DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF SOCIAL SCIENCES
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MASTER'S THESIS

RISK ASSESSMENT OF COAL CARGO OPERATIONS IN MARITIME TRANSPORTATION: PROBABILISTIC APPROACH

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THESIS APPROVAL PAGE

DECLARATION

I hereby declare that this master's thesis titled as "Risk Assessment of Coal Cargo Operations in Maritime Transportation: Probabilistic Approach" has been written by myself in accordance with the academic rules and ethical conduct. I also declare that all materials benefited in this thesis consist of the mentioned resourses in the reference list. I verify all these with my honour.

..../04/2022
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ABSTRACT

Master's Thesis

Risk Assessment of Coal Cargo Operations in Maritime Transportation: Probabilistic Approach

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Both onboard and at the port terminal, bulk shipment operations are high-risk activities. Moreover, coal shipments are one of the most dangerous and perilous cargoes shipped by sea, requiring particular understanding in terms of shipment, storage, and transportation. The IMSBC Code (International Maritime Solid Bulk Cargoes), developed by the IMO (International Maritime Organization), specifies and arranges specific recommendations for the safe loading and transportation of coal cargoes. It says that coal can self-heat and that some coals are vulnerable to this type, which can lead to spontaneous combustion.

As a result, the primary goal of this research is to determine the underlying causes of self-heating/ignition onboard due to coal cargo traffic, develop a risk management strategy based on quantitative and qualitative risk evaluation, and apply FFTA (Fuzzy Fault Tree Analysis) principles to reduce the risk of self-heating/ignition onboard, and develop a risk management strategy focuses on quantitative and qualitative risk evaluation. An ET diagram is constructed under the supervision of six maritime professionals to accomplish quantitative risk analysis using the bow-tie approach by first addressing the initiating event, which was determined to be self heating/ignition during the loading, discharging operation and transportation.

The qualitative fault tree of Self Heating/Ignition includes 16 intermediate events and 23 basic events (root causes), constituting it a

comprehensive fault tree. This study is expected to offer a variety of benefits to the maritime sector and literature as the first implementation of FTA for self heating/ignition due to coal cargo in maritime shipping.

Keywords: Fuzzy Fault Tree Analysis (FFTA), Event Tree Analysis (ETA) The IMSBC Code, Maritime Transportation & Trade, Coal Cargo, Risk Assessment,

ÖZET

Yüksek Lisans Tezi

Denizyolu Taşımacılığında Kömür Yükü Operasyonlarının Risk Değerlendirmesi: Olasılıksal Yaklaşım

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Denizcilik İşletmeleri Yönetimi Anabilim Dalı

Denizcilik İşletmeleri Yönetimi Programı

Hem gemide hem de liman terminalinde dökmeyük taşıma operasyonları yüksek riskli faaliyetlerdir. Dahası kömür sevkiyatları, denizyolu ile taşınan en tehlikeli kargolardan biridir ve sevkiyat, depolama ve nakliye açısından özel bir anlayış gerektirir. IMO tarafından yayınlanan IMSBC kodu, kömür yüklerinin güvenli bir şekilde yüklenmesi ve taşınması için özel tavsiyeleri belirtir ve düzenler. IMSBC kodu kömürün kendi kendine ısınabileceğini ve bazı kömürlerin bu türe karşı savunmasız olduğunu ve bunun da kendiliğinden yanmaya yol açabileceğini belirtmektedir.

Sonuç olarak, bu çalışmanın temel amacı, kömür yük trafiği nedeniyle meydana gelen kendi kendine ısınma/tutuşma riskini en aza indirmek, altında yatan nedenleri belirlemek ve nicel, nitel risk değerlendirmesi ve FFTA ilkelerine dayalı bir risk yönetimi stratejisi geliştirmektir. Altı denizcilik uzmanının gözetiminde, yükleme, boşaltma ve taşımacılık işlemi esnasında kendi kendine ısınma/tutuşma olduğu belirlenen başlangıç olayı ile papyon yaklaşımı kullanılarak nicel risk analizini gerçekleştirmek için ET diagramı oluşturulmuştur.

Kendiliğinden Isınma/Ateşlemenin niteliksel hata ağacı, kapsamlı bir hata ağacını oluşturan 16 ara olay ve 23 temel olay (kök neden) içermektedir.

Bu çalışmanın, deniz taşımacılığında kömür yükü nedeniyle kendi kendine ısınma/ateşleme için FTA'nın ilk uygulaması olarak denizcilik sektörüne ve literatüre çeşitli faydalar sunması beklenmektedir.

