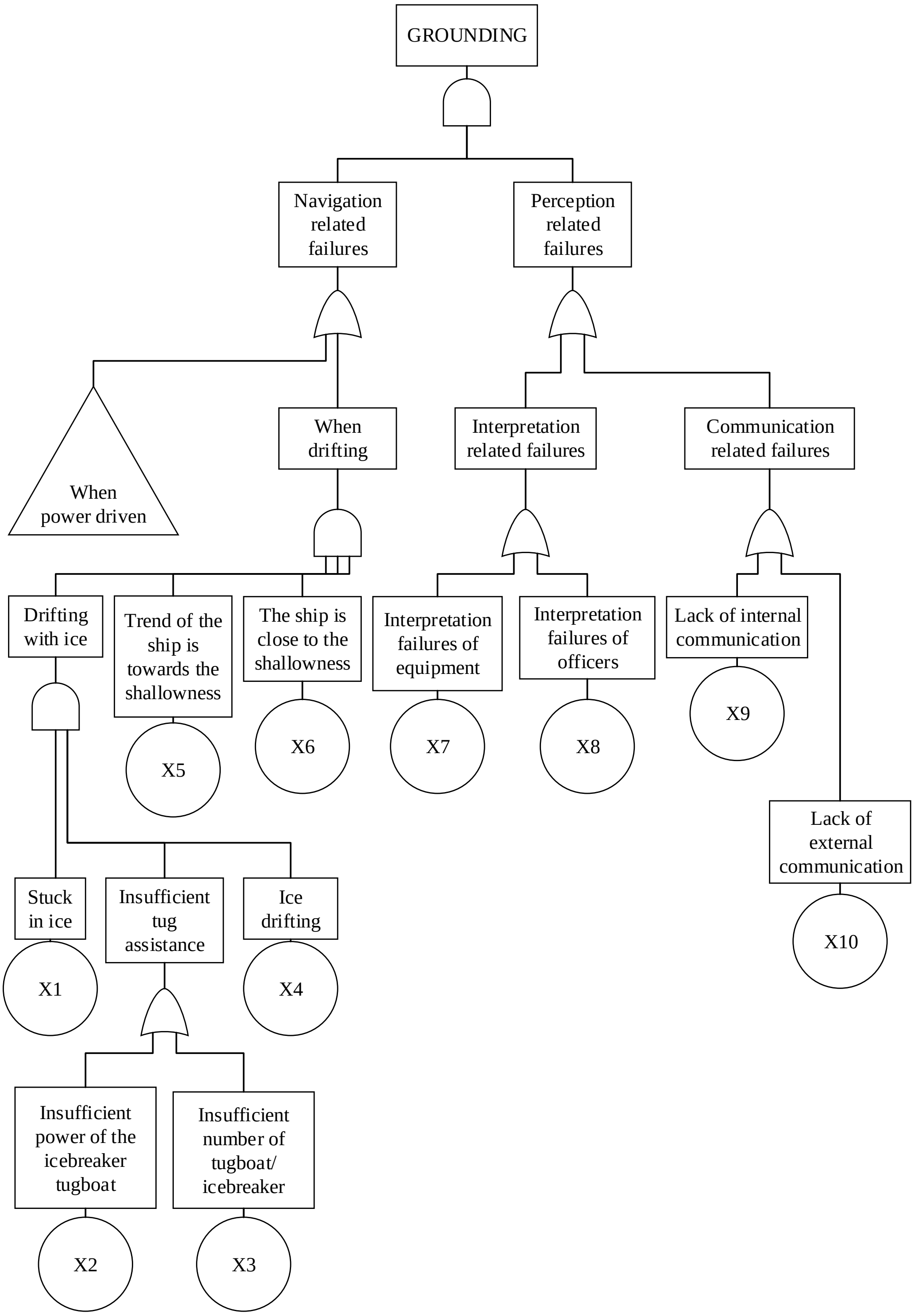

Figure C.1: Fault tree of grounding

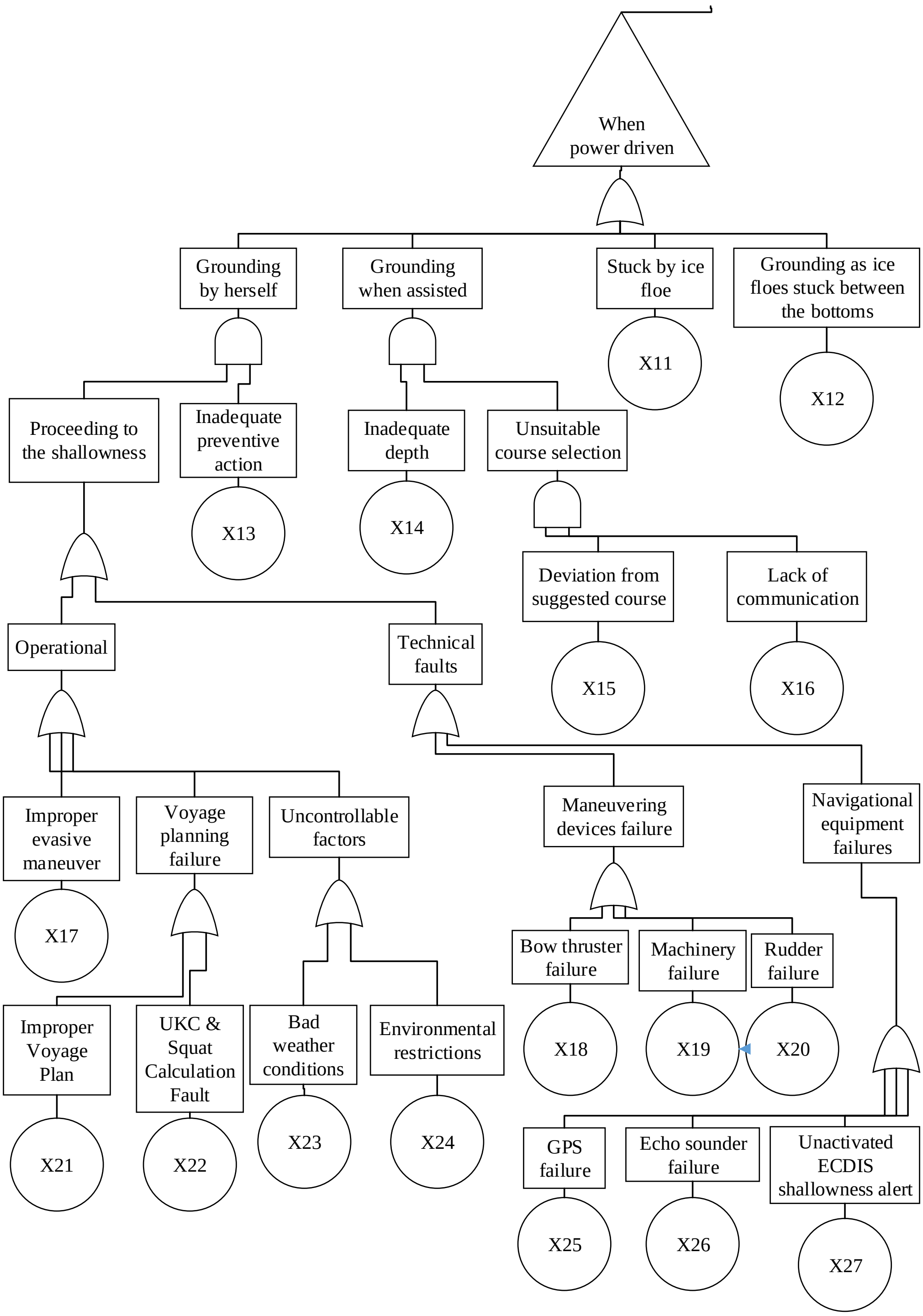

Figure C.2: Transfer fault tree of grounding when power driven

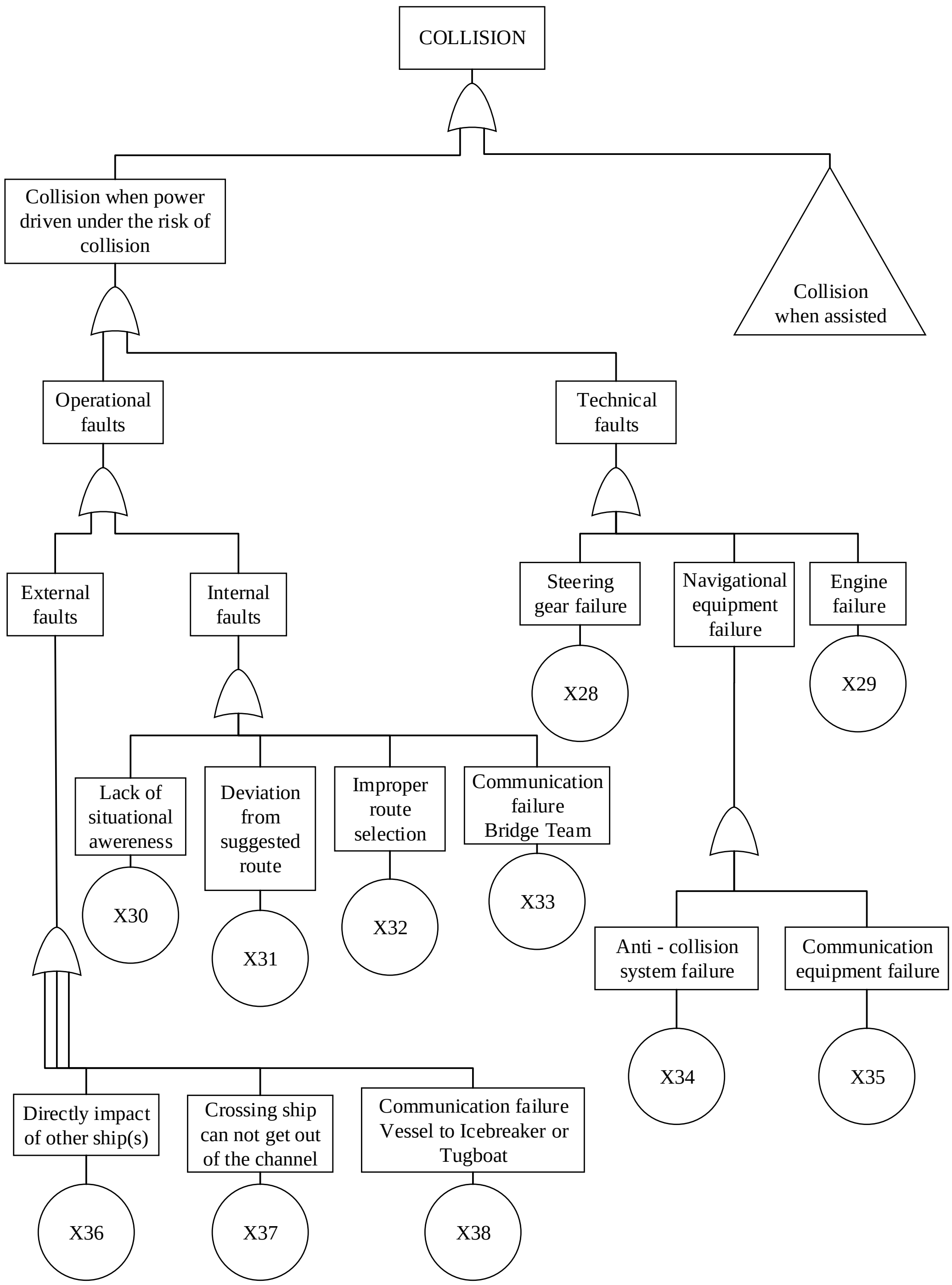

Figure C.3: Fault tree of collision

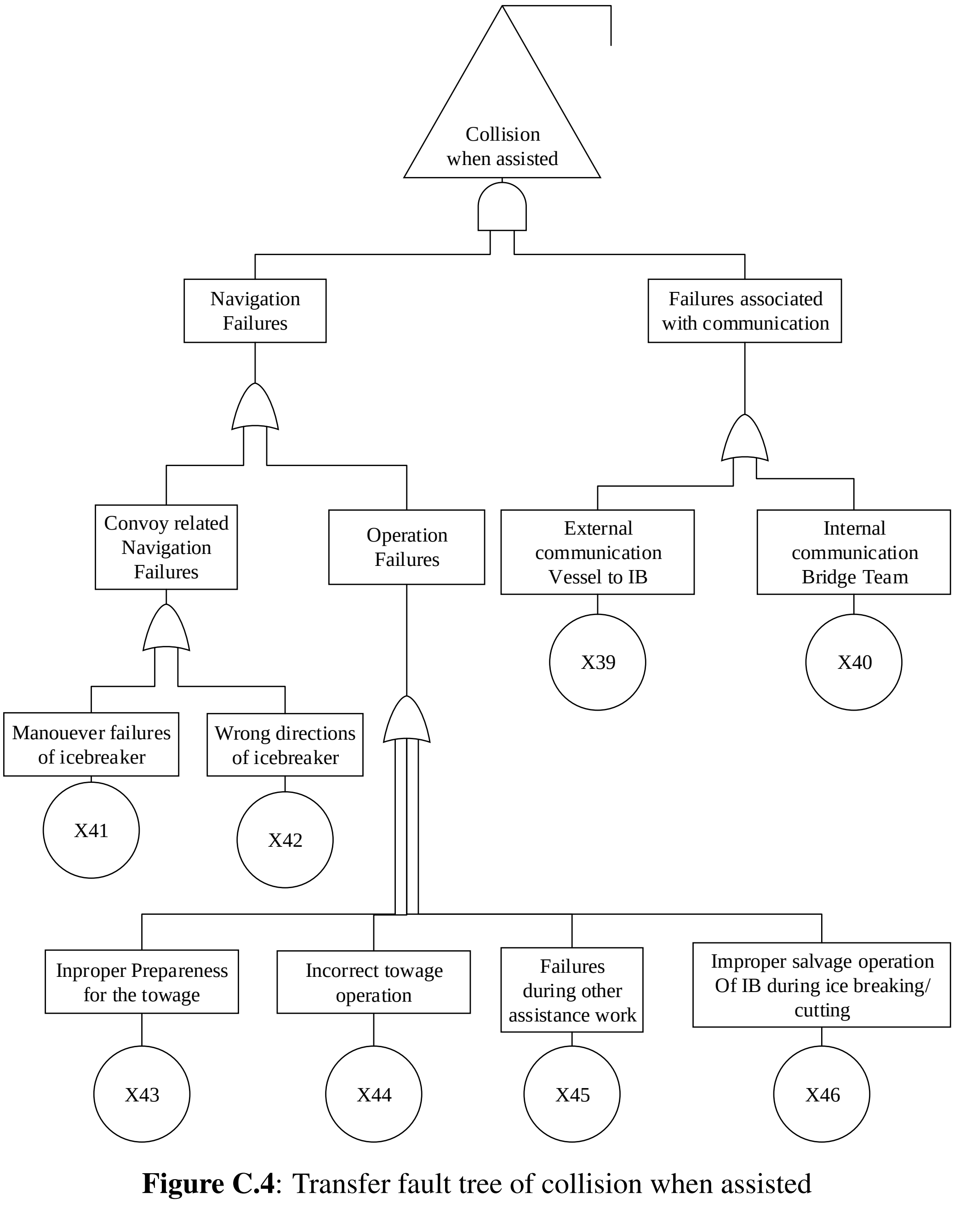

Figure C.4: Transfer fault tree of collision when assisted

APPENDIX D

Table D.1: Distribution of vessel types to the countries

Vessel Types	Denmark	Canada	Russian Federation	Greenland	Iceland	USA	Norway
Container	8	-	2	5	19	-	-
Tug/Barge	-	10	-	-	3	9	-
Bulk carrier	5	15	23	6	2	14	68
General Cargo	83	9	14	11	74	-	28
Passenger	33	6		36	41	2	46
Tanker	10	7	12	5	29	1	12
Government	-	12	7	16	28	16	-
Fishing	2	27	-	-	152	335	-
Oil/Gas service	-	2	-	1	-	-	-
Pleasure Craft	-	1	-	1	3	-	-
Research	-	-	-	-	-	-	3
Total:	141	89	58	81	351	377	157

Table D.2: Accident types

Contributor to accidents	Number of accidents	Percentage
Accident to Person	50	76.92
Collisions and contacts	4	6.15
Grounding	4	6.15
Machinery Failure	3	4.62
Flooding and Foundering	2	3.08
Fires and explosions	2	3.08
Capsizing and listing	0	0.00
Total	65	100

