ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A QUANTITATIVE RISK ANALYSIS APPROACH ON LIQUEFACTION OF DRY BULK CARGO IN MARITIME TRANSPORTATION.

M.Sc. THESIS

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Maritime Transportation Engineering Programme

MAY 2019

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

DENİZ TAŞIMACILIĞINDA KURU DÖKME YÜKLERİN SIVILAŞMASI ÜZERİNE SAYISAL BİR RİSK ANALİZİ YAKLAŞIMI.

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Date of Defense : 12 June 2019

To my beloved ones,

FOREWORD

I would like to express my gratitude to my family and friends due to their encouragements in the course of thesis. I am also grateful to my advisor Assoc. Prof. Dr. Emre Akyuz his involvement in this dissertation. In addition, I present my regards to Prof. Dr. Özcan Arslan and Prof. Dr. Serap İncaz their constructive comments and feedback as members of the thesis jury committee.

Additionally, I would like to express my special gratitude to my colleagues from Cofco International Freight S.A.; especially Alessio La Rosa, Capt. Ulunay Terzi, Tüvana Şişlioğlu, Capt. Ertuğrul Çağlayan, Tuba Özdiler, from Olam Shipping Capt. Özgür Zağlı, from Yeditepe International Marine Survey Consultation and Supervision Co. Inc. Capt. Can Yiğit Dinç, from Ince Shipping & Trading Co.Inc. Capt. Gözde Turan, Meadway Shipping and Dasin Shipping for their utmost support during evaluation/survey process of the thesis.

May 2019 Capt. Aylin ÇOŞKUN

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ABBREVIATIONS

BE	**:** Basic Event
BN	**:** Bayesian Network
CC	**:** Consensus Coefficient
ETA	**:** Event Tree Analyse
FTA	**:** Fault Tree Analyse
FFTA	**:** Fuzzy Fault Tree Analyse
FMEA	**:** Failure Mode Effect and Analysis
FPSO	: Floating Production Storage and Offloading
FPs	: Fuzzy Possibilities
FP_T	: Fuzzy Probability
FRF	**:** Fuzzy Risk Factor
FSA	: Formal Safety Assessment
GM	: Metacentric Height
HAZOP	: Hazard & Operability Study
LSA	: Life-Saving Appliance
IBC Code	**:** International Bulk Chemical Code
IE	**:** Intermediate Event
IGC Code	**:** International Gas Carrier Code
IMDG	**:** International Maritime Dangerous Goods
IMSBC Code	**:** International Maritime Solid Bulk Cargoes Code
IMO	**:** International Maritime Organisation
ISM	**:** International Safety Management
MCS	**:** Minimal Cut Set
PHA	**:** Preliminary Hazard Analysis
QRA	**:** Quantitative Risk Analysis
RPN	**:** Risk Priority Number
SAM	**:** Similarity Aggregation Method
SOLAS	**:** Safety of Life at Sea
TE	**:** Top Even
TML	**:** Transportable Moisture Limit

V-FIM **:** Vesely-Fussell Importance Measure

SYMBOLS

AA	**:** Average Agreement
$CC\ (E_u)$	**:** Consensus Coefficient of expert
E_k	**:** Expert judgement
$I_i^{VF}\ (t)$	: Occurrence probability of MC_b
N	: Number of MCS
$P(T)$	: Occurrence probability of TE
$P(MCSi)$	: Probability of the MCS_i
$Q\ (t)$	**:** Probability of the top event
$RA(E_u)$	**:** Relative Agreement degree
$S\ (\tilde{A}, \tilde{B})$	**:** Similarity among the two fuzzy numbers
T	**:** Total failure probability of TE
$\mu A(x)$	**:** Membership function
x_1	**:** Trapezoidal fuzzy sets numbers
X^*	**:** Fuzzy possibility

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A QUANTITATIVE RISK ANALYSIS APPROACH ON LIQUEFACTION OF DRY BULK CARGO IN MARITIME TRANSPORTATION.

SUMMARY

Solid bulk cargo transportation has been growing around world. However, increased solid bulk cargo carriage activities can pose potential damage to ship crew, commodity and maritime environment. According to the IMSBC Code (International Maritime Solid Bulk Cargoes Code), solid bulk cargoes contain serious risks such as unstable of ship, cargo liquefaction, fire or explosion due to chemical content of cargo, etc. for maritime transportation. Since safety is one of the core topics for maritime transportation, the IMSBC Code classified those cargoes into three groups. The group A involves cargoes that might liquefy during transportation due to moisture content exceed the TML (Transportable Moisture Limit). There are numerous fatal accidents recorded so far resulting from cargo liquefaction. It may cause shifting of cargo on-board ship and consequence of liquefaction may pose total loss of ship due to capsizing.

In the view of above, this thesis will perform a comprehensive quantitative risk analysing on cargo liquefaction of dry bulk cargo in maritime transportation as the consequences of it may cause serious harms. The thesis aims at increasing safety awareness through solid bulk cargo carriage on-board ships. It will focus on potential risk of cargo liquefaction. A robust methodological approach involving Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) under Fuzzy Logic environment will be adopted to conduct a risk analysing. Whilts the the FTA method is used to identify basic events which may cause to an accident event, the ETA defines the event sequences from initiating events to accident scenarios. Hence, the basic events (BE) will be determined and fault tree diagram is constructed from top to down direction to understand causation of cargo liquefaction on-board ships. The fault tree diagram will illustrate the pathway within the system. Hence, the potential failures that may cause cargo liquefaction on-board bulk carriers will be analysed quantitatively.

With the study undertaken this thesis, it is estimated to reach solid following targets; i.) To introduce potential hazards and consequences of cargo liquefaction problem, ii.) To apply robust quantitative risk analysing methodology in maritime transportation, iii.) To combine FTA and ETA analysis methods under Fuzzy logic environment, iv.) An extensive risk analysing through cargo liquefaction problem on-board ship, v.) To improve safety management system on-board dry bulk cargo ship, v.) To contribute IMSBC Code in managing potential risks associated with dry bulk cargoes.

In conclusion, the thesis will contribute maritime safety researchers and maritime professionels for minimizing potential risks before loading of hazardous solid bulk cargoes such as nickel ore, iron ore, concentrates cargoes which may liquefy on-board ships. Accordingly, necessary control actions will be recommended. The outcomes of the thesis will be presented to maritime stakeholders such as P&I Clubs, Flag states, charterers, higher education centers, and institutions to enhance safety awareness through cargo liquefaction phenomenon. The maritime professionals will also take

benefits of the outcomes to enhance safe of solid bulk cargo shipment and to prevent maritime pollution. The findings of this research will provide utmost contribution to IMSBC Code with respect to the safety precautions of cargo liquefaction.

DENİZ TAŞIMACILIĞINDA KURU DÖKME YÜKLERİN SIVILAŞMASI ÜZERİNE SAYISAL BİR RİSK ANALİZİ YAKLAŞIMI.

ÖZET

Kuru dökme yük taşımacılığı dünyada giderek artmaktadır. Ancak artan kuru dökme yük taşımacılığı gemi personeline, taşınan yüke ve deniz çevresine ciddi tehlikeler teşkil etmektedir. Uluslararası Denizcilik Katı Dökme Yük Kodu'na (IMSBC Code) göre, kuru dökme yükler gemi stabilitesini bozma, sıvılaşma, kimyasal içeriklerinden dolayı yangın ya da patlama gibi çeşitli tehlikeler içermektedir. Deniz taşımacılığında emniyet en önemli unsur olarak öne çıkmakla beraber, IMSBC Kod tehlikeli kuru dökme yükleri 3 gruba ayırır. Grup A tipi yükler, içerisinde bulundurduğu nemin taşınabilir nem limitini (TML) aşması durumunda sıvılaşan yükleri içermektedir. Kuru dökme yük sıvılaşması nedeniyle birçok ölümcül deniz kazası kayıtlara geçmiştir. Yükün sıvılaşması, ambar içerisinde yükün kaymasına ve geminin alabora olarak tam ziyasına sebep olabilir.

Bu bilgiler ışığında, bu tez deniz taşımacılığında kuru dökme yüklerin sıvılaşması durumu üzerine geniş kapsamlı sayısal bir risk analizi yapmayı hedeflemektedir. Kuru dökme yüklerin ambar içerisinde sıvılaşmasının sonuçları çok ciddi tehlikeler içerebilir. Bu tez ile kuru dökme yük taşımacılığının emniyet farkındalığının artırılması amaçlanmaktadır. Tez, kuru dökme yüklerde sıvılaşma problem üzerine odaklanacaktır. Bu kapsamda risk analizi değerlendirmesi için, Hata Ağacı Analizi (FTA) ve Olay Ağacı Analizi (ETA) yöntemleri bulanık mantık yöntemi altında uygulanacaktır. Hata Ağacı Yöntemi, sıvılaşma kaynaklı deniz kazasına neden temel olayları belirlemede kullanılırken, Olay Ağacı Yöntemi ise kazaya ait senaryo ile ardışık olayların sonuçlandırılmasında kullanılacaktır. Böylece, kazaya sebep veren temel olaylar belirlenecek ve yukarı aşağı yönlü olacak şekilde hata ağacı diagramı ile kuru dökme yüklerde ortaya çıkabilecek sıvılaşmaya ait hatalar analiz edilecektir. Hata ağacı diagramı sistemde ki arızaları gösteren bir yoldur. Böylece, dökme yük gemilerinde sıvılaşmaya sebep olan potansiyel hataların sayısal olarak analizini mümkün kılar.

Bu tez ile gerçekleştirilen çalışmada, aşağıda belirtilen somut hedeflere ulaşılması beklenir; i.) Kuru dökme yüklerde ortaya çıkan sıvılaşma probleminin potansiyel tehlikelerini ve sonuçlarını tanıtmak, ii.) Deniz taşımacılığında uygulanabilecek sayısal bir risk analizi yöntemi ortaya koymak, iii.) Hata Ağacı ve Olay Ağacı yöntemlerinin bulanık mantık yöntemi altında birleştirmek, iv.) Yükün sıvılaşması üzerine yapılacak kapsamlı bir risk analizi çalışması, v.) Kuru dökme yük gemilerinde emniyet yönetim sistemini geliştirmek, v.) Kuru dökme yük ile ilgili potansiyel risklerin yönetilmesinde Uluslararası Denizcilik Katı Dökme Yük Kodu'na (IMSBC Code) katkıda bulunmak.

Sonuç olarak, bu tezin deniz emniyeti araştırmacıları ve profesyonel denizcilere; nikel cevheri, demir cevheri, konsantre dökme yükler gibi gemi ambarında sıvılaşabilen yüklerin oluşturabileceği risklerin azaltılması ile ilgili konularda katkıda bunması beklenir. Buna göre gerekli kontrol önlemleri tavsiye edilir. Bu tezin sonuçlarının,

kuru dökme yüklerin sıvılaşma problemi üzerine emniyet farkındalığının geliştirilmesi için P&I klüp, bayrak kontrolü, gemi kiralama şirketleri, yüksek eğitim kurumları gibi denizcilik paydaşlarına sunulması planlanmaktadır. Ayrıca, profesyonel denizciler bu tezin sonuçlarından emniyetli kuru dökme yük taşımacılığı ve deniz kirliliğinin önlenmesi konularında yarar sağlayacaktır. Bu araştırmanın bulguları, kargo sıvılaştırmasının emniyet önlemleri konusunda Uluslararası Denizcilik Katı Dökme Yük Kodu'na (IMSBC Code) azami katkı sağlayacaktır.

1. INTRODUCTION

Safety is core topic in maritime literature since researchers have been focusing on proactive solutions to minimize maritime accidents at sea. The International Maritime Organisation (IMO), regulatory body of maritime affairs, have been setting a wide range of conventions and codes to enhance maritime safety and minimize potential risks. International Convention for the Safety of Life at Sea (SOLAS), for instance, is one of the fundamental conventions adopted by IMO to determine minimum requirements for commercial ships related with safety issues (An, 2016). The convention involves numerous codes related with improvement of safety standards at ships such as ISM Code (International Safety Management), LSA Code (Life-Saving Appliance), IBC Code (International Bulk Chemical Code), IGC Code (International Gas Carrier Code), IMDG Code (International Maritime Dangerous Goods) etc. Although various codes and conventions were adopted by the IMO, the safety level at sea has yet to reach desired level. To all apperiances show that maritime accident at sea is still on going (Knudsen and Hassler, 2011). The consequences of maritime accidents pose serious harms to human life, maritime environment and commodity (Akyuz and Celik, 2018).

Maritime affairs have many hazards due to the nature of work and those may create substantial consequences (Montewka et al., 2014). Therefore, each operation performed on-board ships represents high risk. In order to enhance maritime safety at sea, risk factor must be reduced to acceptable level. The risk can be defined as a function of the occurrence probability of hazard/failure and severity of consequences (Gul and Guneri, 2016; Akyuz 2015). In the maritime industry, risk assessment plays a critical role to enhance safety, in particular tanker ship management. For instance, the IMO introduced FSA guidelines (Formal Safety Assessment) in 2002 years under MSC (Maritime Safety Committee) and MEPC (Maritime Environment Protection Committee) circular. The aim of the guidelines was to improve safety at sea by conducting risk analysing. Likewise, the ISM code defines the risk assessment requirement under chapter 1 paragraph 1.2.2.2 – section objectives. According to the

code, each company should evaluate all identified risks to crew on-board ship, maritime environment and vessel. (ISM Code, 2002). Shipping companies complied with risk assessment tools and process created under ISM Code. Particularly, Designated Person Ashore (DPA) and safety inspectors (under department of HSEQ) focus on risk assessment procedures and plans through the shipboard operations. Risk mitigation measures can be recommended according to the risk assessment evaluation for each procedure performed on-board ship. Since risk composes of two substantial parameters, which are occurrence probability and severity of consequence, human error probability through critical shipboard operation is of paramount to determine risk level. According to the statistics, human errors contribution to maritime fatal incidents are of more than 80 percent (Akyuz, 2016; EMSA, 2015; Corovic and Djurovic, 2013). Probability of human error is one of the key elements of quantitative risk analysis (QRA), in particular calculating of likelihood. Therefore, most of risk analysing methods discuss human error contribution. In this thesis, a quantitative risk analysing will be performed by considering potential human error in liquefaction of dry bulk cargo shipment.

Liquefaction can be seen some specific type of dry bulk cargoes where moisture content exceeding their transportable moisture limit (IMSBC Code). There are various ship incidents recorded so far resulting from liquefaction such as MV Mega Taurus, MV Oriental Angel, MV Jag Raghul, etc. (Colak and Satir, 2014). It may cause shifting of cargo on-board ship and consequence of liquefaction may pose total loss of ship due to capsizing. A specific case study is discussed at this thesis to analyse potential risks during liquefaction. In this context, the thesis is organised as follows. This section introduces topic and idea behind the study. Section 2 gives extended literature reviewing relating with maritime risk analysing and cargo liquefaction. Section 3 defines the methodology used in the paper. Section 4 applies methodology to cargo liquefaction phenomenon and shows how a comprehensive insight can be gained in terms of risk analysing. Section 5 discusses findings and recovery actions with respect to the cargo liquefaction risk analysing. Section 6 expresses conclusion of thesis along with practical contribution to maritime industry and limitation of study.

1.1 Purpose of Thesis

Quantitative risk assessment is of paramount for maritime transportation due to nature of work. Although a wide range of researches have performed in maritime transportation with respect to the risk analysing in recent years, the study focusing on risk of cargo liquefaction is very scarce. Besides introducing theoretical background of cargo liquefaction, evaluating and prioritising potential risks is one of the key aspects of quantitative maritime risk analysing. In this sense, the aim of this thesis is to conduct an extended risk anaylsis through cargo liquefaction problem, which may pose potential hazards for crew, maritime environment and commodity itself in maritime transportation. A robust methodological approach utilising Fault Tree Analysis (FFTA) and Event Tree Analysis (ETA) under Fuzzy Logic environment is addressed to tackle with aforementioned issue. In the light of above, the thesis is expected to achieve following solid targets in maritime transportation industry.

i.) Detailed expression of potential hazards and consequences of cargo liquefaction problem,

ii.) Present a robust quantitative risk analysing methodology application in maritime transportation,

iii.) Integration of FTA and ETA analysis methods under Fuzzy logic environment,

iv.) Comprehensive risk analysing cargo liquefaction problem on-board ship,

v.) Determine risk mitigation measures for potential hazards during cargo liquefaction,

vi.) Enhance safety management system on-board ship

vii.) Contribute to IMSBC Code in managing potential risks associated with dry bulk cargoes.

1.2 Impact of Thesis

Since risk analysing is one of the most important topics in maritime literature, the thesis addresses a comprehensive risk assessment upon a phenomenon subject in maritime transportation. Cargo liquefaction in dry bulk cargo shipment has yet to receive much attention. However, it has been considering as a major risk for dry bulk cargo ships (DNV GL, 2015). As the cargo liquefaction is considerable important phenomenon for maritime transportation, this thesis performs an extended risks

analysis on the case of cargo liquefaction. The thesis remedies gap between maritime literature and transportation industry. In the light of above, following items are considered as the impacts of proposed thesis on maritime transportation industry and maritime literature.

i.) A hybrid quantitative risk analysing method will be applied to specific case entitled liquefaction of dry bulk cargoes.

ii.) Potential failures/events that may cause cargo liquefaction on-board dry bulk cargo ships will be determined and necessary preventive action will be recommended.

iii.) The outcomes of the research will be presented to industry stakeholders such as P&I Clubs, Flag states, higher education centers, institutions.

iv.) Maritime professionals will take benefits of the outcomes to enhance safe of solid bulk cargo shipment and to prevent maritime pollution.

v.) The findings of this research will provide utmost contribution to IMSBC Code with respect to the safety precautions of cargo liquefaction.