Anahtar Kelimeler: Bulanık Hata Ağacı Analizi (FFTA), Olay Ağacı Analizi (ETA), IMSBC kod, Deniz Ticareti ve Taşımacılığı, Kömüt Yükü, Risk değerlendirmesi

RISK ASSESSMENT OF COAL CARGO OPERATIONS IN MARITIME TRANSPORTATION: PROBABILISTIC APPROACH

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CHAPTER TWO
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CHAPTER THREE

RISK ASSESSMENT OF COAL CARGO OPERATIONS IN MARITIME TRANSPORTATION, PROBABILISTIC APPROACH

ABBREVIATIONS

ABS	The American Bureau of Shipping
AEC	Associated Equipment Company
AGCS	Allianz Global Corporate and Specialty
ALARP	As Low as Reasonably Practicable
AMSA	Australian Maritime Safety Authority
ATSB	Australian Transport Safety Bureau
BC	Before Century
BC CODE	Code of Safe Practice for Solid Bulk Cargoes
EMSA	European Maritime Safety Agency
EPA	Environmental Protection Agency
EU	European Union
ETA	Estimated Time of Arrival
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
FMEA	Failure Modes and Effect Analysis
FORM	First Order Reliability Methods
GISIS	Global Integrated Shipping Information System
G20	The Group of Twenty
HAZOP	Hazard and Operability Studies
HFACS	Human Factors Analysis and Classification System
HIRA	Hazard Identification and Risk Assessment
IAPH	The International Association of Ports and Harbors
ICMA	International Crisis Management Association
ICS	The International Chamber of Shipping
IEA	International Energy Agency
IMO	International Maritime Organization
IMDG	International Maritime Dangerous Goods Code
IMSBC	International Maritime Solid Bulk Cargoes
IR	Infra-Red
ISM	International Safety Management

IUMI	International Union of Maritime Insurance
LEL	Lower Explosive Level
LNG	Liquid Natural Gases
MAIB	Maritime Accident Investigation Branch - UK
MARPOL	International Convention for the Prevention of Pollution from Ships
MC	Moisture Content
MCA	Maximum Credible Accident
MCS	Minimal Cut Set
MHB	Materials Hazardous Only in Bulk
MPS	Minimum Path Set
MSHA	Mine Safety and Health Administration - US
MT	Metric Tonne
Mt	Million Tonnes
NASA	National Aeronautics and Space Administration
OECD	The Organisation for Economic Co-operation and Development
P/C	Per Cent
P&F	The Proctor Fagerberg Method Test
P & I	Protection and Indemnity insurance
PPM	Parts Per Million
PRA	Probabilistic Risk Analysis
RMT	Rewiev of Maritime Transportation
SOLAS	Safety of Life at Sea
TE	Top Event
TML	Transportable Moisture Limit
TLV	Threshold Limit Value
UEL	Upper Explosion Limit
UKAEA	The UK Atomic Energy Authority
UNCTAD	United Nations Conference on Trade and Development

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INTRODUCTION

Shipping is one of the greatest diverse sectors in the world. Shipping should not be considered solely in terms of a single country's perspective. It should, on the other hand, be considered in the perspective of global development, particularly in the domain of international commerce (Farthing, 1993).

We must also comprehend the global economy when evaluating the shipping industry. Because it is such a cost-effective technique of carrying massive amounts of freight all across the world, shipments is essential to international commerce (UNCTAD, 2020). Maritime transportation has a long history of being a key component of economic progress. The father of economics, Adam Smith, considered shipping as a low-cost mode of transportation that could also open up markets. Smith (1776) stated this "Sea freight has opened up a broader market for all sorts of businesses. Along the seaside, industry of all types naturally diversifies and develops." Sea freight encourages specialization and allows for the sale of low-cost commodities.

Furthermore, the epidemic's global health and economic tragedy has changed the landscape for sea transport and commerce, significantly affecting development prospects. The amount of international maritime trade declined by 4.1 % in 2020 (UNCTAD, 2020). As a result of market turmoil, demand shortages, and global economic instability caused by the epidemic, the world economy was badly damaged by a double supply and demand shock. As a consequence, The COVID-19 epidemic hindered maritime transportation, although the consequences were less severe than previously anticipated. Maritime commerce contracted by 4.1 % in 2020 as a result of the shock in the first half of the year. However, there was an embryonic, if uneven, rebound in the second half of the year, and by the third quarter, volumes had returned for both containerized commerce and dry bulk commodities (UNCTAD, 2020).