Table D.3: Number of incidents, deaths and injuries for the vessel types for 19-year period

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Number of Incidents																			
Fish Catching, Processing/Trawlers	1		1	3	1	5	7	2			1	1		4	1	3			
Passenger /Cruise Ship					1	2	1	3	4		2	1	1	2	1	2	1		2
Passenger Ro-Ro Vehicle/Passenger Ferry								1											
Survey/Research						1													2
Port Service/Tug							1												
Commercial/Offshore Supply						1												1	
Commercial/Drilling						1												1	
Commercial/Naval support, RFA										1									
Dry Cargo Reefer													1						
Small Sail Training Vessels										1									
Non-Commercial /Pleasure craft								1											
Tanker/combination carrier														1					
	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Number of Deaths																			
Fish Catching, Processing/Trawlers						1													
Passenger /Cruise Ship																			1
Passenger Ro-Ro Vehicle/Passenger Ferry																			
Survey/Research																			1
Port Service/Tug																			
Commercial/Offshore Supply																		1	
Commercial/Drilling																			
Commercial/Naval support, RFA										1									
Dry Cargo Reefer																			
Small Sail Training Vessels										1									
Non-Commercial /Pleasure craft																			
Tanker/combination carrier																			
	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Number of Injuries																			
Fish Catching, Processing/Trawlers	1		3	2	1	3	6	1			1	1		3	1	4			
Passenger /Cruise Ship					1	2	1	3	3		2	1	1	1	1	1	1		1
Passenger Ro-Ro Vehicle/Passenger Ferry																			
Survey/Research																			1
Port Service/Tug							1												
Commercial/Offshore Supply						1													
Commercial/Drilling						1													
Commercial/Naval support, RFA																			
Dry Cargo Reefer																			
Small Sail Training Vessels																			
Non-Commercial /Pleasure craft								*											
Tanker/combination carrier																			

Table D.4: Root causes of the marine accidents

Contributor to accidents	Time Occurrence
Negligence/carelessness of injured person	13
Personnel unfamiliar with equipment/not trained in use	6
Inattention	2
Perception Abilities	1
Situational Awareness or Communication Inadequate	3
Design Inadequate	1
Heavy Weather	2