2. LITERATURE REVIEW

Risk analysing is a hot topic, which has been discussing for last decades. The risk analysing will identify which factors have significant effect on the process. The risk can be defining as the combination of the probability of incident/failure occurrence and severity of incident/failure (ABS, 2013). In this context, identification potential hazards or failures are utmost important to determine risk level. Risk assessment, by the way, is covering the whole process of evaluating potent risks including hazard/failure identification, severity analysis and relevant control measures. In the literature, risk analysing methods are divided into two categories: qualitative methods and quantitative methods. Some of methodologies are integrated and called as semi-quantitative methods. The qualitative risk analysing methods mostly used for decision-making in various disciplines such as petrochemical, nuclear, transportation, process, heath, etc. It can be used if the risk level is considered as low and does not require full analysis. Also, qualitative risk analysing methods can be a practical solution in case data scarce is exist. The quantitative risk analysing methods are often used to calculate the level of risk in numeric. This type of methods is including analysing of likelihood, severity of consequences and risk level.

There have been various risk analysing methods utilised to determine potential risks. The methods including qualitative or quantitative aims at performing sensitive risk assessment. The methods have wide applicability in different industires. Table 2.1 shows basic risk analysing methods used literature in different industries.

A Failure Mode Effect and Analysis (FMEA) is an applicable risk analysing methods introduced by Moss and Kurty (1983). Potential failure modes and their effects are identified with detailed worksheet to conduct an extensive risk analysing. The method includes both quantitative and qualitative analysing. It allows user to find our risk priority number (RPN) which addresses the most significant failure modes in the system.

Table 2.1: Basic risk analysing methods used in practice.

Acronym	Method	Introduced by
FMEA	A Failure Mode Effect and Analysis	Moss and Kurty, 1983
	Bowtie method	Royal Dutch/Shell Group, 1970
HAZOP	Hazard & Operability Study	Imperial Chemical Industries, UK, 1960s
	What-if	Goldstein and Healy, 1995
PHA	Preliminary Hazard Analysis	Kolluru et al., 1996
	Consequences Analysis	
ETA	Event Tree Analysis	
FTA	Fault Tree Analysis	Bell Laboratories by H.A. Watso, 1962
BN	Bayesian Network	Bayes & Price, 1763
MM	Markov Model	Markov, 1906

The linguistic priority terms are defined as Occurrence (O), severity of failure (S) and detectability (D) to rank the RPN and perform the risk analysing.

A bowtie method is another robust tool to carry out an extensive risk analysing. The method sketch a diagram showing the potential risks that the user tackling. It is quite easy to apply any industries where the nature of works contains hazards. Due to the shape of diagram, the method is called as bowtie. It consists of a couple of steps to determine risk level of the process: identification of potential hazards, determining top event, assessing potential threats and consequences analysis (Ruijter and Guldenmund, 2016).

Hazard & Operability Study (HAZOP) is another rigid risk analysing tool, which is a capable of identifying potential causes of undesirable system condition. The method is widely used in product and process industries such as nuclear, petrochemical, etc. The aim of the HAZOP method is to perform a comprehensive examination of the operation to evaluate operational hazards. It includes a few steps to determine risk such as conducting a brainstorming for the potential causes of process, examination of the outcomes and determining operational risks (Dunjo et al., 2010).

What-if analysis is another powerful tool to assess risk in various industries. The method aims at identifying potential hazards or certain event sequences, which might address undesirable consequences. The method is practical to apply any industries. Therefore, it can present vas application area in various disciplines (Sheridan, 2008).

Preliminary Hazard Analysis (PHA) is also used as a robust risk analysing method in the literature. The method consists of identification and prediction of potential risk

sources as well as negative incidents. (Dogramadzi et al. 2014). The technique is often used in the preliminary level of the system design. The basic application steps of the method are to identify potential hazards, to evaluate severity of potential hazards, to determine risk and to take necessary remedial action for the hazards associated with potential risks. The method could be seen as a premature stage of What-if technique and requires fairly simple procedures when comparing (Alverbo et al., 2010).

The method called as consequence analysis, is performed to assess the extent of the possible consequences associated to a top event of incident or accident and it is generally an integral part of a risk analysing. The main objective of the consequence analysis is to identify potential outputs following a dangerous incident associated with risk (Ortmeier et al., 2005).

Event Tree Analysis (ETA) is a powerful binary logic risk assessment tool. It constructs a binary logic whether incident/event of process has happened or not happened. It is capable of evaluation the consequences that may arise from an event or a failure (Shih et al., 2016). The method can be applicable to any industries to conduct a comprehensive risk assessment, but it is efficiency increasing for model incidents where various control measures are in place. It is able to enhance features in ascertaining how numerous initiating incidents can produce in event of interest (Shih et al., 2016). The outcomes of the method are introduced graphically and depicted as a binary logic diagram.

Fault Tree Analysis (FTA) is one of the most useful risk analysing tools. It is widely used risk assessment researches. It can be applicable to system reliability as well. The method was introduced by Bell Telephone Laboratories and then adopted to other industries. The objective of the method is to construct logic diagrams which are displaying the state of the system failures/errors. It aims to perform extensive risk analysing for the specific event which is also called as top event. In order to find out the probability of risk for top event, probability of basic events or root events are evaluated (Kabir, 2017).

Bayesian Network is a hot and robust method widely used in safety and reliability analysis. Application of Bayesian Network to risk analysing research have been increasing since it provides conditional dependency among the events/failures. The method bases on type of probabilistic graphical demonstration where Bayesian

inferences are used. There have been a wide range of researchers undertaken to different industries adopted Bayesian Network in risk analysing (Khakzad, 2015).

Markov models can be defined as a sequence of events, the likelihood for each where dependency is existing. The method has been successfully applied to risk assessment in recent decades. It basically constitutes extensive representation of possible chains of events. It assists user to place well-suited logic to deal with events, unlike simulation-based assessment (Wu et al., 2018).

2.1 Literature Review of Risk Analysing on Maritime Transportation

A detailed literature reviewing associated with maritime risk analysing have been undertaken, the findings show that there are a wide range of research papers conducted since year of 2000. Most of them were dealing with risk assessment, risk management and risk associated with technical management. There are 67 research papers existing in the maritime literature with respect to risk analysing since year of 2000. More than 52 papers are full-length research papers published as article in electronic journals. 12 of them are seemingly full-length conference proceeding papers and rest of them are book chapters. Figure 2.1, in this context, demonstrates graphical distribution of papers in electronic journals with respect to the maritime risk analysing. According to the figure 2.1, journal of Ocean Engineering and Safety Science gave the wide coverage to the risk analysing papers on the topic of maritime transportation. Reliability Engineering & System Safety and Maritime Policy & Management journals appears as the second broad publisher to the topic of maritime risk analysing.

Furthermore, the Figure 2.2 depicts graphical distribution of researches upon maritime risk analysing subject to the recent years. The researchers have been increasing gradually since year of 2010. The findings show that the how the topic has gained popularity as the risk analysing is of paramount importance to enhance maritime safety and minimize maritime pollution prevention.

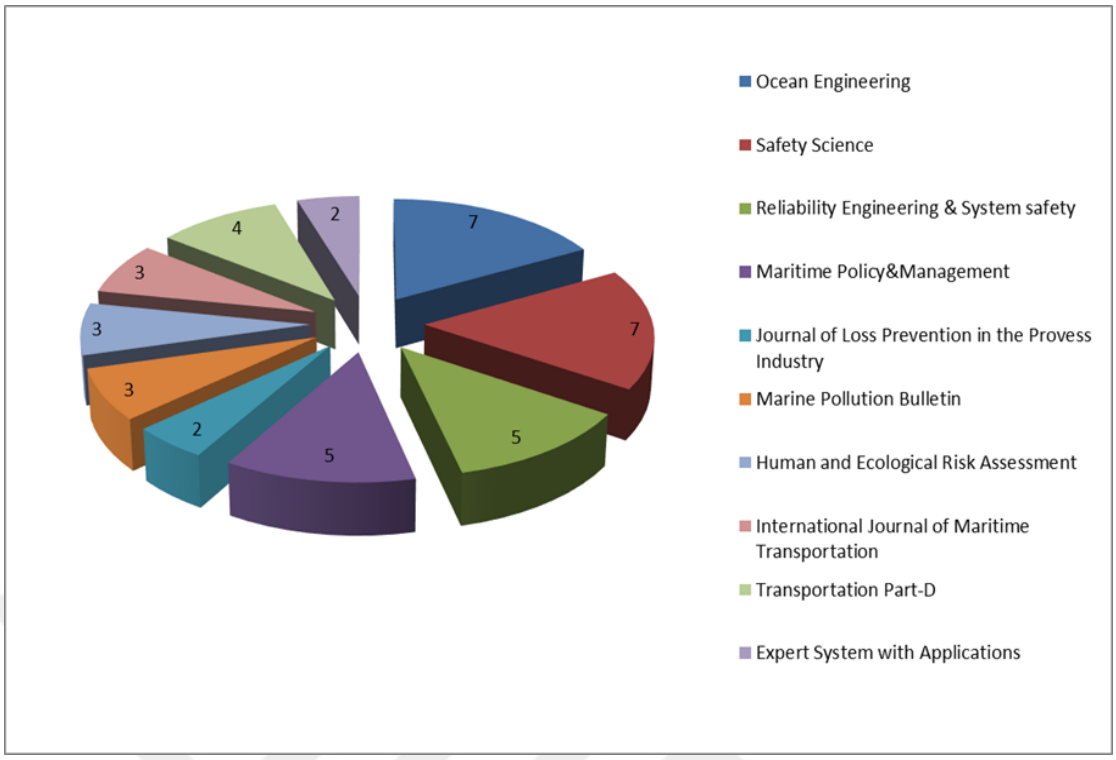

Figure 2.1: Distribution of full-length articles published in journals since 2000.

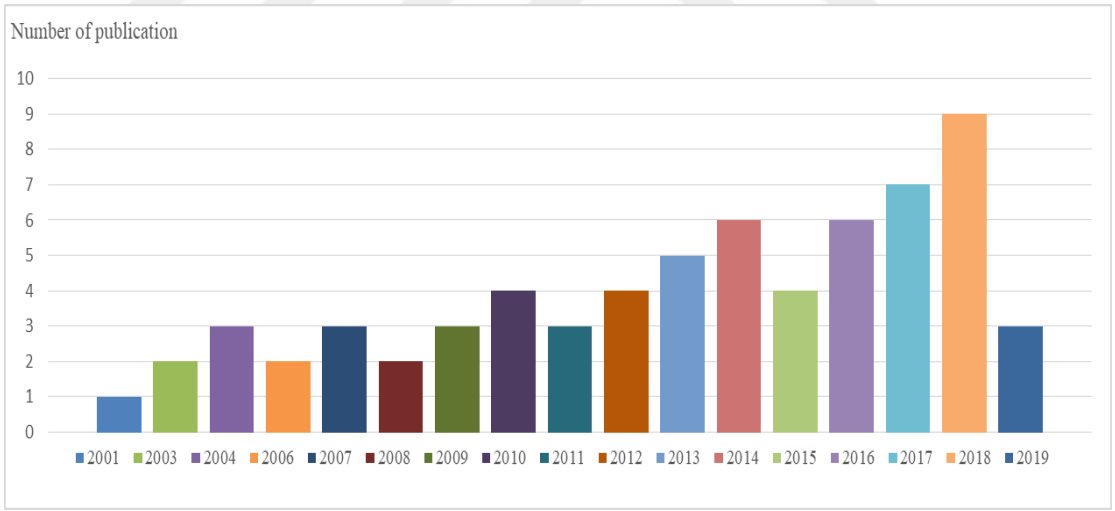

Figure 2.2: Distribution of researches on maritime risk analysing subject to the recent years.

Since risk analysing is critical challenge for maritime transportation, there have been numerous implementations performed under different topics. As illustrated in Figure 2.3, collision/grounding cases are the most prominent topics that the researchers focused on risk assessment.

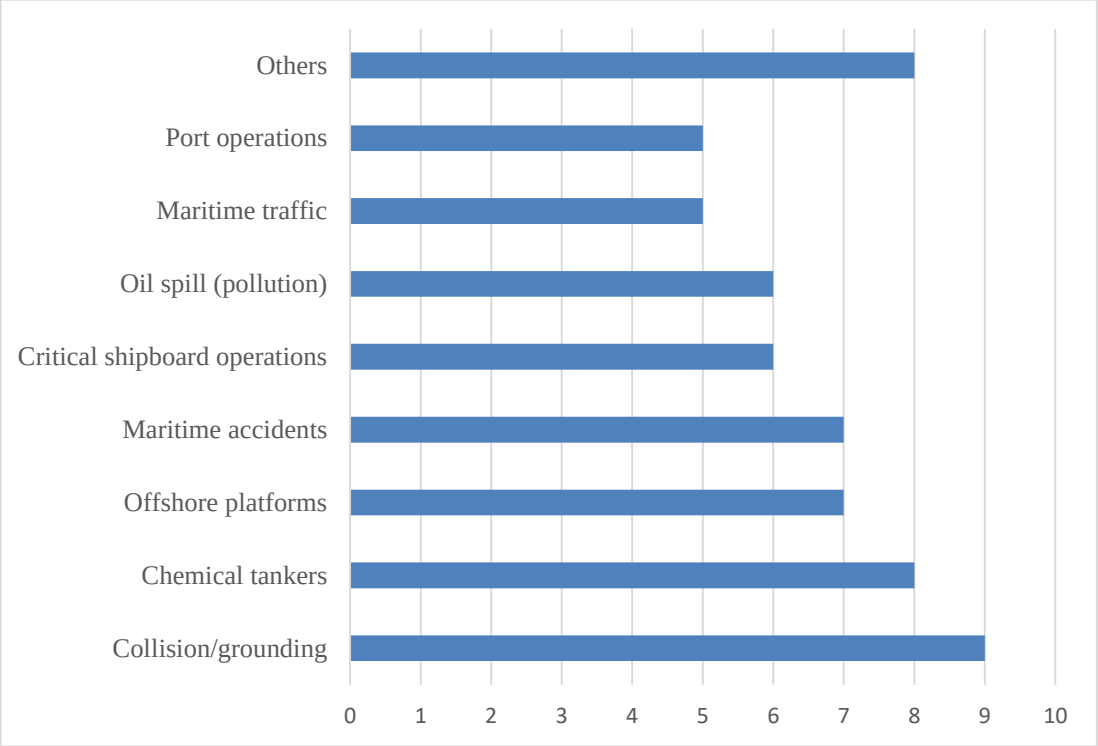

Figure 2.3: Topics researched on maritime risk analysing.

Although ship to ship collision or ship agrounding rarely occurred in maritime transportation, they are of particular importance in maritime accidents. The consequences of the aforementioned cases pose potential harms for human life, commodity and marine environment. The second topic handled in risk analysing studies in maritime literature is chemical tanker ships since the nature of works performed in chemical tankers are quite dangerous. The third major topic with respect to the maritime risk analysing is offshore platforms and critical operation carried out there. Respectively, risk of maritime accidents and critical shipboard operations such as crude oil washing, gas inerting, ballast operation, ballast treatment, tank cleaning, etc. are placed on top when comparing the other maritime risk assessment applications.

In the literature, numerous papers focused on maritime risk analysing such as Soares and Teixeira (2001) who presented a detailed literature reviewing about risk assessment in maritime transportation. In the paper, a comprehensive reviewing through some applications of quantified risk analysing within the maritime transportation was carried out. Reliability assessment was used to evaluate potential risks related to the maritime transportation activities. Since the paper presented as the

state of art in risk analysing, no specific risk assessment methodology was used. A Bayesian Network approach was used to determine potential risks in maritime transportation. The method was integreted with FTA and innovative approach called as Human and Organisational Factors (HOF) into risk analysis was presented (Trucco et al., 2008). In the paper, the authors quantified the HOF in the risk analysing and carried out to the ship to ship collision case in open sea. The proposed approach was recommended to utilise on accident reporting or accident investigation.

Another risk analysing research, performed by Vanem et al. (2008), discussed potential hazards associated with LNG carriers in maritime transportation. In the paper, authors introduced a modular risk analysing approach by adopting event tree analysis for critical accident scenarios. The findings of the research showed that there are five major contributions found on risks associated with LNG carriers; collision, contact, grounding, fire and explotion. Likewise, Balmot et al. (2009) presented a hybrid risk assessment methodology namely MARISA (MAritimeRISkAssessment) which applied to enhance maritime safety. The paper aimed at identifying risk factor of ship for each case. In order to achieve this purpose, the paper utilises fuzzy logic theory and determined fuzzy risk factor (FRF). Hence, dynamic risk for each ship is assessed by taking into consideration of environmental condition such as sea state, wind, weather condition, visibility, etc.

A risk analysing on the topic of chemical tanker operations was conducted to evaluate potential precautions (Arslan, 2009). The paper investigates priorities of precautions which needs to be taken by the chemical tanker ship management. The Analytic hierarchy process method was used to prioritise associated risk on-board chemical tanker ships. A risk-based approach combining fuzzy sets into the Fault tree analysis was presented to improve investigation of maritime accident (Celik et al., 2010). In the paper, fuzzy extended fault tree analysis was used to carry out a comprehensive risk assessment for maritime accident. A case study of machinery breakdown and subsequent fire on-board a containership demonstrated as a risk assessment application. The findings of paper contribute to enhance of ship safety management by minimizing potential operational risks.

Balmat et al. (2011) proposed a robust decision-making system to support maritime risk assessment. A fuzzy sets theory was utilised to evaluate potential risks in maritime industry as well as pollution prevention measures. The paper is based on the MARISA

approach. A fuzzy risk factor for each individual ship is determined with respect to the ship characteristics and weather conditions. Beside early stage of the research, this paper takes into consideration the speed of ship and position of ship. A ship to ship collision risk analysis was conducted to determine potential risks during collision case (Goerlandt et al., 2012). Monte Carlo simulation method is adopted in the risk assessment algorithm for this research. An oil tanker ship collision incident is handled to highlight different assumption risks on the case. A similar study was performed to assess potential risk of a RoPax type vessel collided with another ship (Montewka et al., 2014a). In the paper, the uncertainty is tackled with by considering consequences of the events. The authors present a qualitative scoring approach to assess potential risks and uncertainty.