Furthermore, coal cargoes are certainly one of the most dangerous commodities transported by sea, requiring exceptional competence in terms of handling, stowage, and transportation. The International Maritime Organization's Code of Safe Practice for Solid Bulk Cargoes contains extensive recommendations for the safe loading and carrying of coals. It asserts that coal may heat up on its own and that particular coals are prone to self-heating, which could result in spontaneous combustion. Because such shipments can be combustible, explosive, poisonous, corrosive, pollutant of the environment, and hazardous to human life, they always necessitate extremely cautious and skilled handling (The IMSBC Code, 2008).

The primary goal of this research is to explore the key causes of self-heating/ignition onboard due to coal cargo traffic, as well as to develop a risk management strategy based on quantitative and qualitative risk evaluation and FFTA principles to reduce the risk of self-heating/ignition onboard. Under the supervision of six maritime professionals, an ET diagram is constructed to perform risk evaluation using the bow-tie method by first addressing the initiating event, which was ascertained to be Self heating/Ignition while the loading and discharging operation, as well as the transportation of Coal Cargoes. The likelihood of the occurrences was calculated using the expert's judgments.

CHAPTER ONE

MARITIME TRADE AND COAL TRANSPORTATION

Coal is the source of fuel with the oldest history of use, dating back to 3000 BC in China and Wales. Many distinctive Chinese beliefs and practices are documented in Marco Polo's "Description of the World" (1298), including the utilization of "stones that burn like logs" (coal). Coal mining was widespread in UK by the thirteenth century, particularly in Durham, Nottinghamshire, Derbyshire, Staffordshire, and North and South Wales. Coal shipments accounted for roughly half of England's maritime trade by the early seventeenth century (When pollution meant punishment. Retrieved from https://www.downtoearth.org.in/indepth/when-pollution-meant-punishment-19737, Access on 24.11.2021).

Coal was the fuel that ignited Europe's and ultimately America's Industrial Revolutions. By the late 1890s, the United States (U.S.) had overtaken over as the 's largest coal producer. After becoming the world leader since the commencement of the formal industry in the 1500s, Britain is presently placed second. Germany came in third, highlighting its expanding manufacturing would in compared to continental adversary France. Coal's supremacy in energy consumption peaked in the early twentieth century, thereafter which oil and natural gas gained over. By the late twentieth century, China's fast economic growth, rising demand for power, and enormous coal reserves had pushed it to the top of the world's coal output (Basdeo S.4 September 2019.Old King Coal. Retrieved from https://victorianweb.org/science/environment/basdeo.html. Access on 24.11.2021).

The earliest documented environmental legislation of coal was issued in 1306 by King Edward II of England, who prohibited the burning of maritime coal while Parliament was in session thanks to the offensive smoke it generated. In the 1960s, sulfur dioxide from coal combustion was connected to acid rain, and carbon dioxide emissions became a problem in the 1980s, when climate change became a significant contributor to climate change (Basdeo S., 2019).

Furthermore, coal is mostly composed of biological material that has been heated and compacted in the long time. It is mostly made up of carbon, together varying numbers of other elements, and the coal grade is determined by the ratio of carbon to other elements. The calorific price rises like the grade develops leading to excessive pressure and temperature throughout long periods of time. Shipping is a crucial component of the global economy, and its prolonged and well-documented history offers maritime economists with a unique perspective on the evolution of the industry's economic actors and structures.

In addition, the COVID-19 epidemic would have an influence on worldwide maritime trade and global supply networks in 2020. Overall, though, maritime transport was able to navigate the crisis, and the impact on some areas of the supply chain was not as severe as previously anticipated. Carriers were able to absorb the first shock and handle decreased demand levels. However, port and landside operations struggled to adapt, and the world's seafarers found themselves in a hazardous situation as a result of an unprecedented worldwide crew-change problem (UNCTAD, 2020).