Alcohol/Drugs Use	2
Illness	1
Perception of Risk	3
Violation of procedures	1
Visual Environment-Darkness	1
Stumbling/tripping over fixed door sill, step, obstruction	7
Vessel movement weather conditions	6
Procedures Inadequate	2
Lack of communication or coordination	2
Vigilance	1
Improper or inadequate footwear/clothing/PPE	2
Lifting/carrying - poor manual handling	6
Poor/slippery/uneven surface	3
Wave washing inboard	2
Hit by swinging load/falling gear	2
Involving portable tools/equipment/machinery	2
Exposure to dangerous atmosphere or substance	1
Fire/Explosion	1
Auxiliary machinery	1
Material/mechanical defect	5
Bridge Procedures	4
Maneuverability	1
Navigation/Communication -Equipment	4
Navigational Instruments (Radar, GPS, ECDIS etc.)	3
Inadequate Passage Planning/Track Monitoring	2
Fatigue	1
Poor Decision Making	1
Task difficulty	1
Equipment not available	1
Visibility	1
Flooding/Foundering	1
Company standing orders inadequate, insufficient, conflicting	1
Publications/plans not up to date	1
Safety management system failure	2
Procedures inadequate	1
Competence	1
Wire/rope/net jamming, jumping slipping or coming off sheave	2
Other factors	2
Total	109