Another risk assessment paper was conducted for maritime transportation systems where a case study involving collision of RoPax vessels discussed (Montewka et al., 2014b). Since the collision of vessels pose utmost harm for human life, maritime environment and commodity itself, the paper coped with potential hazards. In the paper, it is presented a systematic proactive approach to predict risks during collision case. Bayesian Belief Networks method was adopted by the authors to use a set of analytical methods for prediction of the risk parameters. The proposed approach applied to a specific case study on collision of RoPax ships. Likewise, a hierarchical Bayesian Network method was used to perform an extensive risk analysing for major maritime accident (Khakzad et al., 2014). In the paper, Bayesian Network method was used to regulate incorporation of overall data as well as dependency among the incident data and near-miss incident data. An off-shore operation as a real case study is selected to demonstrate the applicability of the method.

A fuzzy-based risk analysing approach was proposed by Turkoglu and Mentes (2015) for off-shore operational risk analysing. The proposed approach contributes to gather accurate values of the parameters such as rate of failures and likelihood. The authors perform a detailed risk analysing for selected off-shore platforms to enhance operational safety level. A comprehensive accident investigation is carried out to determine potential hazards due to the human errors. A FPSO (Floating production storage and offloading) unit is selected as a case study.

Another risk analysing paper was performed on the topic of offshore engineering systems (Yang and Wang, 2015). A generic Fuzzy Evidential Reasoning (FER) method was used to conduct risk assessment on offshore engineering system. A comparison between the standard risk analysing method and FER is discussed. In the light of findings, historical failure data is not appropriate for dynamic risk analysing since it is presenting subjective results. Probabilistic risk assessment was performed to evaluate risk and sustainability associated with ship collision accidents (Dong and Frangopol, 2015). In the paper, authors calculated ship collision probability by considering operational condition and traffic data vicinity. The paper applied a specific case on a maritime transportation system on Delaware River to assess maritime traffic.

Another paper discussing risk analysing of maritime transportation was introduced by Goerlandt and Montewka (2015) to enhance maritime safety awareness. In the paper, Bayesian Network model is used to perform probabilistic risk quantification. The model is illustrated with a case study which is dealing with oil spill from tankers in ship-to ship collision. The paper enables to evaluate likelihood of oil spill sizes in the maritime environment.

A Fuzzy DEMATEL (decision making trial and evaluation laboratory technique) hybrid approach under formal safety assessment (FSA) environment was used to evaluate risk by considering driving factors such as geographical location (Mentes et al., 2015). The hybrid method is applied to a case study to determine the most common causes of unintentional damages on cargo ships at coasts and open seas of Turkey.

A detailed risk analysing literature reviewing was performed focusing on applications refrering to the accidental risk of maritime transportation (Goerlandt and Montewka, 2015). The literature reviewing showed that maritime risk is heavily tried to probability including perspectives and definitions. Akyuz (2015) performed a quantitative risk assessment papers tackling with a specific shipboard operation in crude oil tankers. In the paper, a comprehensive risk analysing was undertaken on the topic of gas inerting process which poses potential harms for ship crew and environment. The author utilises modified CREAM (cognitive reliability and error analysis method) technique for risk assessment to increase safety awareness in maritime transportation. The findings of the paper reveal potential errors due to human factor and risk levels during gas inerting operation on-board crude oil tanker ships. Tang et al. (2016) discussed potential risks for emergent water pollution. Bayesian

Network approach was used to identify the likelihood of potential pollution risk. The paper focuses on potential risks of water pollutions caused by leakage of pollutants into water. Human factor including human error and fatigue of emergent accidents are taken into consideration in the research.

An evidential reasoning approach under fuzzy rule base technique was used to determine navigational risks of inland waterway transportation (Zhang, 2016). In the paper, a fuzzy rule base technique and an evidential reasoning algorithm was combined to conduct risk analysing. A case study is demonstrated with a three different region to applicability of proposed hybrid approach. A real-time multi-vessel collision risk was evaluated to enhance maritime safety at sea (Xhen et al., 2017). In the paper, a spatial clustering process is used to detect clusters of encounter vessels. To demonstrate the applicability of model, a specific case study covering west coastal waters of Sweden is tested.

An integrated risk analysing based on uncertainty was discussed to improve safety of cargo vessels in maritime transportation (Akyildiz and Mentes, 2017). The paper utilised fuzzy based risk analysing under decision-making approaches such as analytic hierarchy process (AHP) and technique for order preference by similarity to an ideal solution (TOPSIS). Christian and Kang (2017) proposed a methodology to evaluate potential risks of maritime spent nuclear fuel transportation. Monte Carlo simulations are adopted to calculate collision probabilities and impact energy for each case. An experimental case study is demonstrated during ship collision and cask damages.

A fuzzy based FMEA (Failure Mode and Effects Analysis) approach was introduced to carry out detailed risk analysing in maritime transportation (Akyuz, 2017). In the paper, a case study on the topic of hatch cover failures of bulk carrier ships is illustrated. Risk priority numbers of potential failures are determined by capturing nonlinear causal relationships. Risk mitigation measures are recommended to enhance operational safety level of bulk carrier ships. A hybrid risk-based approach was presented by using multi-criteria decision-making methods in maritime transportation. A fuzzy analytic hierarchy process (FAHP) with fuzzy VIKOR (FVIKOR) methods under Fine-Kinney approach was used to perform risk assessment (Gul et al., 2017). The authors carried out a risk analysing and determined potential operational hazards during ballast tank maintenance process on-board ship.

A case study on risks for dangerous cargo operations in chemical/oil tankers was performed to improve maritime safety (Sakar and Zorba, 2017). The fuzzy Bayes Network approach was adopted to determine probabilistic relationships between the causes of fire and explosion accidents which occurred during the tank cleaning process in chemical/oil tanker ships. At the end of paper, necessary precautions are recommended to prevent risks of fire and explosion in the tank cleaning process. A probabilistic collision-risk analysis of vessel with offshore platforms was discussed by using automatic identification system (AIS) database (Mujeeb-Ahmed et al., 2018). A statistical distribution of the ship traffic was performed. Thereafter, the information was used to estimate collision frequencies and impact energies for various categories of vessel by using a simple probabilistic method.

A Bayesian Network approach was used for maritime transportation risk analysing (Baksh et al., 2018). A case study of oil-tanker navigating Northern Sea Route (NSR) was performed to investigate the possibility of marine accidents such as collision, foundering and grounding. The study demonstrates the priority of the model in investigating operational risk of maritime accidents. A similar study was performed for risk assessment of a ship stuck in ice in Arctic waters (Fu et al., 2018). The paper introduces a Frank copula-based fuzzy event tree analysis approach to evaluate potential risks of severe ship accidents in Arctic waters. Necessary risk control measures are discussed to ensure safe operation in maritime transportation through Artic Area.

A quantitative maritime risk assessment approach was adopted by integrating Bayesian rules and least squares estimation method to determine the dominant factors contribute to collision accidents (Zhang et al., 2018). The findings of the paper indicate that risk of smaller ships is higher than larger ships. An analytic hierarchy process (AHP) under fuzzy sets environment were used to evaluate the severity of hazards for search and rescue operations (Karahalios, 2018). In the paper, the method includes common criteria in ascertaining the risk factors of identifying a ship with radio communication failures. A specific case study is performed to illustrate the applicability of the proposed method.

An oil spill risk analysing was performed by using interval type-2 fuzzy FMEA approach (Akyuz and Celik, 2018a). Hence, a quantitative risk-based approach was presented to perform a comprehensive risk analysis. Risk priority numbers were

determined for the potential failure modes during oil spill incident. An oil spill case resulting from the collision of chemical/oil tanker ship was illustrated as an application. Risk mitigation strategies were recommended to pollution prevention in maritime environment. A similar study was performed to determine role of human factor in risk assessment (Akyuz and Celik, 2018b). A hybrid approach combining Success Likelihood Index Method (SLIM) with fuzzy logic is used to determine risk level. The paper offers a quantitative risk assessment and applied to a specific case on-board ship. Ballast water treatment system is illustrated as a case study.

Aziz et al. (2019) has performed a fresh study on the topic of operational risk assessment for vessel. In the paper, bow-tie approach has been used to assess risk. A single engine ice-breaker bulk carrier is demonstrated as a case study for this paper.

In the light of detailed literature reviewing, it points out that there are various risk analysing papers undertaken by the researchers. However, there is no specific study performed through cargo liquefaction on-board ship. In this context, the aim of this thesis is to conduct comprehensive risk analysing on the topic of cargo liquefaction problem on-board bulk carrier ships. Next chapter defines the methodology used in the research.

3. METHODOLOGY

This chapter defines methodological background of the research discussed on the thesis. The method includes two numerical methods, which consists of Fault Tree Analysis (FTA) under fuzzy sets environment and Event Tree Analysis (ETA). The method is sometimes called as bow-tie technique since it looks like a bow-tie. In this context, the next section defines each methodology used in the thesis.

3.1 Fuzzy Sets

Zadeh (1965) introduced fuzzy numbers to tackle with vagueness or imprecision in judgement of human in decision-making. The fuzzy sets are considered as an extension and simplification of conventional sets of numbers. It is also known as context of set membership function which is showing degree of membership in the sets. The main difference among the fuzzy set and classical set of number is element involving. Since the fuzzy set involves elements that address imprecise property of membership, the classical set provides precise membership. For instance, it is always difficult to describe quantitatively how an object appears.

In practical, fuzzy sets theory will use if there is an imprecision in judgement of human in the decision-making. The linguistic variables are utilised to convert idea of decision maker into the reasonable knowledge (Akyuz and Celik, 2015). The theory will be used in any methods which judgement of experts/decision-makers can be expressed in natural language such as low, medium high, very high, etc. (Castigla and Giardina, 2013).

The theoretical definition of fuzzy sets can be depicted as follows. In the theory, basically a fuzzy subset A in X is characterized by a membership function $\mu_A(x)$, which is conjucted with each element x in X with a real number in the interval [0, 1]. The equation $\mu_A(x)$, illustrates the membership of x in the fuzzy set A (Akyuz, 2016; Castigla and Giardina, 2013). The membership function of fuzzy sets is particularly defined as triangular or trapezoidal. The triangular fuzzy set numbers are defined as

triplets x_1, x_2, x_3 and the membership function $\mu_A(x)$ is expressed as following formulas (Akyuz, 2016).

$$\mu_A(x) = \begin{cases} \dfrac{x - x_1}{x_2 - x_1}, x_1 \leq x \leq x_2 \\ \dfrac{x - x_2}{x_3 - x_2}, \quad x_2 \leq x \leq x_3 \\ 0, \qquad otherwise \end{cases}, \quad where\ x_1 < x_2 < x_3 \qquad (\mathbf{3.1})$$

x_1, x_2, x_3, x_4 can be stated to express the trapezoidal fuzzy sets numbers. Accordingly, the membership function $\mu_A(x)$can be described as following equations.

$$\mu_A(x) = \begin{cases} \dfrac{x - x_1}{x_2 - x_1}, x_1 \leq x \leq x_2 \\ 1 \quad x_2 \leq x \leq x_3 \\ \dfrac{x - x_4}{x_3 - x_4}, \quad x_3 \leq x \leq x_4 \\ 0, \qquad otherwise \end{cases}, \quad where\ x_1 < x_2 < x_3 < x_4 \qquad (\mathbf{3.2})$$

3.2 Fault Tree Analysis (FTA)

Fault Tree Analysis is one of the robust risks analysing tool which is generally used for most of disciplines. The method tackles with occurrence of unwanted events where nature of work such as nuclear, petrochemical, aviation, transportation, etc. poses higher risks. It enables systematic approach to predict risk level of complex system. Since the method is capable to solve complex systems, it has been widely used in literature, particularly in maritime transportation.

In the literature, conventional FTA method was rarely used due to some limitations addressed. For instance, Tanaka et al. (1983) discussed probabilities of basic events (BE) on the topic of trailblazer case. Thereafter, FTA extended with various methodology to overcome potential limitation of it. For example, fuzzy algebra was integrated into the FTA to assess system on basis of distribution of possibilities of BEs (Misra and Weber, 1990). Likewise, Cheng and Mon (1993) presented a hybrid methodology by considering the failure probabilities of BEs associated with triangular fuzzy sets.

Zhang eat al. (2019) has recently been proposed a robust tool combining Human Factors Analysis and Classification System (HFACS) to the FTA for factors of

collision accidents risk. A qualitative risk analysis is carried out to analyze collision risk factors.

In the view of basic literature reviewing conventional FTA application in maritime transportation, it can be noted that although the method has some limitations, it is still applicable to perform risk analysing. The FTA was developed by Bell laboraties in 1963. The method performs a systematic risk assessment tackling with the likelihood of undesired incidents. A fault tree scheme is depicted to determine root causes of the problem (Goodman, 1988). It commences with the construction of tree associated with "top event". The logic events of the FTA are illustrated in Figure 3.1.

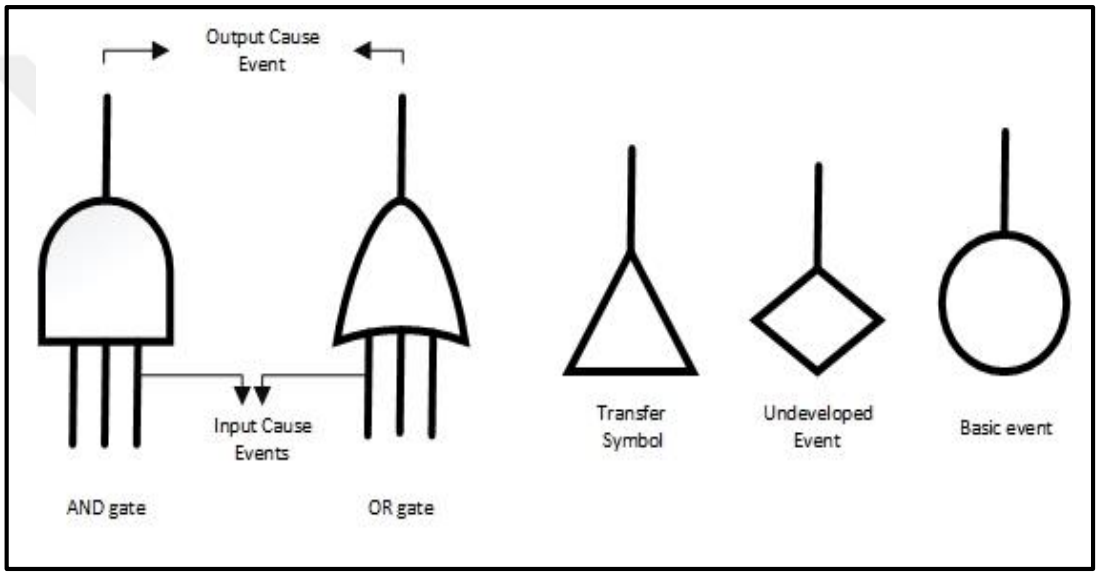

Figure 3.1: Symbol used in FTA method (Senol et al., 2015).

Top events address most risky situation that the risk analysing has been performed. Basic events are the factors that lead to occurrence of top events. The fault tree diagram is constructed top to down direction since the graphic depicts the pathway within the system. The common logic symbols illustrated in Figure 3.1 defines the fault tree diagram. Accordingly, AND and OR gates are the most common logic gates utilised in the FTA. In the method, AND gate means that outputs exist only if all inputs events exist. For instance, the fuel, ignition and oxygen are required for fire occurrence. Hence, AND gate is used in this context because all three need to be presented at the same time to occur fire. Likewise, OR gates mean that output event exists if any one input event exists. Any of event occurrence is enough to exist OR gate. The rest of logic symbol such as basic event (BE) states a basic initiating failure/events to lead top event. Undeveloped event, on the other hands, means that an event which is not

requiring further development or not requiring further resolution. A triangular symbol defines “transfer” which states the diagram tree is developed for further fault tree diagrams (Stapelberg, 2008). In this insight, the main aim of the FTA is to create a logic diagram in order to follow all branches of events that might contribute to accident in risk management. The FTA consists of following main steps (Dhillon, 2008).

Step 1: This step enables to define the top event of the FTA with physical borders, initiating conditions as well as limitation of external loads.

Step 2: In this step, the FT diagram is constructed and each failure modes are defined and evaluated.

Step 3: This step provides to place minimal cut and path sets.

Step 4: A qualitative analysing of fault tree is performed.

Step 5: A quantitative analysing of logic is carried out. Then, likelihood of the top event and reliability of BEs are evaluated.

Step 6: Discussion and reporting is conducted to analyse outcomes.

3.2.1 Notation and quantification process of logic gates

Let $Q_0(t)$ is the probability of the top event occurs at time t, $q_i(t)$ probability of the basic event i occurs at time t. $Q_0(t)$ is the probability of the minimal cut set j fails at time t. (Senol et al., 2015).

Let states for the basic event i happens at time t.

Accordingly, AND gate can be calculated as;

$$\text{Let } q_1(t) = P(E_i(t)) \text{ for i=1,2.} \qquad \textbf{(3.3)}$$

Probability of top event $Q_0(t)$ can be stated as;

$$Q_0(t) = P(E_1(t) \cap E_2(t)) = P(E_1(t) \square E_1(t)) = q_1(t) \square q_2(t) \qquad \textbf{(3.4)}$$

In case of a single AND gate with n events, then;

$$Q_0(t) = \prod_{j=1}^{n} q_j(t) \tag{3.5}$$

On the other hands, OR gate can be formulated as;

Let denotes $q_1(t) = P(E_i(t))$ for i=1,2.