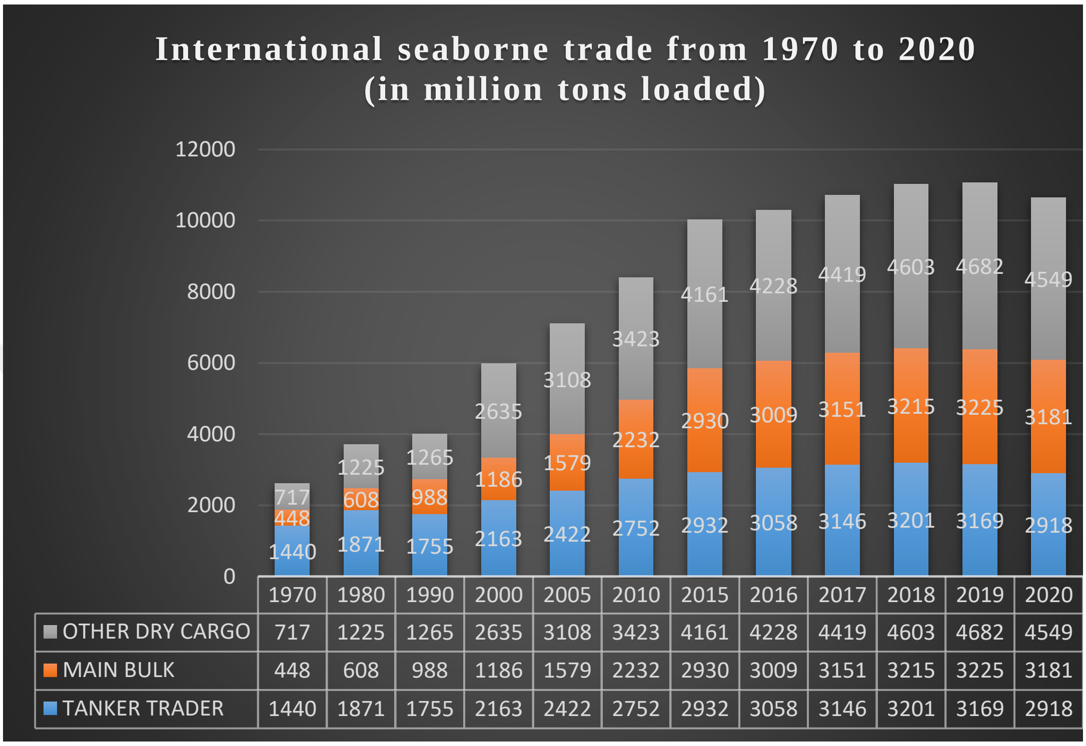
Because maritime transport accounts for roughly 90% of worldwide trade through ocean transport, seaways, and inland waterways, the contribution of maritime transport in international trade is considered essential. Maritime transport is critical to the global economy since it carries over 90 % of global trade and is, by far, the most cost-effective method to move massive merchandise and raw resources all throughout world, according to the International Maritime Organization (IMO). Furthermore, the maritime industry has made significant contributions to the global economy over the last three decades. In addition, the international trade has been irreparably harmed by the COVID-19 pandemic of 2020. The value of global commerce decreased by 4,1 %. In 2020, global economic productivity decreased by 3,5 %, merchandise commerce decreased by 5,4 %, and international maritime shipments decreased by 3,8 % to 10,65 billion tons. However, UNCTAD predicts that global maritime commerce would rebound by 4,3 % in 2021, and that recovery will continue through 2022–2026, albeit at slower rates due to the slowing global economy. Although the short-term view is favorable, the medium- and long-term outlooks are uncertain: the recovery will be guided by the pandemic's future route as well as the attendant lockdowns and limitations. A long-term recovery also depends on maintaining trade flows by establishing favorable macroeconomic and fiscal circumstances while reducing trade protectionism (UNCTAD, 2021).

The pandemic of 2020 has highlighted the importance of sea transport for the persistent delivery of crucial supplies and worldwide trade through times of trouble, rehabilitation, and reintegrate into society. Numerous organizations have launched recommendations and assistance, including the European Union (E.U), IMO, the UN Conference on Trade and Development, and other international organizations, recognizing the importance of maintaining business connectivity in the industry while also safeguarding port workers and seafarers from the epidemic.