APPENDIX E

A sample page of the MAIB report which is prepared on my name for this research is given below.

Incidents recorded by MAIB as occurring North of 66° 33′ 1993 to 2011

Case Number **0018/1999** **10/12/1998** **Flooding/Foundering**

Regulation	**Accident**		Status	**Closed**			
Location	**High seas**	**Non UK**		**6653.0 N**	**552.0 E**		
Natural Light	**Darkness**	Sea State		**Rough**			
Visibility	**Mod. 2 - 5 nm (3)**	Wind Force Range		**7-9**			
Other commercial			Dead	**0** Injured	**0**	**Minor Damage**	
Survey/research				Flag	**U.K.**		
Oceanographic					**2619.00**	gt	
				0.01	Reg. L	**68.60**	LOA

Machinery

Ship

Flooding

THIS 68 METRE SURVEY VESSEL WAS IN HEAVY WEATHER. SEAS ON BEAM PASSED DOWN VENTILATOR INTO ENGINE ROOM AND ENTERED THE MAIN SWITCHBOARD. ALL POWER WAS LOST. TEMPORARY REPAIRS ALLOWED VESSEL TO REACH PORT.

Table E.1: The MAIB report of marine accidents in the Arctic region, data filtered by the author

No	Date	Incident	Location	Natural Light	Visibility
1	22.05.1993	Accident To Person	High seas	Light	good (5 - 10)
2	02.02.1995	Accident To Person	High seas	Darkness	Poor <2 nm (1,2)
3	03.02.1996	Accident To Person	High seas	Light	NA
4	16.02.1996	Accident To Person	coastal waters	Light	Good (5 - 10)
5	05.05.1996	Machinery Failure	Coastal waters	Light	Good (5 - 10)
6	26.06.1996	Grounding	Coastal waters	Light	good (5 - 10)
7	21.01.1997	Accident To Person	High seas	Darkness	Good (5 - 10)
8	27.07.1997	Accident To Person	High seas	Light	NA
9	18.02.1998	Accident To Person	High seas	Light	good (5 - 10)
10	23.03.1998	Accident To Person	High seas	Light	good (5 - 10)
11	28.06.1998	Accident To Person	High seas	Darkness	Good (5 - 10)
12	28.06.1998	Accident To Person	na	Darkness	good (5 - 10)
13	01.08.1998	Collision	coastal waters	Light	Poor <2 nm (1,2)
14	02.08.1998	Collision	coastal waters	Light	Poor <2 nm (1,2)
15	04.08.1998	Accident To Person	High seas	Light	Good (5 - 10)
16	30.08.1998	Accident To Person	coastal waters	Light	good (5 - 10)
17	16.09.1998	Grounding	Coastal waters	Light	Mod. 2 - 5 nm (3)
18	10.12.1998	Flooding/Foundering	High seas	Darkness	Mod. 2 - 5 nm (3)
19	26.01.1999	Accident To Person	Port/harbour area	Light	good (5 - 10)
20	03.02.1999	Accident To Person	High seas	Light	NA
21	12.05.1999	Machinery Failure	High seas	Darkness	Good (5 - 10)
22	06.06.1999	Accident To Person	High seas	Light	good (5 - 10)
23	15.07.1999	Accident To Person	High seas	Light	Good (5 - 10)
24	18.07.1999	Accident To Person	Coastal waters	Light	Good (5 - 10)
25	13.10.1999	Flooding/Foundering	Coastal waters	Light	Mod. 2 - 5 nm (3)
26	29.10.1999	Accident To Person	High seas	Light	good (5 - 10)
27	19.12.1999	Accident To Person	High seas	Light	NA
28	09.06.2000	Accident To Person	na	Darkness	Poor <2 nm (1,2)
29	14.06.2000	Accident To Person	Coastal waters	Light	Poor <2 nm (1,2)
30	28.06.2000	collision	Coastal waters	na	Good (5 - 10)
31	29.06.2000	collision	Coastal waters	na	Good (5 - 10)
32	09.07.2000	Accident To Person	High seas	Darkness	NA
33	27.08.2000	Fire/Explosion	Coastal waters	Light	Good (5 - 10)
34	19.10.2000	Accident To Person	na	ns	good (5 - 10)
35	07.01.2001	Machinery Failure	Port/harbour area	Light	Good (5 - 10)
36	18.04.2001	Accident To Person	Coastal waters	NA	NA
37	05.07.2001	Accident To Person	High seas	na	na
38	28.07.2001	Accident To Person	Coastal waters	NA	Mod. 2 - 5 nm (3)
39	01.03.2002	Accident To Person	Port/harbour area	Light	good (5 - 10)
40	27.08.2002	Person Overboard	Port/harbour area	Darkness	NA
41	10.06.2003	Accident To Person	High seas	Light	NA
42	03.07.2003	Accident To Person	High seas	Darkness	Good (5 - 10)
43	30.07.2003	Accident To Person	Coastal waters	Light	NA
44	20.03.2004	Accident To Person	port/harbour area	Light	good (5 - 10)
45	10.07.2004	Accident To Person	High seas	Light	NA