Probability of top event $Q_0(t)$ is

$$\begin{aligned} Q_0(t) &= P(E_1(t) \cup E_2(t)) = P(E_1(t)) + P(E_1(t)) - E_1(t) \cap E_2(t) \\ &= q_1(t) - q_2(t) - q_1(t) \square q_2(t) = 1 - (1 - q_1(t)) \square (1 - q_2(t)) \end{aligned} \tag{3.6}$$

In case of a single AND gate with n events, then;

$$Q_0(t) = 1 - \prod_{j=1}^{n} (1 - q_j(t)) \tag{3.7}$$

3.2.2 Cut set assessment and top event probability

In the view of above equations, cut set assessment can be calculated with following formula since a minimal cut set (MCS) fails in case all *r* basic events fail simultaneously. The likelihood of the cut set *j* fails at the time of t is (Senol et al., 2015);

$$\phi_j(t) = \prod_{i=1}^{n} q_{j,i}(t) \tag{3.8}$$

Top event probability will be defined according to the equation (3.9) since MCS is associated to the TE by an OR gate. Hence, minimum one of the MCSs fail the TE occurs. The following equation shows probability of TE;

$$Q_0(t) \leq 1 - \prod_{j=1}^{k} (1 - \phi_j(t)) \tag{3.9}$$

3.3 Event Tree Analysis (ETA)

Event tree analysis is of paramount for the most of risk analysing research since it is capable to define consequential events. It is commonly used to investigate consequences of events to figure out mitigation strategies rather than loss prevention. Figure 3.2 depicts basic structure of the ETA approach. As illustrated, the fundamental approach of the ETA which consists of only two options such as yes/no, on/off, failure/success, etc. It aligns to start on the left with initiating event and process continues to the right by comparing progressively. In the figure, each branching is referred as a node. After performed detail analysing and creating the event tree diagram, the risk of each path is assessed.

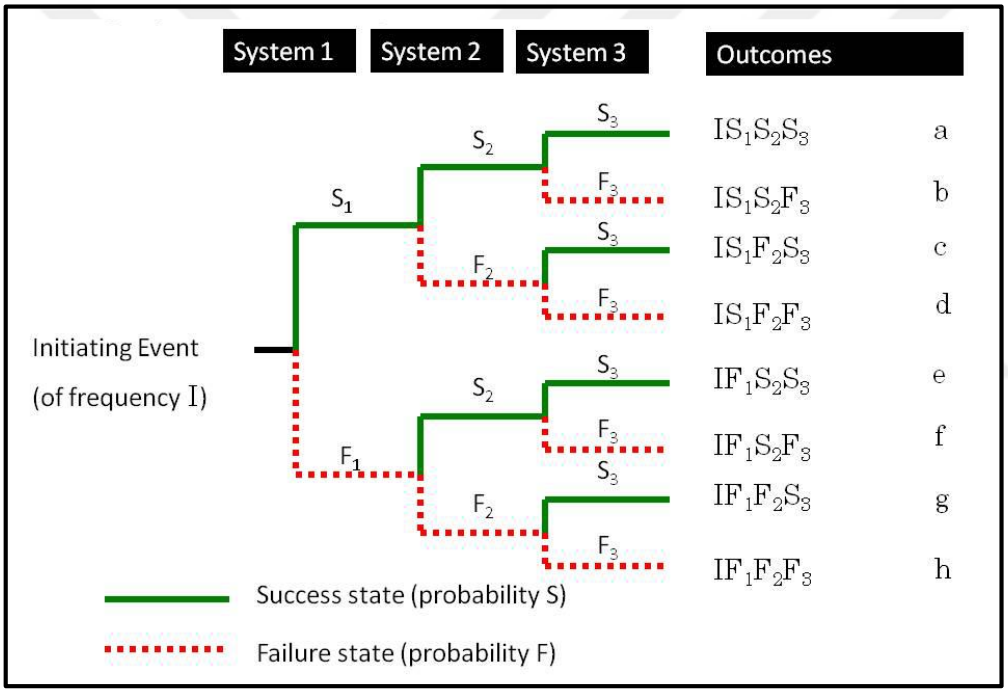

Figure 3.2: Basic structure of the ETA.

In the literature with respect to the maritime transportation, the ETA was applied to FTA and called as bow-tie analysis. For instance, the ETA was applied to the maritime accident investigation cases. Raiyan et al. (2017) performed a study on the topic of maritime accident. In the paper, authors applied event tree to perform quantitative study in analyzing maritime accidents in Bangladesh. Another paper utilising ETA approach has been introduced to analyse potential risks in Strait of Gibraltar (Endrina et al., 2018).

The method comprises of a couple of steps to perform a risk assessment. The basic steps of the method are listed below.

i. Determining the primary event of concern.

ii. Determining the control which are nominated to cope with the prior event such as safety control system or operator actions.

iii. Establishing the event tree diagram starting with the initial event and proceeding through faults of safety.

iv. Building the final accident sequences.

v. Identifying the critical faults which require to be referred.

In the event tree analysis method, some of rules to be applied to compute potential risks. In order to find total frequency of each output, it should be multiplied along with branches, counting from left to right from initiating event to final output. Thereafter, the sum of all output frequency will insert to equal frequency of the initiating event.

3.4 Fuzzy Fault Tree Analysis (FFTA)

This section gives basic information about FFTA as well as literature reviewing performed in maritime transportation. The fuzzy sets theory is used under FTA approach to cope with vagueness and ambiguity. The method is extended with fuzzy sets theory since there is lack of data to calculate failure probability in maritime transportation.

The fault tree analysis under fuzzy sets environment plays critical role to determine potential root causes of events. The fuzzy fault tree analysis (FFTA) is widely applicable to carry out risk analysing in various disciplines such as petrochemical, nuclear, transportation, etc. In the maritime industry, a couple of robust papers have been undertaken to adopt FFTA during risk analysing. For instance, Celik et al. (2010) introduced a risk-based modelling by using fault tree analysis under fuzzy sets environment. The paper applied on maritime accident investigation and contributed to enhance maritime safety as well as to prevent risk of maritime accident. Likewise, another risk-based approach paper was presented to perform risk analysing of leakage in abandoned oil and natural gas well in ocean engineering (Lavasani et al., 2015). In the paper, authors utilised FFTA to conduct risk analysing for leakage through PA oil

and natural-gas wells in off-shore industry. Since there is lack of failure probability data, fuzzy sets are employed to tackle with ambiguity.

A root cause analysis was performed to investigate the marine accidents in recent years (Kum and Sahin, 2015). The FFTA is adopted in this paper to carry out a detailed risk analysing. To illustrate the model, fault trees of collision and grounding accidents for the Arctic Region is established to prevent similar accident in advance. Another paper using FFTA was applied to evaluate potential risks during cargo contamination in chemical tanker ship (Senol et al., 2015). Root causes of cargo contamination are found by gathering occurrence of probabilities under FFTA approach. A similar study was performing to analyse potential risks in off-shore industry (Sahin et al., 2017). The FFTA is adopted to carry out risk analysing. The fuzzy analytic hierarchy process (FAHP) is also used to extend the method for checking the consistency since it is one of the robust multi criteria decision making method. A real-case study on collapse of off-shore platform is selected to apply the proposed method.

A collision risk modelling was introduced by using FFTA in maritime transportation industry. A case study on collision between supply vessel and off-shore platform is demonstrated to enhance maritime safety and minimize potential risk (John and Osue, 2017). A recent study has been performed to analyse potential risks during mooring operations (Kuzu et al., 2018). In the paper, the FFTA is used to conduct risk assessment. A case study on parted rope injuries during mooring operations is performed to depict the model applicability. A similar study was performed to investigate potential risks in the case of crankcase explosion in marine engineering (Unver eta al., 2019). The FFTA is used to determine risk probabilities during crankcase explosion in marine diesel engine.

3.5 Integration of Methodologies

This section expresses integration of methodology to perform a comprehensive risk analysing. In the thesis, Fault Tree Analysis and Event Tree Analysis is combined under fuzzy sets environment since there is uncertainty of crisp value of probability. A conceptual framework of the integrated methodology is illustrated in Figure 3.3.

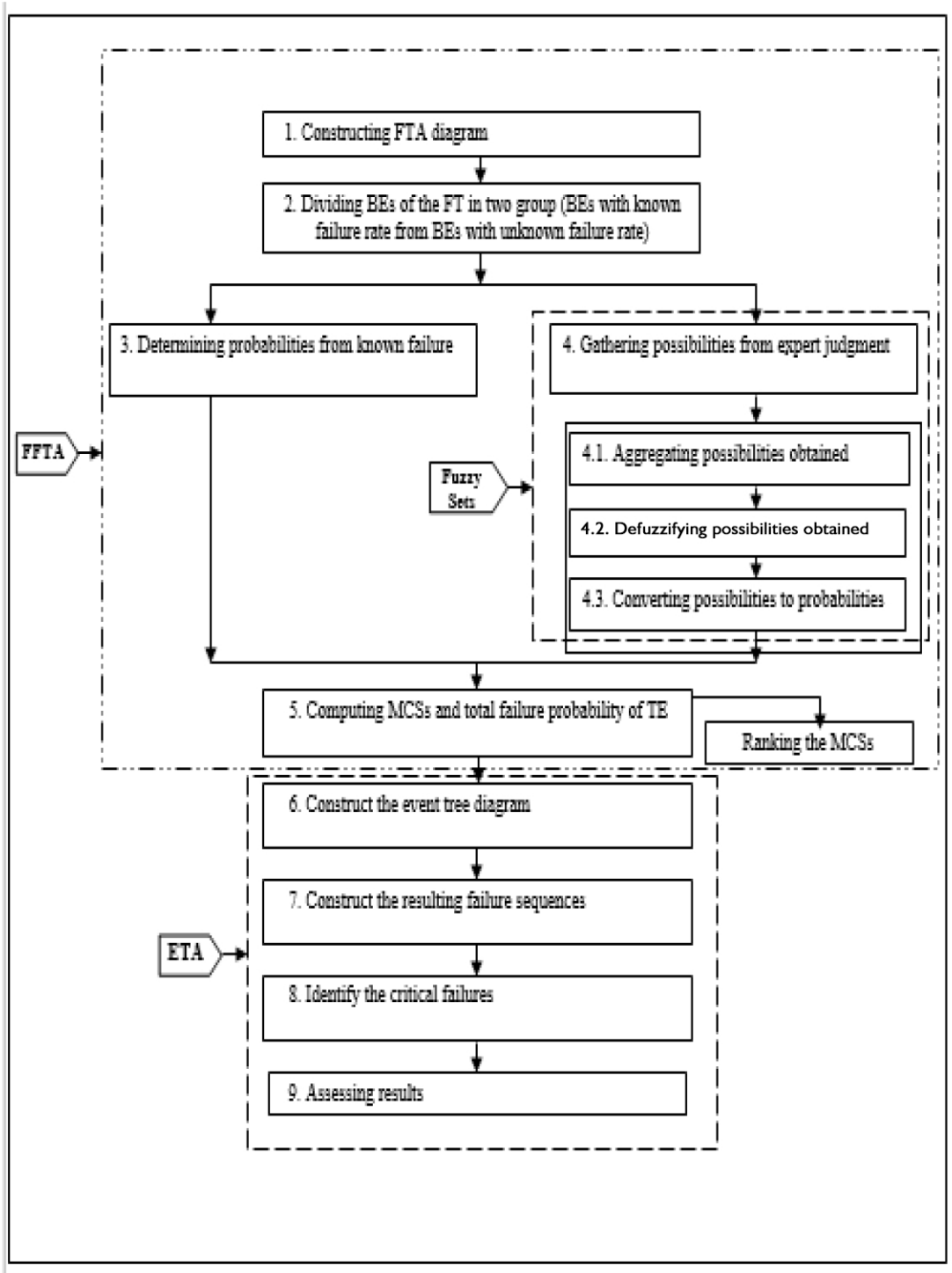

Figure 3.3: Conceptual framework of methodology.

In conventional FTA, the failure likelihood of system is considered as crisp values in estimating the failure probability of the Top Event (TE) (Khan and Husain, 2001). One of great challenge to calculate failure rate of component for maritime transportation is scarcity of data (Lavasani et al., 2015). To tackle with aforementioned limitations, the fault tree analysis under fuzzy sets theory was adopted. The fundamental objective of the FFTA is to state potential failures of the system defined in the process. It is capable of evaluating probability of TE by utilising analytic methods that are requiring reliability in quantitatively (Lavasani et al., 2015). The judgement of expert is an alternative solution for data scarcity in maritime transportation (Soner et al., 2017).

In the decision-making process, most of stance are based on qualitative statements and possibility. The probabilistic terms are rarely used due to the data scarcity. In this context fuzzy sets are adopted to tackle with ambiguity and vagueness. Hence, possibilities judgements acquired by experts are transformed to probabilities to compute likelihood (Celik et al., 2010). Implementation of fuzzy sets theory improves accuracy of judgements and enables to elicit expert judgement in natural language as linguistic parameters (Akyuz and Celik, 2018a). Although, it appears that no major difference is of between two words, probability can be stated as numerical value of possibility of a failure/event. It refers to a quantitative expression in probabilistic safety analysis.

In the light of fundamental background of methods and conceptual framework, the hybrid-risk based approach including FFTA and ETA (bow-tie approach) comprises of following implementation steps.

3.5.1 Constructing FT diagram

The first step of the hybrid methodology is to create FT diagram whose aim is to find out probability of TE. Hence, unexpected event/failure of the system is extensively analysed. A block diagram is constructed to display the failure of the system from top event to basic events. The TE is of paramount importance for the system and risk analysing will be performed to calculate probability of TE which has catastrophic consequences for human, commodity and environment at all. Figure 3.4 illustrates a basic fault tree diagram.

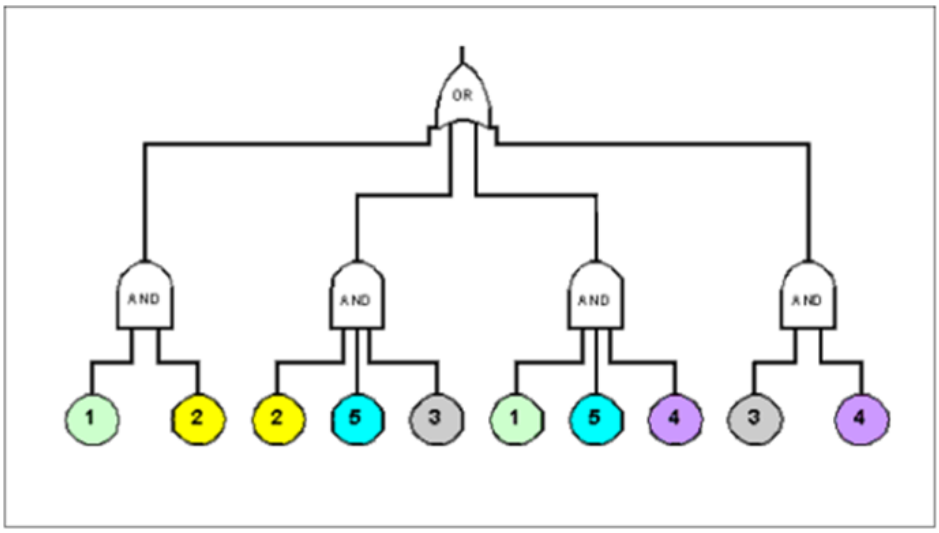

Figure 3.4: Basic fault tree diagram.

3.5.2 Determining probabilities from known failure

After construing fault tree diagram based on chain logic of the system, probabilities are determined from database. Since there is lack of failure probability data in maritime transportation industry, the probability of failure is calculated by using expert elicitation.

3.5.3 Calculating possibility from expert judgement

Ship management companies keep their data records due to requirements of international code and convention. However, they are not eager to share their data records due to commercial reason. Therefore, there is always data scarcity in maritime transportation industry. Maritime safety researchers and practitioners have attempt to extend their scientific researches without using data. Gathering operational data on the nature of maritime works is very challenging and mostly unknown. To address this concern, the experts' judgements are used to cope with vagueness and scarcity (Lavasani et al., 2015). The experts give their viewpoint for each basic event since the BE plays critical role to initiate chains of events. The judgement of experts, on the other hands, may not be equal since they have different level of experiences, education, institutional and intellectual accumulation of knowledge, etc. This is called as heterogeneous group of experts. At this point, the expert's evaluation is affected by the degree of importance. The weighting score of experts is required to increase

accuracy rate of assessment and to avoid the research questionable. There have been a couple of studies assessing weighting score associated with experts' elicitation. Yuhua and Datao (2005) presented a study handling weighting score of relative quality of different experts. The score can be ascertaining according to the education, age, edcution level, title of experts, etc.

In the view of above, the expert judgement is used to calculate possibility of each basic event. The linguistic terms used for experts are practical way to convert possibilities to probabilities. Meantime, table 3.5 demonstrates weighting scores of heterogeneous group of expert (non- homogenous) (Senol et al., 2015).

Table 3.1: Weighting scores of non-homogenous experts.

Group	Classification	Score
Professional position	Ship Operator	5
	Master of ship	4
	Academician	3
	Chief officer	2
	Junior officer	1
Sea service time	≥ 16 years	5
	11-15	4
	6-10	3
	3-5	2
	≤ 2	1
Education Level	PhD	5
	Master	4
	Bachelor	3
	HND	2
	School level	1
Shore service time	≥ 20	5
	15-19	4
	10-14	3
	6 – 9	2
	≤ 5	1

Hsu and Chen (1994) introduced a group of expert elicitation method which was proposed for non-homogeneous group of experts. The method is regarded as SAM (Similarity Aggregation Method) to convert linguistic terms to their corresponding fuzzy numbers. The basic steps of SAM methodology are descriped as follows.

Step 1. Aggregating obtained possibilities: In the first step of SAM, the possibilities are aggregated. To achieve this purpose, assume each expert, $E_k(k = 1, 2, \ldots, M)$ states his/her viewpoint on a particular attribute contrast to specific context by a

predefined set of linguistic variables. Then, the linguistic terms of experts are converted to related fuzzy numbers. The detail of equations is explained as follows (Senol et al., 2015; Lavasani et al., 2015).

1. Calculating degree of agreement:

In the sub-step, $E_u$andE_v defines each pair of experts and $S_{u\,v}(\tilde{R}_u, \tilde{R}_{u,})$ gives views of experts where $S_{u\,v}(\tilde{R}_u, \tilde{R}_v) \in [0,1]$. In this context, $\bar{A} = (a_1, a_2, a_3, a_4)$ and $\bar{B} = (b_1, b_2, b_3, b_4)$ are two generic trapezoidal fuzzy numbers. The equation (3.10) is utilised to calculate degree of similarity between two fuzzy numbers by adopting the similarity function of S.

$$S(\tilde{A}, \tilde{B}) = 1 - 1/4 \sum_{i=1}^{4} |a_i - b_i| \qquad (\mathbf{3.10})$$

where $S(\tilde{A}, \tilde{B}) \in [0,1]$.