Hence, IMO Secretary-General Kitack Lim encouraged the UN to recommend that states identify sailors, port staff, and other critical maritime workers as "important persons" at the start of the coronavirus epidemic.(IMO Circular Letter No: (MSC.1/Circ.1636. Retrived from https://www.imo.org/en/MediaCentre/PressBriefings/pages/44-seafarers-UNGA-resolution.aspx) In addition to the IMO, the International Chamber of Shipping (ICS) and the International Association of Ports and Harbors (IAPH) together urged G20 leaders to assist the maritime industry and global supply chains. Crews should also be classified as critical employees, according to the letter. The IMO also released a Circular Letter on March 27, 2020, that included a number of suggestions for governments and key national institutions fort he sake of preserving the flow of products going. The letter particularly requested that countries recognize maritime experts as "important employees" who provide a vital service, regardless of nationality. Finally, The IMO in its Circular Letter No.4204/Add.35/Rev.3 25 January 2021 announced that Fifty-three IMO Member States and one Associate Member, Hong Kong, deputed and recognized sailors as critical personnel (IMO Circular Letter No.4204/Add.6. Retrived form https://www.imo.org). The pace of worldwide maritime trade dipped to its lowest point since the international economic meltdown of 2008–2009 in 2020.World economic production, merchandise trade, and, by extension, maritime trade, have been hampered by lingering trade conflicts and excessive policy uncertainty. In 2020, maritime transport volumes decreased by 3,8 %, and reached 10,648 billion tons. Briefly, Maritime transport is a paramount key to economic globalization (Shi and Li, 2017).

Furthermore, according to UNCTAD-RMT 2020, 7,730 billion tons of dry cargo were shipped worldwide in 2020. In 2020, the world's merchant fleet handled over 3,181 billion tons of seaborne principal bulk commodities. Iron ore, grain, coal, bauxite, alumina, and phosphate rock are all considered "major bulks.

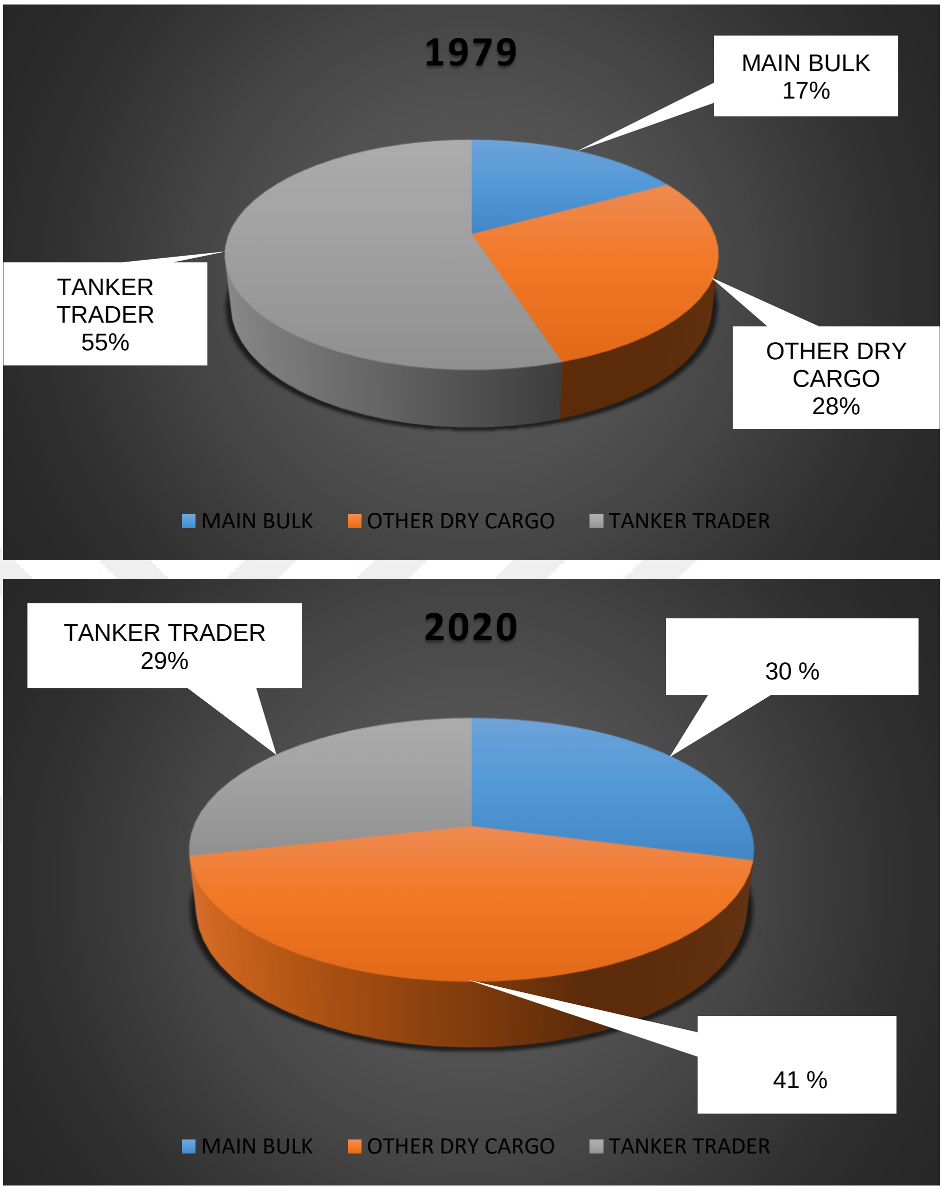
Figure 1: International Seaborn Trade from 1970 to 2020



Source: UNCTAD, 2021

While main bulk cargo accounted for about 18 % of entire maritime volumes in 1970, dry cargo has increased in importance over time, accounting for even more than one-thirds of total maritime commercial volumes in 2020.