Table E.2: (Continued): The MAIB report of marine accidents in the Arctic region, data filtered by the author

No	Coordinates	Sea state	Wind Force	Dead	Injured
1	7240.0 N 2600.0 E	Moderate	0-3	0	1
2	7032.0 N 1714.0 E	Rough	7-9	0	3
3	7123.0 N 2158.0 E	NA	4-7	0	1
4	7053.0 N 2019.0 E	NA	4-6	0	1
5	6906.0 N 108.0 W	Moderate	4-6	0	0
6	6945.0 N 1905.0 E	NA	0-3	0	0 material damage
7	7020.0 N 1719.0 E	Calm <2 ft	0-3	0	1
8	6743.0 N 1153.0 E	NA	NA	0	1
9	6725.0 N 1058.0 E	na	7-9	0	1 no damage
10	6752.0 N 1145.0 E	NA	4-6	0	1
11	7416.0 N 1010.0 E	Calm <2 ft	NA	0	1
12	7416.0 N 1010.0 E	Calm <2 ft	NA	0	1
13	7454.0 N 1851.0 E	NA	4-6	0	0 material damage
14	7454.0 N 1851.0 E	NA	4-6	1	1 material damage
15	8351.0 N 335.0 W	Moderate	4-6	0	1
16	7200.0 N 6000.0 E	Calm <2 ft	NA	0	1
17	7814.0 N 1405.0 E	NA	0-3	0	0 material damage
18	6653.0 N 552.0 E	Rough	7-9	0	0 Minor Damage
19	6848.0 N 1639.0 E		Range	0	1
20	7030.0 N 1730.0 E	NA	7-9	0	1
21	7320.0 N 2302.0 E	Moderate	0-3	0	0 No damage
22	7121.0 N 2423.0 E	Calm <2 ft	4-7	0	1
23	6823.0 N 1325.0 E	Calm <2 ft	NA	0	1
24	7447.0 N 3224.0 E	NA	0-3	0	2
25	6755.0 N 616.0 W	NA	0-3	0	0 No damage
26	7434.0 N 1713.0 E	NA	4-6	0	1
27	7341.0 N 1709.0 E	NA	7-9	0	1
28	6927.0 N 1559.0 E	Calm <2 ft	NA	0	1 no damage
29	6635.0 N 1556.0 W	Rough	7-9	0	1
30	7433.0 N 336.0 W	Calm <2 ft	NA	0	0
31	7433.0 N 336.0 W	Calm <2 ft	NA	0	0 ship lost
32	8923.0 N 12358.0 W	Calm <2 ft	0-3	0	1
33	7015.0 N 118.0 W	NA	4-6	0	0 No damage
34	7455.0 N 1807.0 E	NA	4-6	0	1
35	8004.0 N 2605.0 W	NA	Range	0	0 Minor Damage
36	6734.0 N 13023.0 W	Moderate	4-6	0	1
37	6757.0 N 1238.0 W	Calm <2 ft	0-3	0	1
38	7056.0 N 2530.0 E	NA	4-6	0	1 no damage
39	6830.0 N 1700.0 E	Sheltered Waters	NA	1	0 No damage
40	6940.0 N 1858.0 E	Sheltered Waters	NA	1	0
41	6810.0 N 1258.0 E	moderate	0-3	0	1
42	6840.0 N 815.0 W	NA	4-6	0	1
43	6637.0 N 2342.0 W	Moderate	4-6	0	1
44	6725.0 N 1153.0 E	NA	NA	0	1
45	7255.0 N 1912.0 E	Calm <2 ft	0-3	0	1

Table E.3: (Continued): The MAIB report of marine accidents in the Arctic region, data filtered by the author