The larger value of $S(\tilde{A}, \tilde{B})$ the greater similarity among the two fuzzy numbers of $\tilde{A}\ and\ \tilde{B}$.

2. Calculate Average Agreement (*AA*) degree AAE_u of the experts:

In the second sub-step, an equation (3.11) is employed to compute average agreement degree of the experts.

$$AA(E_u) = \frac{1}{M-1} \sum_{u \neq v}^{M} S(\tilde{R}_u\ , \tilde{R}_v) \qquad (\mathbf{3.11})$$

3. Determine Relative Agreement (RA) degree, $RA(E_u)$ of the experts:

Equation (3.12) is utilised to determine relative agreement degree of experts.

$$E_u(u = 1,2, \dots, M) as RA(E_u) = \frac{A(E_u)}{\sum_{u=1}^{M} A(E_u)} \qquad (\mathbf{3.12})$$

4. Predict Consensus Coefficient (CC) degree, *CC* (E_u) of the experts:

Following equations are used to predict consensus coefficient degree of the experts.

$$E_u: (\mathrm{u} = 1,2, \dots, \mathrm{M})$$

$$CC(E_u) = \beta . w(E_u) + (1 - \beta) . RA(E_u) \qquad (\mathbf{3.13})$$

5. Aggregate result of the experts' judgements:

The final sub-step of the SAM is to aggregate result of the experts' judgments (*AG).* The following equation si used for calculation.

$$\tilde{R}_{AG} = C(E_1) \times \tilde{R}_1 + C(E_2) \times \tilde{R}_2 \ldots . C(E_M) \times \tilde{R}_M \qquad (\mathbf{3.14})$$

Step 2. Defuzzifying of aggregated expert judgment (Fuzzy Possibility): The second step is to defuzzify of aggregated expert judgement. Triangular or trapezoidal fuzzy numbers are converted into crisp numbers under fuzzy sets. In this aspect, the center of area (COA) technique is used for Defuzzification (Lavasani et al., 2015). Following equation is used for COA technique.

$$X^* = \frac{\int u_i(x) x dx}{\int u_i\,(x)} \qquad (\mathbf{3.15})$$

In the equation, X^*gives fuzzy possibility, $u_i(X)$ defines aggregated membership function and *X* states the output variable.

Step 3. Converting possibilities to probabilities: In the third step, possibilities obtained from judgement of experts are converted into probabilities. To accomplish this, Onisawa (1988) presented a formula to transform fuzzy failure possibilities to fuzzy failure probabilities. The rate of fuzzy probability (FP_T) are taken from fuzzy possibility (*FPs*) rates. The following equations illustrate how *FPs* rates of MCSs are converted to the FP_T values.

$$Pr = \begin{cases} \frac{1}{10^k}, FPs \neq 0 \\ 0, FPs = 0 \end{cases} \qquad (\mathbf{3.16})$$

$$K = [\left(\frac{1 - FPs}{FPs}\right)]^{1/3} \times 2.301 \qquad (\mathbf{3.17})$$

3.5.4 Computing MCSs and total failure probability of TE

Fault tree diagram contains numerous MCSs since it is one of the most critical components of the FTA. The MCS is used to determine structural vulnerability of the system. The MCS can be illustrated with following formula.

$$T = MCS_1 + MCS_2 + \cdots + MCS_N = \bigcup_{i=1}^{n_c} MCS \tag{3.18}$$

In the view of above, the occurrence probability of TE can be calculated with following equation. The following equation is valid only certain limited conditions each MCS is independent.

$$\begin{aligned} P(T) &= P(MCS_1 \cup MCS_2 \cup \ldots \cup MCS_N) \\ &= P(MCS_1) + P(MCS_2) + \cdots P(MCS_N) - (P(MCS_1 \cap MCS_2) \\ &\quad + P(MCS_1 \cap MCS_3) + \cdots P\left(MCS_i \cap MCS_j\right) \ldots) \ldots \\ &\quad + (-1)^{N-1} P(MCS_1 \cap MCS_2 \cap \ldots \cap MCS_N) \end{aligned} \tag{3.19}$$

The MCS, which is a collection of BE, is used to obtain probability of the TE in the method. The TE will occur if all of BE are being succeed. The BEs are undesired events in the system and cause to the TE. According to the Andrews and Moss (2002), fault tree has MCS introduced by $i = 1, \ldots\ldots, n$. At this point, if there is one MCS, it would be the TE "*Z"*. In this context, following formula can be used.

$$Z = MC_1 + MC_2 + \cdots + MC_{n_c} = \bigcup_{i=1}^{n_c} MC_i \tag{3.20}$$

In the equation, $P(MCS_i)$ gives probability of the MCS_i and N states the number of MCS.

3.5.5 Ranking the MCS

Fault tree diagram is able to give priority of each MCS in the system since it is one of the most critical elements of FFTA approach during risk analysing. The ranking of the MCS addresses magnitude degree in the course occurrence of the system TE. In the light of Vesely-Fussell Importance Measure (V-FIM), the MCSs can be ranked. Following equation can be recommended to calculate ranking the MCS.

$$I_i^{VF}(t) = \frac{Q_i(t)}{Q_s(t)} \qquad (\mathbf{3.21})$$

In the equation, $I_i^{VF}(t)$ defines the magnitude of MC_i, $Q_i(t)$ states occurrence probability of MC_b and $Q_i(t)$ gives occurrence probability of the TE in all MCS.

3.5.6 Constructing event tree diagram

In this step, event tree diagram is constructed by identfying an initating event of the failure/system. It is requiring to define the safety functions designed to tackle with the initiation followed by the affect of the system safety. Then, event tree is built up.

3.5.7 Constructing results of accident/failure sequences

In this step, accident/failure event sequences are descripted. The relevant events are the other critical of events that may cause in the accident consequence, which may emerge after the initiating event.

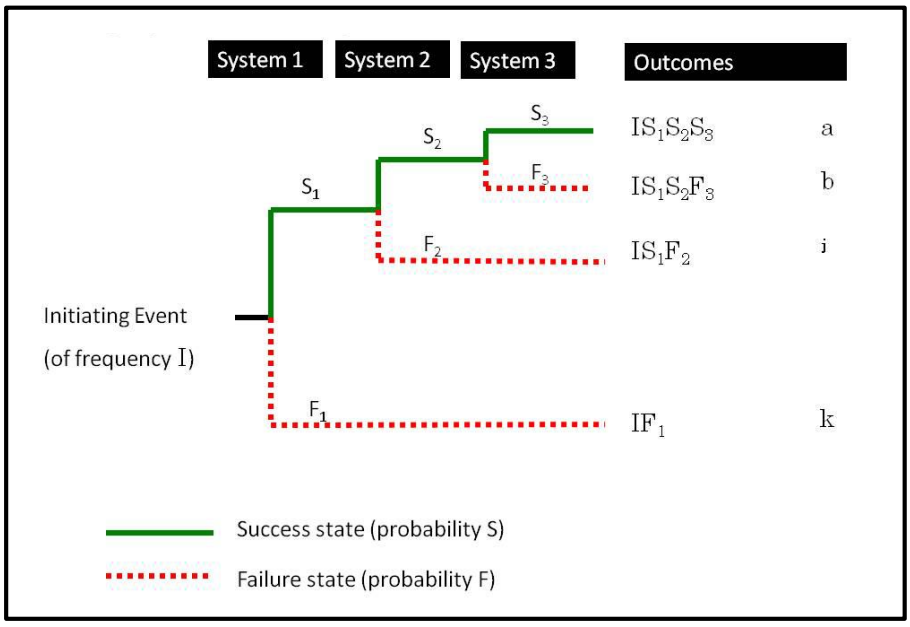

Figure 3.5: Accident/failure sequence in ETA.

3.5.8 Identfying critical failures

In this step, the initial event is placed on the left corner of the diagram and related segment events on the right side in order. Thereafter, it can be written a lateral line from the initiating event to the first event. Then, a vertical line is drawn at the end of lateral line. The TE of the lateral line shows success and the lower end of the system depicts failures. Likewise, the process is continued untill at the end of events.

3.5.9 Assessing results

In the final step, the overall results, which have been emerged from initiating events, are evaluated. In order to improve simplicity, the initial events and the sequences are marked with diffirent symbol or colour (Wang, 2018).

4. QUANTITATIVE RISK ANALYSING IN MARITIME TRANSPORTATION

Safety is highly cited topics in maritime transportation researches and have been gaining interest since last decades. The safety practitioners and researchers have attempt to introduce proactive tools to enhance maritime safety as well as pollution prevention. The risk is one of the important pillar of the maritime safety assessments since it has a contrast of meaning in practice. In other words, it is necessary to decrease potential risks in order to improve safety. The basic process of the risk management is illustrated in Figure 4.1 where the process starts with identifying potential risks (Plan). The second step is to evaluate risks and eliminate (Do). The next step is to take control measures and monitor progress (Check). The final step is to review and provide improvement (Act).

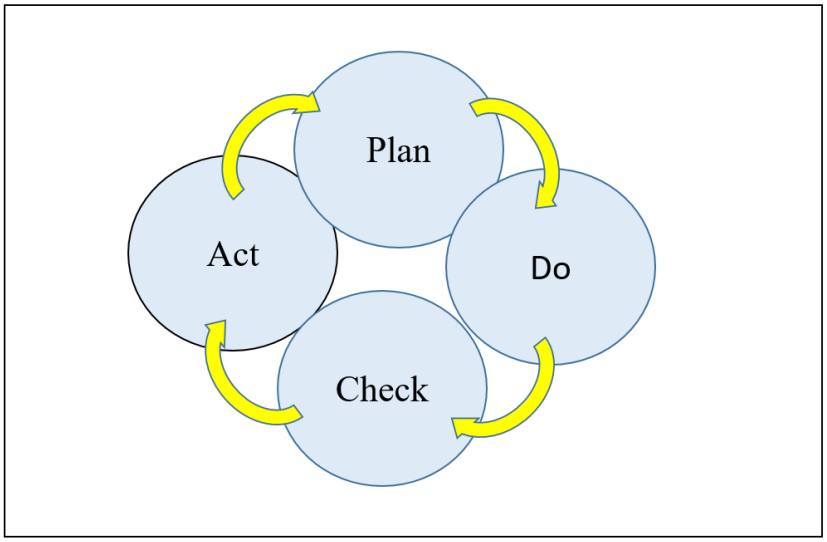

Figure 4.1: The basic process of the risk management.

In the maritime transportation, the regulatory body of maritime affairs - IMO, introduced a guidance namely called Formal Safety Assessment (FSA) which aims to structure a systematic risk analysing approach to enhance maritime safety. It consists of some fundamental implementation steps such as identification of potential hazards, analysing risks, recommending risk control measures and cost-benefit analysis (IMO,

2018). Although FSA addresses a risk assessment guidance for shipping companies, it does not develop a specific risk analysing tool in practice. Therefore, maritime professionals are looking for efficient and practical methods to predict risk exposure to improve safety and risk awareness in maritime transportation. Since shipboard operations pose potential harms to ship crew, commodity and maritime environment due to the nature of work, maritime professionals are trying to improve risk control strategies by adopting proactive approaches.

The bow-tie approach (FTA and ETA) under fuzzy sets logic utilised in the thesis is one of the robust proactive risk analysing tool to estimate risk quantitatively. The basic illustration of the approach is depicted in Figure 4.2.

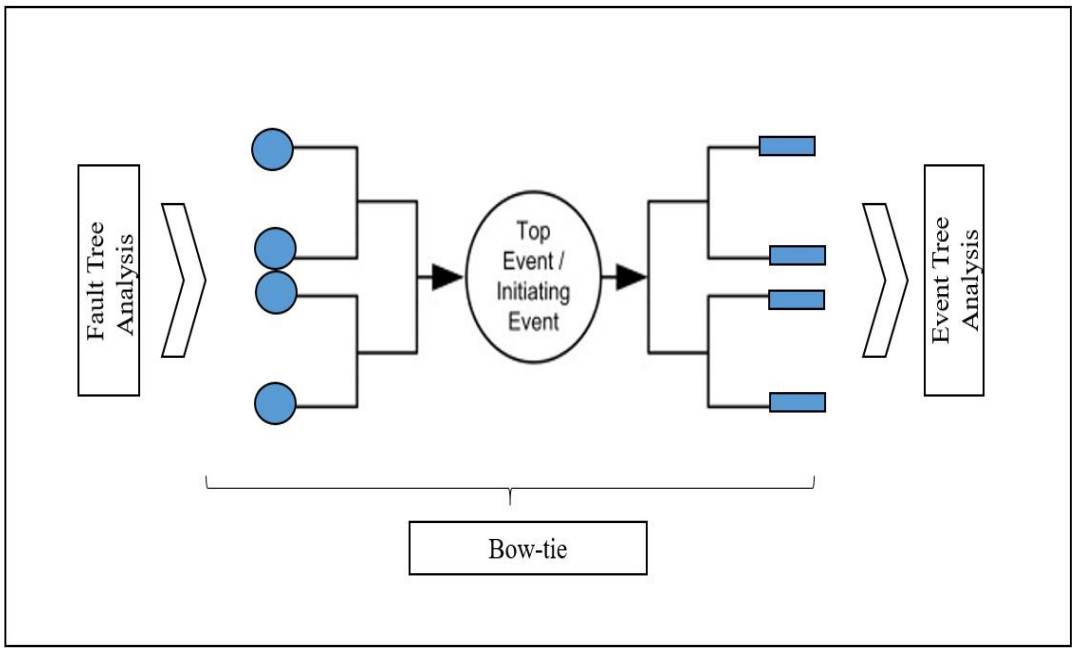

Figure 4.2: The bow-tie approach.

In the view of above, this thesis performs a quantitative risk analysing by considering potential human error during liquefaction of dry bulk cargo shipment in maritime transportation. The liquefaction come out specific type of dry bulk cargoes where moisture content exceeding their transportable moisture content (IMSBC Code). There are various ship incidents recorded so far resulting from liquefaction such as MV Mega Taurus, MV Oriental Angel, MV Jag Raghul, etc. (Colak and Satir, 2014). A specific case study is demonstrated to analyse potential risks of cargo liquefaction in maritime transportation.

4.1 Analysing Risk of Cargo Liquefaction in Dry Bulk Cargo Shipment

The seaborne trade is of more than 80 percent of the total trade volume of world according to the UNCTAD report (UNCTAD, 2018). Most of seaborne trade is of dry bulk cargo shipment. Dry bulk cargo ships (bulk carrier) consists of about 40 percent of total world ship fleet. There are wide range of dry bulk cargo types around the world. The stowage and carriage of those cargoes play critical role for safe shipping. The IMSBC Code (International Maritime Solid Bulk Cargoes Code) is introduced by the IMO to govern safe carriage of the dry bulk cargoes shipment. The code was adopted under SOLAS convention in chapter VI. The aim of the code is to manage safe stowage of dry bulk cargoes. It can provide detailed information about potential hazards of solid bulk cargoes carried in ships and provides necessary guidance for correct carriage procedures of dry bulk cargoes.

The potential hazards associated with dry bulk cargo carriage such as improper cargo distribution, loss or reduction of stability and chemical reactions of cargoes are defined in IMSBC Code. According to the code, solid bulk cargoes are classified under three categories. Group A, B and C are introduced as follows (Munro and Mohajerani, 2016):

i. Group A cargoes: These types of cargoes can be liquefied if the cargoes shipped at a moisture content pass over their Transportable Moisture Limit (TML).
ii. Group B cargoes: These types of cargoes may possess a chemical harm that may create a dangerous situation for the ship stability.
iii. Group C cargoes: These types of cargoes can be classified neither Group A nor group B but still pose hazardous such as cargoes of cement, sand, etc.

In the thesis, we are focusing on Group A types of cargoes which may liquefy due to the excessive moisture content. The liquefaction can be defined as a quick transition of the particles, which may transform the cargo from the solid state to viscous fluid (Jonas, 2012). Since the liquefaction is a great challenge for dry bulk cargo shipments, the risk assessment is required to enhance maritime safety. In the literature, there is a

few research undertaken on the topic of dry bulk cargo liquefaction problem. For instance, Zografakis (2013) was performed a comprehensive thesis on the topic of solid bulk cargo liquefaction. The thesis includes experimental procedures and steps that needs to be followed. It also conducted a detailed reviewing for maritime incidents that may arise due to cargo liquefaction in solid bulk cargoes transportation. Likewise, Munro and Mohajerani (2016a) performed a research to discuss the collective potential causes of liquefaction of dry bulk cargoes on maritime transportation. Hence, the research can give some recommendation to avoid similar incidents caused by solid bulk cargo liquefaction for bulk carriers.

Rose (2014) mainly focused on the TML testing method on-board ships. The research corroborated accuracy of the current TML test methods and present finding on them. A technical paper prepared and presented to results performed on three test methods for cargo moisture content defined IMSBC Code 2013 version (Munro and Mohajerani, 2016b). The paper also compared of results where experimental researches undertaken through two testing methods in IMSBC code. A comprehensive numerical analysis on solid bulk cargo liquefaction were performed to validate proposed model for evaluation of cargo liquefaction potential (Vassalos and Boulougouris, 2016). A similar study has been introduced for numerical investigation of dry bulk cargo liquefaction (Ju et al., 2018). In the paper, a new perspective was introduced namely called DEM to validate the experimental analysis of cargo.

In the view of basic literature reviewing conducted on solid cargo liquefaction in maritime transportation, most of them are technical papers dealing with chemical related cargo liquefaction and investigating test procedures of TML. This paper performs a comprehensive quantitative risk assessment on cargo liquefaction. The potential causes of cargo liquefaction will be analysed in detail.

4.2 Problem Statement

Carriage of dry bulk cargoes pose serious risks for bulk carrier ships. These risks have been mentioned in previous section. According to the IMSBC Code, carriage of dry bulk cargo poses various risks such as impro apparently, liquefaction of solid bulk cargoes is one of the most dangerous situations for dry bulk cargo shipment since it causes reducing stability of ships due to the free surface effect. It may also cause cargo shifting. The cargo liquefaction incidents have been continuing with resulting in the

loss of seafarers. Figure 4.3 shows ships numbers exposed to cargo liquefaction around the world seas since 2008.

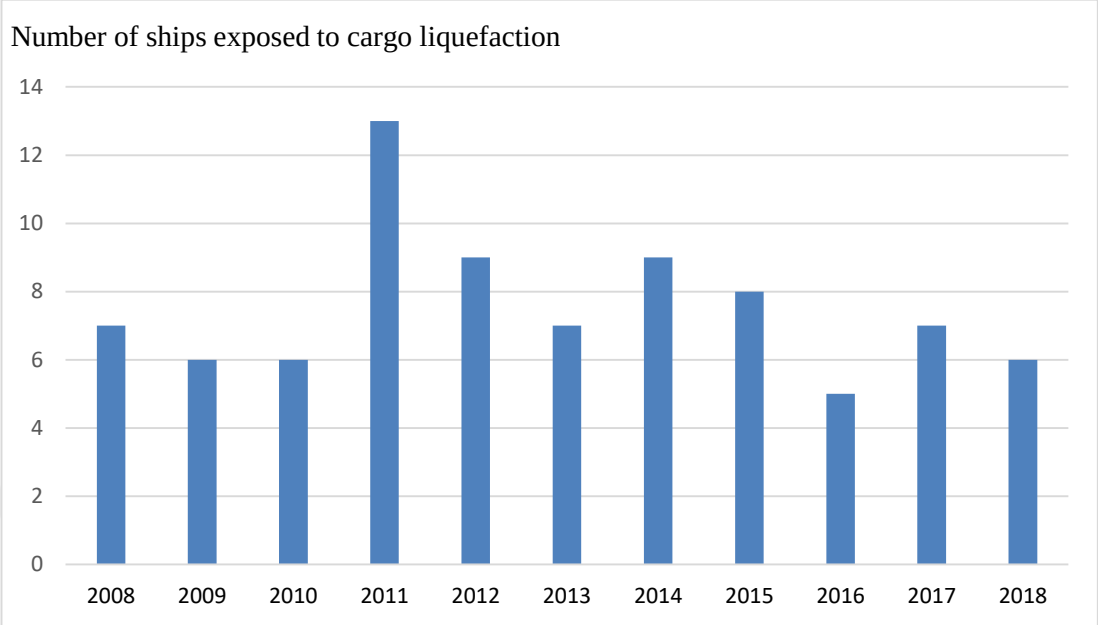

Figure 4.3: Number of ships exposed to cargo liquefaction around the world.

Table 4.1, on the other hands, illustrates some of cases due to cargo liquefaction of solid bulk cargoes. The ships of more than 10,000 deadweight tons and cargo liquefaction was considered as the cause of the causality (DNV-GL, 2015). The ships were sailing around the South-East Asia and it was probably rainy season.

Table 4.1: Some cases due to cargo liquefaction (DNV-GL, 2015).

Vessel	Dwt	Built	Loss of life	Year	Cargo type	Area
Asian Forest	16k	2007	0	2009	Iron ore	India
Black Rose	39k	1977	1	2009	Iron ore	India
Jian Fu Star	45k	1983	13	2010	Nickel ore	Indonesia
Nasco Diamond	57k	2009	21	2010	Nickel ore	Indonesia
Hong Wei	50k	2001	10	2010	Nickel ore	Indonesia
Vinalines Queen	56k	2005	22	2011	Nickel ore	Philippines
Sun Spirits	11k	2007	0	2012	Iron ore	Philippines
Harita Bauxite	50k	1983	15	2013	Nickel ore	Indonesia
Trans Summer	57k	2012	0	2013	Nickel ore	Philippines

As illustrated in Figure 4.3 and Table 4.1, the cargo liquefaction is great challenge for dry bulk cargo shipment, in particular ore cargo such as iron ore, nickel ore transportation (Colak and Satir, 2014). Also, it seems that there is strong tendency

causation of liquefaction to rainy season as the moisture content is one of the fundamental reason of it (Zografakis, 2013). The TML is one of the key function in evaluating in case dry bulk cargo is considered safe for shipping. The TML can indicate the maximum moisture content of dry bulk cargo. The actual moisture content of dry bulk cargo can be measured prior to loading operation. The other key parameter is granular materials which may contain some fine particles. According to the DNV-GL (2015) guidance circular, the particles of the dry bulk cargo materials contact with each other when the transported cargo is in dry bulk form. The friction among the particles produce physical sheering strength. Therefore, the dry bulk cargo inside the ship's cargo holds might be formed to a pile and seems dry. When the ship commences her voyage, the cargo will be accumulated because of ship motion and wave fluctuating. Hence, the gap among the particles will decrease. The water pressure inside the space will increase. This leads to lose of material and the pile of cargo flows out to the surface of the cargo. As a result the cargo transforms to the liquid state. Figure 4.4 illustrates liquefaction of granular materials cargo.

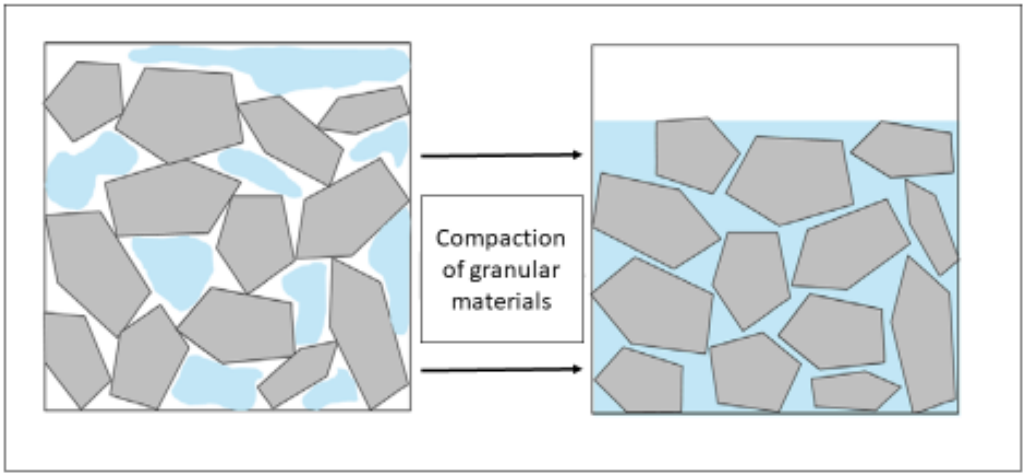

Figure 4.4: Liquefaction of granular materials cargo (DNV-GL, 2015).

On the other hand, non-granular cargoes such as nickel ore, iron ore, etc. has different condition for liquefaction. The basic reason for liquefaction of non-granular cargoes is sort of fatigue of the material (DNV-GL, 2015).

As illustrated in Table 4.1 and Figure 4.3, there are growing numbers of accidents due to cargo liquefaction in dry bulk cargo carriage. When the solid cargo may liquefy, stability of ship becomes critical level. Free surface effect which poses very dangerous situation for ships will occurre if the cargo liquefies. The ship stability becomes very

critical due to free surface effect and even it may list one side and capsize. The other substantial effect of cargo liquefaction through the ship is to list ship one side due to rolling and cargo flowing of dry bulk cargo. At this condition, the ship can experience growing heel angle and may result in a capsizing.

In case the moisture content of dry bulk cargo is in excess of its TML, it may reach its flow moisture point and transforms to liquid form. This may result in an instable condition of ship where the metacentric height (GM) may cause possible loss of the ship (Cargo, 2011). Figure 4.5 shows cargo cargo liquefaction effects to ship stability.

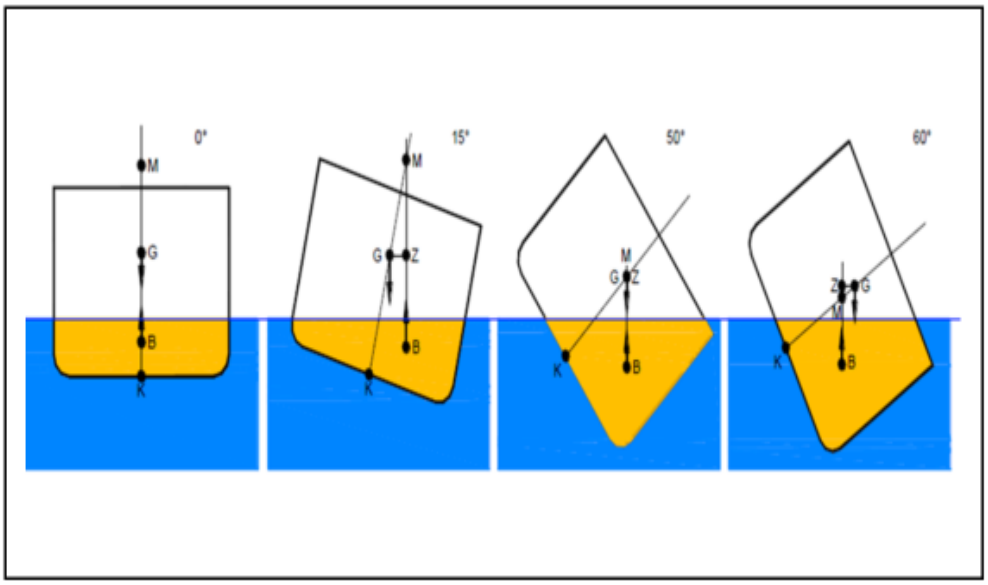

Figure 4.5: Cargo liquefaction effects to ship stability (Colak and Satir, 2014).

Figure 4.6 illustrates tragic maritime accident suspected to be liquefaction of dry bulk cargo in 2005 (Zografakis, 2013). MV Hui Long, Hong Kong registered ship, was loaded with mineral cargo in bulk. During the sailing at open sea, the ship suddenly listed about 15 degrees to port side and the master ordered for abandoned ship. The ship continued to listing on port side and finally capsized. According to the report, MV Hui Long did not have any structural deficiencies. The possible reason of capsizing of the MV Hui Long is attributed to liquefaction of mineral cargo on-board ship (Lloyd's Register, 2013).

Figure 4.6: Capsized vessel - MV Hui Long due cargo liquefaction (Lloyd's Register, 2013).

In the light of above, the cargo liquefaction poses potential hazard for dry bulk cargo carriers (bulk carriers). It becomes a critical issue in dry bulk cargo transportation. The potential causes of cargo liquefaction must be analysed comprehensively. There is lack of research in the maritime industry to tackle with cargo liquefaction phenomenon. To address this concern, the thesis is performing extensive risk analysis under FFTA and ETA approach through cargo liquefaction problem on-board bulk carrier ships.

4.3 Analysis of Respondents

The number of fatal accidents was recorded due to cargo liquefaction in dry-bulk cargo shipment in recent years. The accident analysing reports issued with respect to the aforementioned events did not contain numeric data. Therefore, it is very challenging to obtain numeric data on the nature of cargo liquefaction accident due to scarcity of data. This is one of the core problems for quantitative risk analysis in maritime transportation. To remedy data scarcity, expert judgement is used since it can be a good solution in decision-making problem (Demirel et al., 2019). Ship management companies or ship owners do not eager to share their data as the commercial concerns play critical role. Therefore, safety practitioners or researchers have been seeking an alternative solution such as obtaining expert judgement to get necessary data in maritime transportation.

In the insight, data is gathered from maritime experts who have enough experiences about dry bulk cargo shipment, in particular solid ore cargoes such as nickel ore, iron ore, mineral, etc. This thesis also utilises expert judgements as input data due to data scarcity associated with cargo liquefaction accident on-board bulk carrier ships. A group of marine experts were selected and contacted with them to obtain potential failure possibilities of cargo liquefaction's basic events (BE) with related to the fuzzy scale. The profiles of marine experts are including Master mariners, supercargo (port captain), operation managers (specialist on dry bulk cargoes) and maritime lecturar. Six marine experts were attended survey. They are working on prestigious trade company who has 170 bulk carrier ships on their fleet. The ship fleet includes handymax, supramax, kamsarmax, panamax and capesize bulk carriers. The fleet is engaging various solid bulk cargoes scuh as ores (including nickel ore and iron ore), minerals, grain, etc. Therefore, the marine experts have wide knowledge and experience about cargoes which may liquefy. The marine experts attended survey to address problems in which data of errors are vague. In the light of above, Table 4.2 shows profile details of marine experts who participated to survey.

Table 4.2: Marine expert details.

Marine expert	Position	Years marine experienced	Educational level	Shore-based service time
1	Head of Supramax Freight Operations	7	MSc.	7
2	Dry Bulk Cargo Operation Manager	10	BSc.	6
3	Academician	3	PhD.	10
4	Master of Ship	10	BSc.	4
5	Supercargo	7	BSc.	10
6	Head of Dry Bulk Cargo Operation	10	BSc.	17

4.4 Constructing FTA Diagram

Since the aim of the thesis is to conduct quantitative risks analysing on the topic of cargo liquefaction in dry bulk cargo shipment, a detailed fault tree diagram is constructed under supervision of six marine experts. As expressed in section 4.2,

nickel and iron ore cargoes are apparently the most common dry bulk cargo types in the problem of liquefaction. Therefore, basic events are determined accordingly.

In the FT diagram, top event (TE) is the core event that addresses to the risk analysis. The “cargo liquefaction” is selected as a TE for quantitative risk analysing since the consequences of cargo liquefaction is serious concern for ships, marine environment and crew on-board. Table 4.3 illustrates the potential failures related with dry bulk cargo liquefaction, in particular for nickel ore and iron ore cargoes. Accordingly, Figure 4.7 depicts the FT diagram which was constructed under consensus of marine experts.

Table 4.3: Potential failures related with dry bulk cargo liquefaction.

Failure no	FTA definition	Potential failures
	TE	Cargo liquefaction
1	IE	Technical failure
2	IE	Management failure
3	IE	Operational failure
4	IE	Excessive GM value
5	IE	High moisture content in the cargo
6	BE5	Insufficient cargo control/monitoring during voyage
7	BE7	Lack of awareness of the risk of cargo liquefaction on-board ship
8	IE	Loading wet/humid cargo
9	BE6	Incorrect declaration of the average moisture content of the cargo before loading
10	IE	Loading cargo whose moisture content above TML
11	BE14	Incorrect cargo identification
12	BE1	Untrimmed Cargo
13	BE2	Incorrect weight distribution
14	BE3	Water or other liquids ingress into cargo holds during loading
15	BE4	Not to check stockpiles of cargo at port before loading
16	BE8	Not to appoint an independent survey
17	BE9	Incorrect cargo sampling
18	BE10	Incorrect cargo TML testing in suitable lab
19	BE11	Failure to understand MSDS
20	BE12	Not to follow up procedures of IMSBC Code
21	BE13	Inaccurate can test application

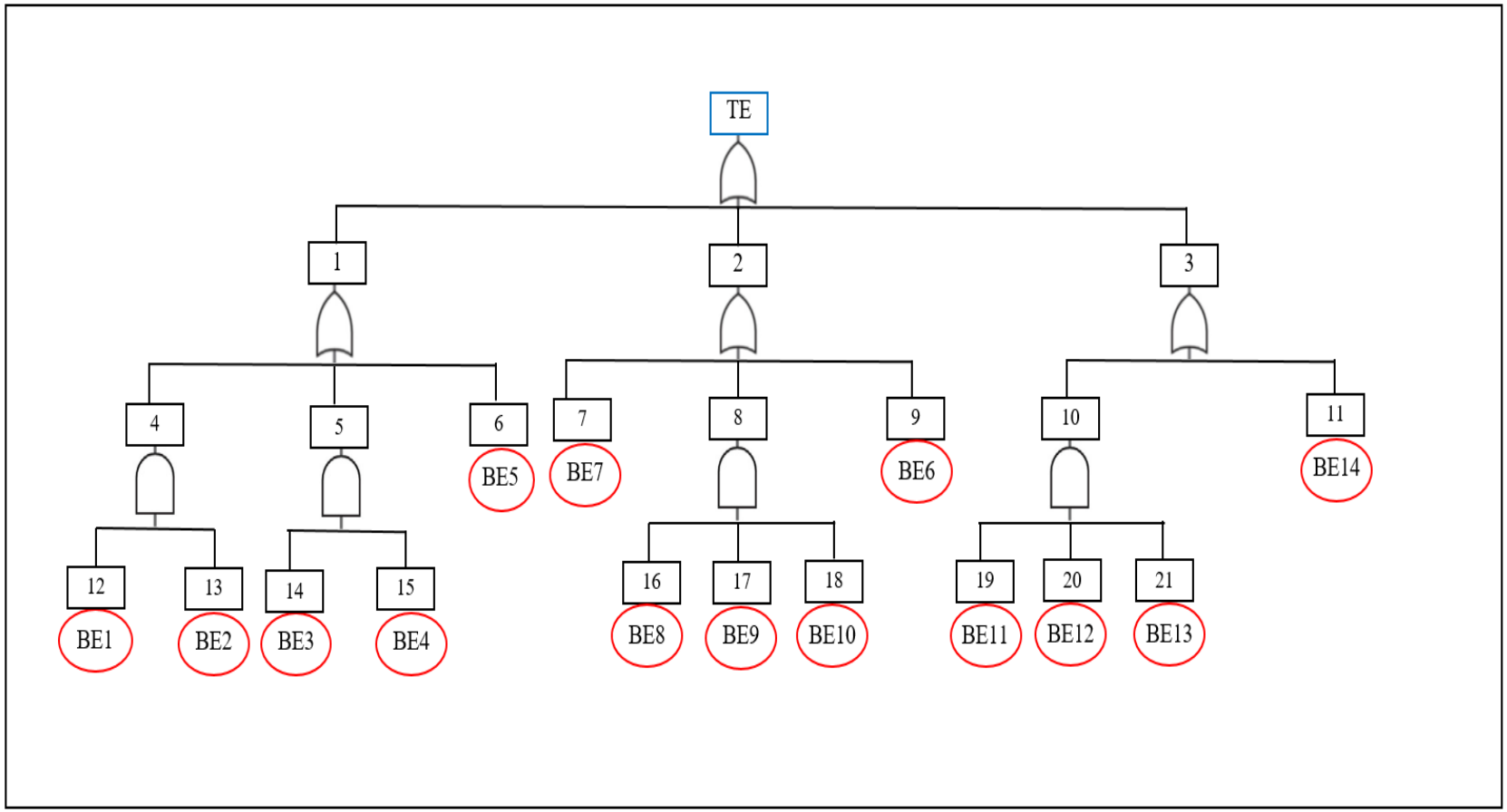

Figure 4.7: FT diagram.