No	Flag	Tonnage	Reg Length	LOA	Type
1	U.K.	835,54	57,94	57,94	Fish catching/processing
2	U.K.	401,96	38,14	41,96	Fish catching/processing
3	U.K.	1175	54,33	61,75	Fish catching/processing
4	U.K.	1175	54,33	61,75	Fish catching/processing
5	U.K.	23,13	16,31	16,27	Fish catching/processing
6	U.K.	1175	54,33	61,75	Fish catching/processing Trawler Stern trawler
7	U.K.	555		38,64	Fish catching/processing
8	U.K.	44588		230,61	Passenger Cruise ship
9	U.K.	640	51,16	51,16	Fish catching/processing Trawler Stern trawler
10	U.K.	640	51,16	51,16	Fish catching/processing Trawler Stern trawler
11	U.K.	63524		245,6	Passenger Cruise ship
12	U.K.	63524		245,6	Passenger cruise ship
13	U.K.	1146	45,8	51,5	Fish catching/processing Trawler Stern trawler
14	Russia	1659	56,9	56,9	Fish catching/processing Trawler Stern trawler
15	U.K.	1177		58,98	Other commercial Associated with offshore industry Offshore supply
16	U.K.	8048		111,49	Other commercial Associated with offshore industry Drilling
17	U.K.	1266	53,85	60,13	Fish catching/processing Trawler Stern trawler
18	U.K.	2619		68,6	Other commercial /Survey/Research/ Oceanographic
19	U.K.	2882		69,2	Fish catching/processing Trawler Stern trawler
20	U.K.	1146	45,8	51,5	Fish catching/processing Trawler Stern trawler
21	U.K.	639	44,98	51,16	Fish catching/processing Trawler Stern trawler
22	U.K.	28891		201,23	Passenger Cruise ship
23	U.K.	2882	61,63	69,2	Fish catching/processing Trawler Stern trawler
24	U.K.	1266	60,15	60,15	Fish catching/processing Trawler Stern trawler
25	U.K.	24,1	15,54	16,92	Fish catching/processing
26	U.K.	1266		53,85	Other commercial Port service Tug
27	U.K.	1146		51,52	Fish catching/processing Trawler Stern trawler
28	U.K.	na		na	Passenger Cruise ship
29	U.K.	28891		201,23	Passenger Cruise ship
30	U.K.	54,79	19,69	20,89	Fish catching/processing
31	U.K.	na	na	na	Pleasure craft (non-commercial) Angling vessel
32	U.K.	70285		204,04	Passenger Cruise ship
33	U.K.	14760		137,67	Passenger Ro-ro, vehicle/passenger ferry
34	U.K.	2882	61,63	69,2	Fish catching/processing
35	U.K.	70327		270,53	Passenger Cruise ship
36	Liberia	69845		245,01	Passenger Cruise ship
37	U.K.	63524		245,6	Passenger Cruise ship
38	U.K.	44588		230,61	Passenger cruise ship
39	U.K.	8861		140,47	Other commercial Naval support & RFA
40	U.K.	na	na	na	Other commercial Small commercial sailing vessel Sail training vessel
41	U.K.	77499		261,31	Passenger Cruise ship
42	U.K.	1233,71	65,12	71,85	Fish catching/processing Trawler Stern trawler
43	U.K.	77499		261,31	passenger cruise ship
44	U.K.	2882	61,63	69,2	Fish catching/processing Trawler Stern trawler
45	U.K.	76152		270	Passenger cruise ship

Table E.4: (Continued):The MAIB report of marine accidents in the Arctic region, data filtered by the author

No	Date	Incident	Location	Natural Light	Visibility
46	24.06.2005	Accident To Person	High seas	Semi-dark	NA
47	20.12.2005	Grounding	Port/harbour area	Darkness	Good (5 - 10)
48	09.02.2006	Accident To Person	High seas	Light	Mod. 2 - 5 nm (3)
49	15.03.2006	Accident To Person	High seas	Light	NA
50	29.04.2006	Accident To Person	High seas	Light	NA
51	24.05.2006	Person Overboard	Port/harbour area	Light	NA
52	09.06.2006	Fire/Explosion	High seas	Light	NA
53	07.07.2006	Accident To Person	Port/harbour area	Light	NA
54	22.10.2006	Accident To Person	High seas	Darkness	NA
55	25.07.2007	Accident To Person	High seas	NA	NA
56	11.08.2007	Accident To Person	High seas	Darkness	NA
57	17.04.2008	Accident To Person	High seas	NA	NA
58	15.06.2008	Accident To Person	Port/harbour area	Light	NA
59	27.06.2008	Grounding	High seas	Light	Good (5 - 10)
60	11.07.2008	Accident To Person	High seas	Semi-dark	Good (5 - 10)
61	02.08.2008	Accident To Person	High seas	Semi-dark	Good (5 - 10)
62	25.08.2008	Accident To Person	High seas	Semi-dark	good (5 - 10)
63	30.06.2009	Accident To Person	High seas	Darkness	NA
64	08.07.2010	Collision	High seas	Light	Good (5 - 10)
65	09.07.2010	Collision	High seas	Light	Good (5 - 10)
66	29.03.2011	Accident To Person	High seas	Light	NA
67	11.06.2011	Accident To Person	High seas	Darkness	NA
68	01.12.2011	Contact	Port/harbour area	Darkness	good (5 - 10)
69	02.12.2011	Contact	Port/harbour area	Darkness	good (5 - 10)