4.5 Obtaining Possibilities From Expert Judgement

According to the figure 4.7, fault tree diagram of cargo liquefaction, there are totally fourteen basic events (BEs) and seven intermediate events (IE) defined for the top event (TE). None of them is the BEs with unknown failure rates. Therefore, possibilities of failure rates of BEs are estimated by expert judgement. Hence, the probabilities of the BEs are combined to calculate the probability of occurrence of the TE (cargo liquefaction). Since there is lack of failure probability data for each BEs, marine expert judgement is used to predict. In this context, fuzzy logic can be a solution to obtain failure probabilities of BEs. The linguistic expression of marine experts is able to convert into the fuzzy numbers (Kuzu et al., 2019; Sahin, 2017). At this insight, Figure 4.8 demonstrates fuzzy rating and membership functions.

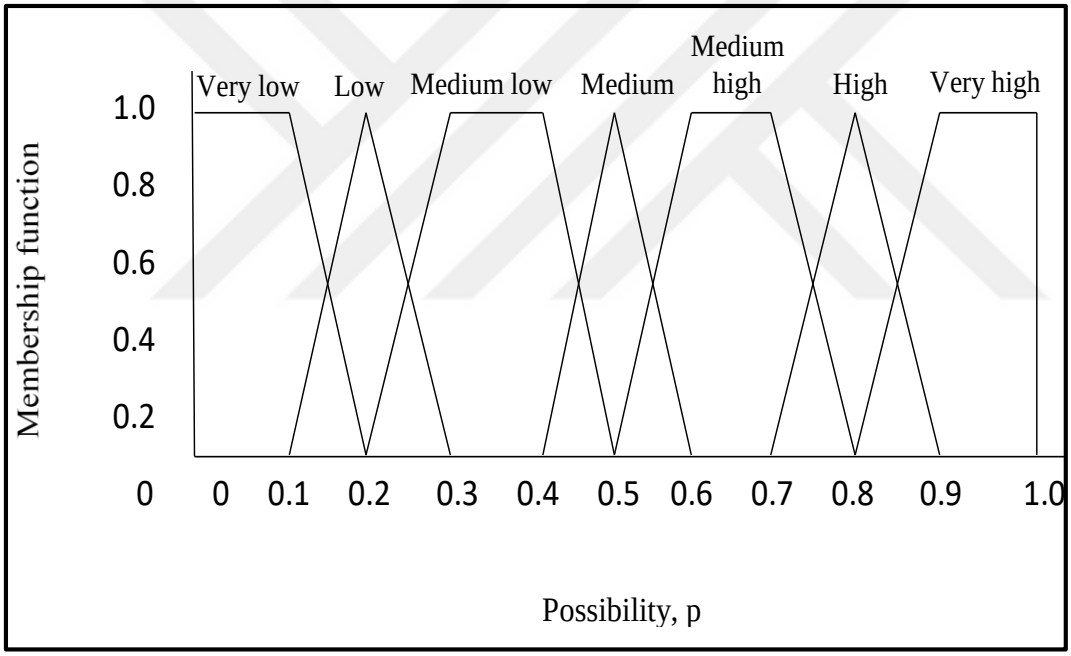

Figure 4.8: Fuzzy rating and membership functions.

Accordingly, Table 4.4 shows linguistic terms and trapezoidal fuzzy numbers (Chen and Hwang, 1992). The conversion scale seven is chosen to be most suitable for this research.

Table 4.4: Linguistic terms and trapezoidal fuzzy numbers of possibilities numbers (Chen and Hwang, 1992).

Linguistic term	Fuzzy numbers
Very low (VL)	(0.0, 0.1, 0.2)
Low (L)	(0.1, 0.2, 0.2, 0.3)
Medium low (ML)	(0.2, 0.3, 0.4, 0.5)
Medium (M)	(0.4, 0.5, 0.5, 0.6)
Medium high (MH)	(0.5, 0.6, 0.7, 0.8)
High (H)	(0.7, 0.8, 0.8, 0.9)
Very high (VH)	(0.8, 0.9, 1.0)

As explained in Table 4.2, the marine experts are not homogeneous. Therefore, their opinion about an attribute may not be equal. This is called as a non-homogeneous (heterogeneous) group of experts (Ölcer and Odabasi., 2005). It is therefore of importance to introduce the dominance factor which is used to adjust the impact level of expert's judgements in the aggregation stage of the methodology. Utilizing the dominance factor could lead to perform more accurate analysis and also perform sensitivity analysis to gain insight into how the changes in expertise levels can affect thesis results within the Fuzzy logic. Accordingly, Table 4.5 shows weights of marine experts participated to survey in compliance with their profiles.

Table 4.5: Weights of marine experts participated to survey.

Marine expert	Weighting factor				TW	Weighting score
1.	5	3	2	4	14	0.18
2.	5	3	2	3	13	0.16
3.	3	2	3	5	13	0.16
4.	4	3	1	3	11	0.14
5.	4	3	3	3	13	0.16
6.	5	3	4	3	15	0.19

In the view of experiences of marine experts, the linguistic judgements of them are showed in Table 4.6 where possibilities of failure rates of each BE are verbally predicted.

Table 4.6: Linguistic judgements of marine experts for possibilities of each BEs.

	M.Exp1	**M.Exp2**	**M.Exp3**	**M.Exp4**	**M.Exp5**	**M.Exp6**
BE1	MH	VL	L	ML	MH	ML
BE2	M	L	ML	VL	M	M
BE3	VH	MH	VH	MH	H	VH
BE4	H	H	H	H	H	VH
BE5	H	L	H	MH	H	H
BE6	VH	VH	VH	H	VH	VH
BE7	MH	VL	H	VH	M	VH
BE8	M	VL	H	MH	ML	H
BE9	MH	MH	H	H	ML	VH
BE10	VH	VL	VH	MH	VH	VH
BE11	MH	VL	MH	H	VH	H
BE12	H	L	H	VH	H	H
BE13	H	M	VH	VH	H	VH
BE14	VH	VH	H	H	VH	H

After gathered experts' judgement for possibilities of each BE of cargo liquefaction, the aggregation steps are adopted. In order to calculate aggregation step of marine experts, equations (3.10), (3.11), (3.12) and (3.13) are used. Accordingly, Table 4.7 denotes similarity functions and similarity values of each BEs.

According to the findings of Table 4.7; average agreement of marine experts (AA), relative agreement (RA) of marine experts and consensus coefficient (CC) are shown in Table 4.8 respectively. At this point, β is nominated as 0.5 since six marine experts are considered as identical (Kuzu et al, 2019; Senol et al., 2015).

Table 4.7: Similarity functions and similarity values of each BEs.

No.	Similarity func.	Similarity value						
		BE1	**BE2**	**BE3**	**BE4**	**BE5**	**BE6**	**BE7**
1	S(E1&E2)	0.70	0.70	0.73	1.00	0.40	1.00	0.43
2	S(E1&E3)	0.70	0.85	1.00	1.00	1.00	1.00	0.85
3	S(E1&E4)	0.55	0.58	0.73	1.00	0.85	0.88	0.73
4	S(E1&E5)	0.70	1.00	0.88	1.00	1.00	1.00	0.85
5	S(E1&E6)	1.00	1.00	1.00	0.88	1.00	1.00	0.73
6	S(E2&E3)	1.00	0.85	0.73	1.00	0.40	1.00	0.28
7	S(E2&E4)	0.85	0.88	1.00	1.00	0.55	0.88	0.15
8	S(E2&E5)	1.00	0.70	0.85	1.00	0.40	1.00	0.58
9	S(E2&E6)	0.70	0.70	0.73	0.88	0.40	1.00	0.15
10	S(E3&E4)	0.85	0.73	0.73	1.00	0.85	0.88	0.88
11	S(E3&E5)	1.00	0.85	0.88	1.00	1.00	1.00	0.70
12	S(E3&E6)	0.70	0.85	1.00	0.88	1.00	1.00	0.88
13	S(E4&E5)	0.85	0.58	0.85	1.00	0.85	0.88	0.58
14	S(E4&E6)	0.55	0.58	0.73	0.88	0.85	0.88	1.00
15	S(E5&E6)	0.70	1.00	0.88	0.88	1.00	1.00	0.58

No.	Similarity func.	Similarity value						
		BE8	**BE9**	**BE10**	**BE11**	**BE12**	**BE13**	**BE14**
1	S(E1&E2)	0.58	1.00	0.15	0.43	0.40	0.70	1.00
2	S(E1&E3)	0.70	0.85	1.00	1.00	1.00	0.88	0.88
3	S(E1&E4)	0.85	0.85	0.73	0.85	0.88	0.88	0.88
4	S(E1&E5)	0.85	0.70	1.00	0.73	1.00	1.00	1.00
5	S(E1&E6)	0.70	0.73	1.00	0.85	1.00	0.88	0.88
6	S(E2&E3)	0.28	0.85	0.15	0.43	0.40	0.58	0.88
7	S(E2&E4)	0.43	0.85	0.43	0.28	0.28	0.58	0.88
8	S(E2&E5)	0.73	0.70	0.15	0.15	0.40	0.70	1.00
9	S(E2&E6)	0.28	0.73	0.15	0.28	0.40	0.58	0.88
10	S(E3&E4)	0.85	1.00	0.73	0.85	0.88	1.00	1.00
11	S(E3&E5)	0.55	0.55	1.00	0.73	1.00	0.88	0.88
12	S(E3&E6)	1.00	0.88	1.00	0.85	1.00	1.00	1.00
13	S(E4&E5)	0.70	0.55	0.73	0.88	0.88	0.88	0.88
14	S(E4&E6)	0.85	0.88	0.73	1.00	0.88	1.00	1.00
15	S(E5&E6)	0.55	0.43	1.00	0.88	1.00	0.88	0.88

Table 4.8: AA, RA and CC values of marine experts for each BEs.

M. Exp.	BE1			BE2		
	AA	***RA***	***CC***	***AA***	***RA***	***CC***
1	0.675	0.16	0.166	0.825	0.17	0.175
2	0.635	0.15	0.155	0.765	0.16	0.163
3	0.735	0.17	0.167	0.825	0.17	0.169
4	0.795	0.18	0.161	0.665	0.14	0.139
5	0.675	0.16	0.160	0.825	0.17	0.169
6	0.795	0.18	0.187	0.825	0.17	0.182

M. Exp.	BE3			BE4		
	AA	***RA***	***CC***	***AA***	***RA***	***CC***
1	0.865	0.17	0.173	0.975	0.17	0.173
2	0.805	0.16	0.161	0.975	0.17	0.167
3	0.865	0.17	0.167	0.975	0.17	0.167
4	0.805	0.16	0.149	0.975	0.17	0.154
5	0.865	0.17	0.167	0.975	0.17	0.167
6	0.865	0.17	0.180	0.875	0.15	0.1710

M. Exp.	BE5			BE6		
	AA	***RA***	***CC***	***AA***	***RA***	***CC***
1	0.85	0.18	0.180	0.975	0.17	0.173
2	0.43	0.09	0.128	0.975	0.17	0.167
3	0.85	0.18	0.174	0.975	0.17	0.167
4	0.79	0.17	0.155	0.875	0.15	0.145
5	0.85	0.18	0.174	0.975	0.17	0.167
6	0.85	0.18	0.186	0.975	0.17	0.179

M. Exp.	BE7			BE8		
	AA	***RA***	***CC***	***AA***	***RA***	***CC***
1	0.715	0.19	0.184	0.735	0.19	0.181
2	0.315	0.08	0.124	0.455	0.12	0.139
3	0.715	0.19	0.178	0.675	0.17	0.167
4	0.665	0.18	0.158	0.735	0.19	0.162
5	0.655	0.18	0.170	0.675	0.17	0.167
6	0.665	0.18	0.184	0.675	0.17	0.180

Table 4.8 (Continue): AA, RA and CC values of marine experts for each BEs.

M. Exp.	BE9			BE10		
	AA	***RA***	***CC***	***AA***	***RA***	***CC***
1	0.825	0.18	0.178	0.775	0.20	0.186
2	0.825	0.18	0.171	0.205	0.05	0.108
3	0.825	0.18	0.171	0.775	0.20	0.1798
4	0.825	0.18	0.159	0.665	0.17	0.153
5	0.585	0.13	0.145	0.775	0.20	0.179
6	0.725	0.16	0.173	0.775	0.20	0.192

M. Exp.	BE11			BE12		
	AA	***RA***	***CC***	***AA***	***RA***	***CC***
1	0.77	0.19	0.183	0.855	0.19	0.182
2	0.31	0.08	0.120	0.375	0.08	0.123
3	0.77	0.19	0.177	0.855	0.19	0.176
4	0.77	0.19	0.164	0.755	0.17	0.152
5	0.67	0.17	0.164	0.855	0.19	0.176
6	0.77	0.19	0.189	0.855	0.19	0.188

M. Exp.	BE13			BE14		
	AA	***RA***	***CC***	***AA***	***RA***	***CC***
1	0.865	0.17	0.175	0.925	0.17	0.171
2	0.625	0.13	0.145	0.925	0.17	0.165
3	0.865	0.17	0.169	0.925	0.17	0.165
4	0.865	0.17	0.156	0.925	0.17	0.152
5	0.865	0.17	0.169	0.925	0.17	0.165
6	0.865	0.17	0.182	0.925	0.17	0.178

In order to aggregate expert judgements for potential failure possibilities of cargo liquefaction, equation (3.14) is used. After obtained aggregated results, defuzzification process is required to transform fuzzy numbers into crisp values. To achieve this purposes, equation (3.15) is used. Table 4.9 gives aggregated expert judgements and defuzzified failure possibilities of each BE.

Table 4.9: Aggregated expert judgements and defuzzified failure possibilities of each BE.

	Aggregated expert judgements on BE failures				Defuzzified possibility
BE1	0.250	0.335	0.418	0.518	0.380
BE2	0.261	0.347	0.378	0.478	0.367
BE3	0.69	0.79	0.873	0.921	0.816
BE4	0.717	0.817	0.834	0.917	0.820
BE5	0.592	0.692	0.707	0.807	0.699
BE6	0.785	0.885	0.971	0.985	0.903
BE7	0.559	0.647	0.712	0.778	0.672
BE8	0.431	0.517	0.564	0.664	0.544
BE9	0.575	0.675	0.741	0.824	0.702
BE10	0.668	0.757	0.857	0.883	0.789
BE11	0.560	0.648	0.713	0.796	0.678
BE12	0.641	0.741	0.756	0.841	0.743
BE13	0.707	0.807	0.858	0.907	0.817
BE14	0.750	0.850	0.901	0.950	0.860

As the possibilities of each BEs failure are obtained from marine experts' judgements, they are converted to the probabilities. To accomplish this, equations (3.16) and (3.17) are used. Hence, fuzzy failure possibilities are transformed into fuzzy failure probabilities. The rate of fuzzy probability (FPT) are taken from fuzzy possibility (FPs) rates. Accordingly, Table 4.10 illustrates probabilities of failures obtained from possibilities.

Table 4.10: Probabilities of failures obtained from possibilities.

BEs	Probabilities of failures obtained from possibilities
BE1	1.97E-03
BE2	1.74E-03
BE3	3.99E-02
BE4	4.10E-02
BE5	1.83E-02
BE6	8.13E-02
BE7	1.55E-02
BE8	6.81E-03
BE9	1.87E-02
BE10	3.29E-04
BE11	1.61E-02
BE12	2.44E-02
BE13	4.02E-02
BE14	5.56E-02

4.6 Calculating MCSs and Total Failure Probability of TE

TE is the most significant events of the FT diagram. BEs are identified to calculate total probability of TE. In this case, cargo liquefaction is selected as the top event. Boolean equations are used to calculate the occurrence probability of the TE of the FT. Equations (3.18) and (3.19) are used to to calculate occurrence probability of the TE. In the view of FT diagram constructed by marine experts and logic gates described in FT, the failure probability of cargo liquefaction (TE) is calculated as 1.63E-01.

After calculated the occurrence probability of cargo liquefaction (TE), the MCS should be determined associated with the FT diagram since there are various MCSs which can be defined as the set of basic events that cause the top event to happen. The ranking of MCS states importance degree during occurrence of the TE (Kuzu et al.2019). Therefore, MCSs are in the FT diagram are also analysed in detail. Table 4.11 shows occurrence probabilities of each MCS and V–FIM list of MCSs by using equation (3.21).

Table 4.11: MCSs, occurrence probability and list of V-FIM.

MCS	Occurrence probability	V–FIM
BE1BE2	3.43E-06	0.0000199
BE3BE4	1.64E-03	0.0094914
BE5	1.83E-02	0.1061761
BE6	8.13E-02	0.4717004
BE7	1.55E-02	0.0899306
BE8BE9BE10	4.19E-08	0.0000002
BE14	5.56E-02	0.3225897
BE11BE12BE13	1.58E-05	0.0000916

4.7 Constructing Event Tree Diagram and Accident Sequence

After obtained occurrence probability of cargo liquefaction (TE) and MCSs, the consequences analysis is required for comprehensive risk analysing. To accomplish this, event tree diagram is constructed including accident/failure sequences. Hence, the relevant events that may cause in the accident consequence are revealed. Table 4.9 shows FT and ET diagram for cargo liquefaction. In the view of six marine experts, event tree diagram is created by considering the cargo liquefaction as an initiating event. Figure 4.10 shows ET diagram for cargo liquefaction.