Table E.5: (Continued): The MAIB report of marine accidents in the Arctic region, data filtered by the author

No	Coordinates	Sea state	Wind Force	Dead	Injured
46	6652.0 N 1207.0 E	moderate	4-6	0	1
47	6740.0 N 1240.0 E	Calm <2 ft	0-3	0	0 material damage
48	7020.0 N 1742.0 E	NA	NA	0	1
49	6800.0 N 1046.0 E	Moderate	4-7	0	1
50	7245.0 N 17.0 E	NA	4-6	0	1
51	7059.0 N 2559.0 E	Moderate	4-6	0	0 No damage
52	6909.0 N 1251.0 E	NA	NA	0	0 Minor Damage
53	6940.0 N 1858.0 E	Sheltered Waters	NA	0	1 no damage
54	7233.0 N 750.0 E	NA	4-6	0	0
55	6644.0 N 2320.0 W	Calm <2 ft	4-6	0	1 no damage
56	7727.0 N 2734.0 E	Calm <2 ft	NA	0	1
57	6941.0 N 1616.0 E	moderate	0-3	0	1 no damage
58	7059.0 N 2557.0 E	Calm <2 ft	0-3	0	1 no damage
59	6918.0 N 5310.0 W	Calm <2 ft	0-3	0	0 material damage
60	7653.0 N 2852.0 E	calm <2 ft	4-6	0	1 no damage
61	7653.0 N 2917.0 E	Calm <2 ft	0-3	0	1 no damage
62	6714.0 N 2637.0 W	Rough	7-9	0	1 no damage
63	7901.0 N 1142.0 E	calm <2 ft	0-3	0	1 no damage
64	7018.0 N 5932.0 W	Calm <2 ft	0-3	0	0 Minor Damage
65	7018.0 N 5932.0 W	Calm <2 ft	0-3	1	0 Minor Damage
66	6718.0 N 1417.0 E	Rough	NA	1	0 no damage
67	7005.0 N 944.0 E	NA	NA	0	1 no damage
68	7040.0 N 2348.0 E	Moderate	4-6	0	0 Minor Damage
69	7040.0 N 2348.0 E	Moderate	4-6	1	1 Minor Damage

Table E.6: (Continued): The MAIB report of marine accidents in the Arctic region, data filtered by the author

No	Flag	Tonnage	Reg Length	LOA	Type
46	U.K.	76152		270	Passenger cruise ship
47	U.K.	5084	102	109	Dry cargo Reefer
48	U.K.	1233	65,12	71,85	Fish catching/processing
49	U.K.	2882	61,63	69,2	Fish catching/processing Trawler Stern trawler
50	U.K.	2882	61,63	69,2	Fish catching/processing Trawler Stern trawler
51	U.K.	70327		293	Passenger cruise ship
52	U.K.	23235	176,08	182,55	Tanker/combination carrier
53	U.K.	24492		191,09	Passenger cruise ship
54	U.K.	2882	61,63	69,2	Fish catching/processing Trawler Stern trawler
55	U.K.	24492	167,67	191,09	Passenger cruise ship
56	U.K.	1621	47,23	55,5	Fish catching/processing
57	U.K.	2880	61,63	69,2	Fish catching/processing Trawler Stern trawler
58	U.K.	90049	265,36	294	Passenger Cruise ship
59	Bahamas	1211		46,95	Passenger cruise ship
60	U.K.	1621	47,23	55,5	Fish catching/processing Trawler Stern trawler
61	U.K.	1621	47,23	55,5	Fish catching/processing Trawler Stern trawler
62	U.K.	2880	61,63	69,2	Fish catching/processing Trawler Stern trawler
63	U.K.	90049	265,36	294	Passenger Cruise ship
64	U.K.	58294		228,34	Other commercial Associated with offshore industry Drilling
65	Norway	4260		85	Other commercial Associated with offshore industry Offshore supply
66	Portugal	16795	147,55	163,56	Passenger Cruise ship
67	bermuda	76152	247,5	270	Passenger Cruise ship
68	U.K.	2820		80,42	Other commercial Survey/research
69	Marshall Islands	4582		81,85	Other commercial Survey/research

CURRICULUM VITAE

Name Surname: Bekir ŞAHİN

Place and Date of Birth: Yozgat, 1984

Address: ITU Maritime Faculty, Sahil Cad. Tuzla 34940, Istanbul, Turkey.

E-Mail: bekirs66@gmail.com

B.Sc.: Maritime Transportation Management Engineering, Engineering Department, Istanbul University

M.Sc.: Engineering Technology, College of Technology, University of Houston

Professional Experience and Rewards: Research Assistant, Maritime Faculty, Istanbul Technical University

List of Publications and Patents:

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