4.8 Analysing Results of Event Tree Diagram

As illustrated in Figure 4.10, cargo liquefaction (TE) is placed on the left corner of the ET diagram and associated events continuing on the right side. There are four level defined for the event tree of cargo liquefaction. The final level (fourth level) shows potential consequences of the event along with occurrence probability. The occurrence probability of each segment (level) is determined by consensus of six marine experts. Figure 4.10, at this point, illustrates the event tree analysis along with occurrence probability of consequences. Accordingly, Table 4.12 gives potential consequences of cargo liquefaction and occurrence probability.

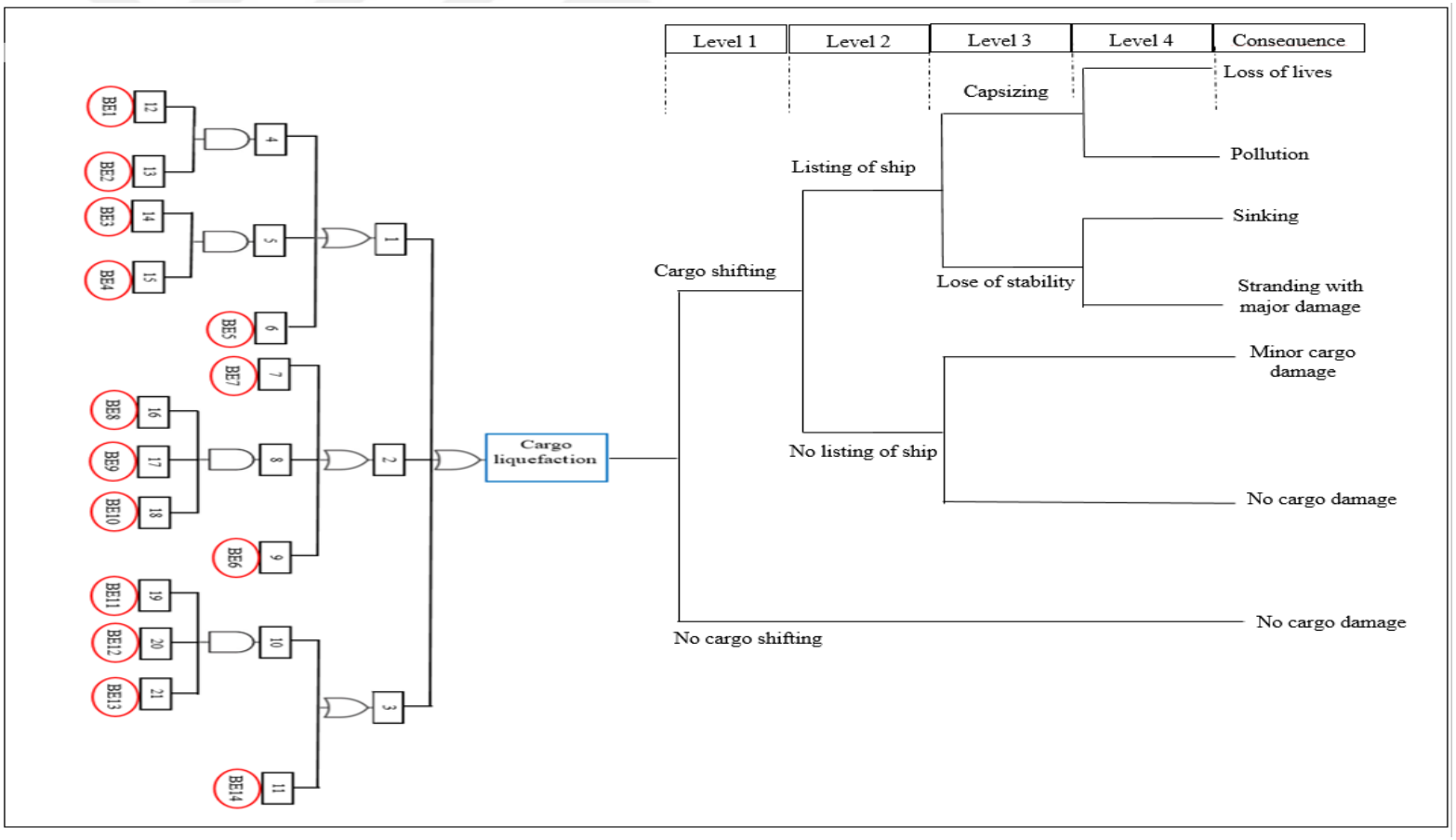

Figure 4.9: FT and ET diagram (bow-tie) for cargo liquefaction.

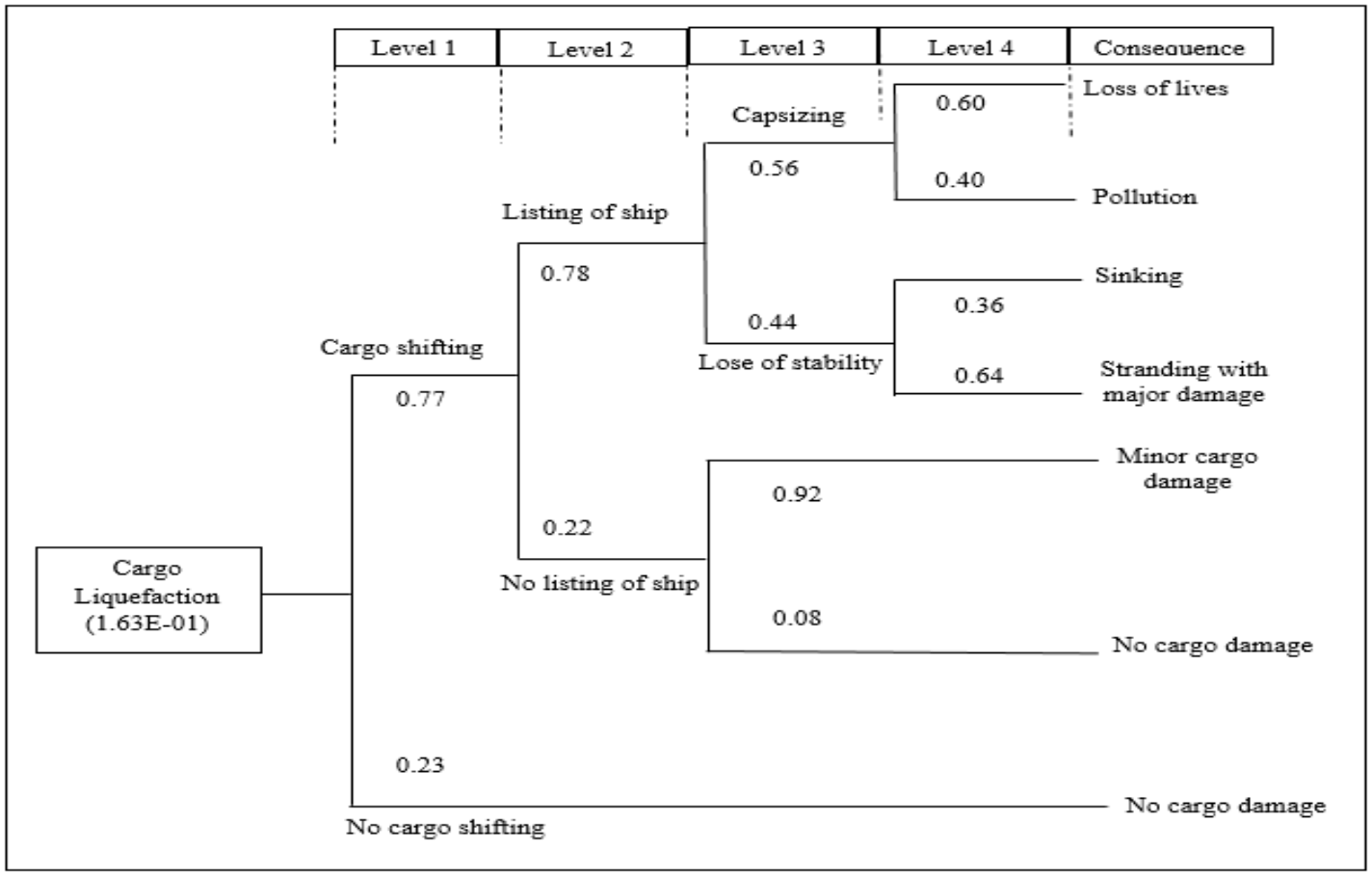

Figure 4.10: Event tree analysis and occurrence probability of consequences.

Table 4.12: Potential consequences of cargo liquefaction and occurrence probability.

Potential consequences	Occurrence probability
Loss of lives	3.29E-02
Pollution	2.19E-02
Sinking	1.55E-02
Stranding with major damage	2.75E-02
Minor cargo damage	2.54E-02
No cargo damage	2.21E-03
No cargo damage	3.75E-02

5. FINDINGS AND DISCUSSIONS

5.1 Extended Discussions on Findings

In the light of extensive risk analysis on cargo liquefaction dry bulk cargo carriage, the risk of top event (cargo liquefaction) is found 1.63E-01 (0.163). 16 out of 100 cases (nickel ore or iron ore shipments) may result in an accident due to cargo liquefaction. It is quite high when compared to the accident statistics. The failure likelihood of the TE reveals that definitely high risk is existing in dry bulk cargo transportation due to cargo liquefaction. In order to perform a comprehensive analysis, it is focused on basic events that may cause to occurrence of TE. In the view of findings, the TE is strongly affected by the BE6 (Incorrect declaration of the average moisture content of the cargo before loading), BE14 (Incorrect cargo identification), BE13 (Inaccurate can test application) and BE3 (Water or other liquids ingress into cargo holds during loading) respectively. The MCSs are also critical events that are affecting failure probability of the TE.

The BE6 (Occurrence probability 8.13E-02), incorrect declaration of the average moisture content of the cargo before loading, is apparently the most important event/failure to cause cargo liquefaction in dry bulk cargo ships. It is important to declare the average moisture content of the dry bulk cargo (nickel or iron ore) by shipper/charterer of cargo prior to loading. In this case, the unprocessed dry bulk cargo is the most dangerous. It is so tough for the Master of ship to certify or evaluate the average moisture content, if there is no mud or chunky clay on the cargo at port or storage area. In order to avoid incorrect declaration of the average moisture content of the cargo, prior to loading operation (when the cargo at port) an independent survey or supercargo should be appointed by ownership. In addition, samples of loading cargo are taken before operation from the depth of cargo storage at port. Also, it must be taken into account that samples should not be taken more than 7 days prior to loading (DNV-GL, 2015).

The BE14 (Occurrence probability 5.56E-02), incorrect cargo identification, is the second most important failure that may cause to cargo liquefaction. Before loading of IMSBC Code group A types cargoes which may liquefy, charterers or shippers provides detailed information about the cargo. However, they sometimes use commercial name of the cargo instead solid bulk cargo names as detailed in IMSBC Code. Therefore, this may cause risk of cargo liquefaction. In order to avoid failure of incorrect cargo identification, the master of ship should be aware of Group A types of cargo and make sure that correct cargo documents are received prior to loading operation. Meantime, the port authority must provide necessary certificate addressing the specs of the solid bulk cargo and conditions for carriage of group A type of cargoes which may liquefy.

The BE13 (Occurrence probability: 4.02E-02), inaccurate can test application, is one of the other critical failure/events. It is quite tough to obtain the dry bulk cargo test in an appropriate laboratory. Can test is able to carry out to check moisture limit of cargo. The test enables a reliable measurement for moisture content of dry bulk cargo (Group A). If the master of ship doubts about the TML of dry bulk cargo, then can test is applicable. Inaccurate can test application may cause liquefaction hazard since it may give inaccurate results showing that moisture content of tested cargo is less than TML. The master of ship makes sure that he/she has enough knowledge and experience about can test. Otherwise, it must appoint an independent surveyor or cargo specialist for advice though can test.

BE3 (Occurrence probability: 3.99E-02), water or other liquids ingress into cargo holds during loading, is also considerable affect on TE. Particularly, prior to loading or during loading operation of cargo, water ingress leads to increase moisture content inside the dry bulk cargo. If the cargo is loaded at anchorage, then barges will be used. In this case; rain or wave wash may penetrate to cargo and allow to increase moisture content. On the other hand, there is risk of rainwater ingress or drainage water penetration into cargo holds during the voyage if the hatch covers are not well secured or not waterproof. In order to prevent water ingress into cargo holds, utmost care is performed. If there is rain risk, the hatch covers are immediately closed. During the voyage, cargo holds should be monitored regularly. Excess water or other indicators of liquefaction risk such as fluid flow or flattening of the cargo is periodically monitored (DNV-GL, 2015).

The MCSs are also important indicators to affect occurrence probability of TE. They figure out that how the system behaves when the input parameters of each component vary (Lavasani et al., 2015). Therefore, the BEs, which create MCS are also substantial. In the light of findings, there are eight MCS in the system and most of them is single event/failure such as BE5, BE6, BE7 and BE14. The rest of them are combination of the other BEs such as BE1BE2, BE3BE4, BE8BE9BE10 and BE11BE12BE13. Utmost care is also required for the MSCs which have the high occurrence probability. According to the Table 4.11 where occurrence probabilities and lists of V-FIM are illustrated, combined MCSs do not pose considerable risk for cargo liquefaction (TE).

After evaluated the failure probability of cargo liquefaction (TE), the consequences should be analysed. In the view of Table 4.12 where potential consequences of cargo liquefaction and occurrence probabilities are shown, no cargo damage has the highest occurrence probabilities (3.75E-02). It means that with the 1.63E-01 probability of cargo liquefaction, no cargo damage is expected in case no cargo shifted due to cargo liquefaction. On the other hands, loss of life (3.29E-02) has the second highest occurrence probability in the event of cargo shifting, listing of ship and capsizing due to cargo liquefaction. Stranding with major damage (2.75E-02) to ship is expected due to cargo liquefaction if the cargo shifted, the ship listed but not capsized. The ship loses her stability and stranding with major damage is expected consequently.

6. CONCLUSION

6.1 Conclusive Remark

Safety is core topic in maritime transportation since the nature of work contains numerous hazards to human life, commodity, ship and environment. Therefore, safety practitioners have attempt to focus on advance tools to enhance safety in maritime transportation. In this context, risk assessment is of paramount to improve safety in operational level. In recent years, risk analysing was regarded as one of the most significant research topics in maritime transportation. Risk is defined as the combination of the probability of an occurrence of a hazardous event and the severity of it (ABS, 2013). This thesis provides insight into the risk analysing approaches for maritime industry, in particular dry bulk cargo transportation. The thesis aims at performing an extensive quantitative risk analysing on cargo liquefaction of dry bulk cargo in maritime transportation since cargo liquefaction leads to severe harms. The thesis encourages increasing safety awareness through solid bulk cargo carriage on-board ships. To achieve this purpose, the Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) under Fuzzy Logic environment is used. The method is also called as Bow-tie approach.

In the thesis, while the the FTA approach is capable of identifying basic events which may cause to an accident event, the ETA approach provides event sequences from initiating events to accident scenarios. Hence, the basic events (BE) are determined and fault tree diagram is constructed from top to down direction to understand causation of cargo liquefaction on-board ships. The potential failures that may cause cargo liquefaction on-board bulk carriers are analysed quantitatively.

Cargo liquefaction is a big phenomenon for solid bulk cargo carriers since the consequences of it could potentially harm for crew on-board ship, maritime environment and commodity. The cargo liquefaction pose serious hazards for dry bulk carriers. The IMSBC Code clearly define the cargoes which may liquefy under Group A. According to the code, these types of dry bulk cargoes (nickel ore, iron ore,etc.)

may liquefy because of moisture level can exceed TML limit. This may cause catastrophic consequences such as capsizing, listing of ship, loss of stability, sinking. Therefore, potential failures/causes of cargo liquefaction phenomenon is analysed under this thesis by exercising a comprehensive risk assessment.

As a result of detailed quantitative risk analysing, the failure probability of cargo liquefaction (TE) is calculated 1.63E-01. The most significant failures (BE) that may cause to cargo liquefaction in dry bulk cargo carriage are BE6 (Incorrect declaration of the average moisture content of the cargo before loading), BE14 (Incorrect cargo identification), BE13 (Inaccurate can test application) and BE3 (Water or other liquids ingress into cargo holds during loading) respectively. The MCSs are also critical events that are affecting failure probability of the TE. Necessary control actions to prevent cargo liquefaction phenomenon on-board dry bulk cargo ships are recommended. Consequently, cargo liquefaction poses a serious concern for maritime industry and IMO has been dealing with the issue but there is no international legislation governing the storage, segregation, handling and monitoring of such cargoes at the loading terminal. The process remains as only guidelines. Therefore, cargo terminals must care utmost attention about storage, handling and monitoring of the cargoes that may liquefy. The international regulatory bodies associated with loading terminals have to create a regulatory framework or code for storage, segregation, handling and monitoring of such cargoes.

Beside its theoretical background, the outcomes of the thesis provide practical contribution to maritime transportation industry, in particular solid bulk cargo shipment. Specifically, shipowners, dry bulk ship operators, supercargoes, ship Masters, maritime professionals and stakeholders such as P&I Clubs, Flag states, etc. can take practical benefits through cargo liquefaction phenomenon on-board bulk carriers.

6.2 Limitation of Research and Future Studies

The thesis suffers some limitations which become during implementation stage. Since obtaining technical or operational data in maritime industry is very challenging due to the nature of work, expert judgements were used as inputs of method. Therefore, it is one of the fundamental limitations of the study. However, introducing the dominance

factor which is used to adjust the impact level of expert's judgements in the aggregation stage of the methodology lead to perform more accurate analysis and to gain insight.

One of the major limitations with quantitative risk analysing methods is data scarcity. Therefore, empirical method such as bow-tie approach (FTA and ETA) can be an alternative solution to tackle with problem. The integration of the FTA and ETA approach under fuzzy logic provides satisfactory result. In the thesis, this concern was made crystal clear. Thus, the validity of the thesis's findings is not questionable.

The further studies may include gathering actual data to calculate occurrence probability of TE as well as consequences. The study may also be extended with interval type-2 fuzzy sets instead of fuzzy sets application into FTA to tackle with more uncertainty in decision-making problem during expert judgement stage.

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