Figure 2: Percantage of the Main Commodities in 1979 and 2020



Source: UNCTAD, 2021

Furthermore, world coal request is expected to fall by 4 % in 2020, the lowest since World War II. Lower power demand as a result of Covid19 limitations and the subsequent economic slowdown was the major cause of the reduction. Many markets have preferential dispatch or usage of renewables. Gas and coal have been forced out of the electrical mix. Lower gas costs prompted a considerable shift away from coal, notably in the U.S. and the E.U., where coal usage declined by 20 % and 21 %, respectively.

The global coal output increased from 3.074 Mt in 1973 to 7.575 mt in 2020. Furthermore, although China's contribution of global output was 13.6 % in 1973, it was 49.7 % in 2020. China is the only major country that saw a rise in coal demand in 2020. In contrast, the People's Republic of China continued the global highest coal manufacturer since 1985, with 3.764 Mt in 2020, accounting for 49.7 % of worldwide output. Since 2017, Chinese productivity has expanded at a pace of roughly 1 % with 71 Mt higher than in 2019 (UNCTAD, 2021).

Growing economy will keep electricity usage going in 2021, while post-Covid stimulus initiatives will help steel, cement, and other coal-intensive industrial products. We forecast a 4 % increase in coal usage in 2021, keeping it well beyond the 2014 record and nearing China's greatest ever levels. More than half of worldwide coal use is accounted for by China's coal power fleet (which includes combined heat and power, or Combined Heat Power - CHP) facilities.

The Chinese electricity system will dictate the future of coal use in China and throughout the world. Rising electricity usage is directly connected to economic growth in China, with demand expanding at a one-to-one rate with GDP. How soon alternatives and nuclear power come on-line will determine how much of the additional electricity demand is met by coal. Coal is predicted to satisfy just 45 % of the projected 8 % rise in energy demand in 2021, due to rapid gains in renewables installations (IEA/OECD, 2020).

Table 1: Production by Major Coal Producers (Mt) in 2020

No	Countries	2017	2018	2019	2020	Change	2020 2019
1	PR of China	3.397	3.549	3.693	3.764	71	% 1
2	India	722	776	769	760	-9	% -1
3	US	703	686	640	485	-155	% -24
4	Indonesia	495	548	616	564	-52	% -8
5	Australia	499	485	503	493	-10	% -2
6	Russian Federation	388	419	418	398	-20	% -5
7	S. Africa	257	256	254	247	-7	% -2
8	Germany	175	169	131	107	-24	% -18
9	Poland	127	122	112	101	-11	% -9
10	Kazakhstan	101	108	105	100	-5	% -5
11	Turkey	74,1	83,9	90	71	-19	% -21
12	Colombia	90.5	84.3	82.1	48.5	-33.6	% -41
	Rest of World	522	518	508		-71.5	% -14
	Total EU28	464	444	375	56,5	-318.5	% -85
	Total OECD	1.762	1.725	1.635	1.424	-211	%-13
	Total non-OECD	5.789	6.079	6.286			
Total	World	7.551	7.805	7.921	7.575	-346	% -4

Source: IEA/OECD, 2020

Furthermore, global coal output climbed by 1% in 2020, twice the proportion of the previous two years. China is the world's largest producer, with 3.764 million tonnes, closely by India with +760 million tonnes. India's productivity fell to its lowest level twenty-first century, and only the second time in history. The US reduced output by 485 million tons, while the EU reduced output by 56.5 million tons, with Germany accounting for half of the reduction. Global coal output nearly rebounded from the 2014-2016 downturn, surpassing 7.575 Mt in 2020, close to the 2017 high. In 2017 and 2018, output climbed by 253 Mt each year after 2016. With 116 Mt decreased in 2020, output rose at a slower rate, indicating a decline in this extractive industry (UNCTAD, 2021).

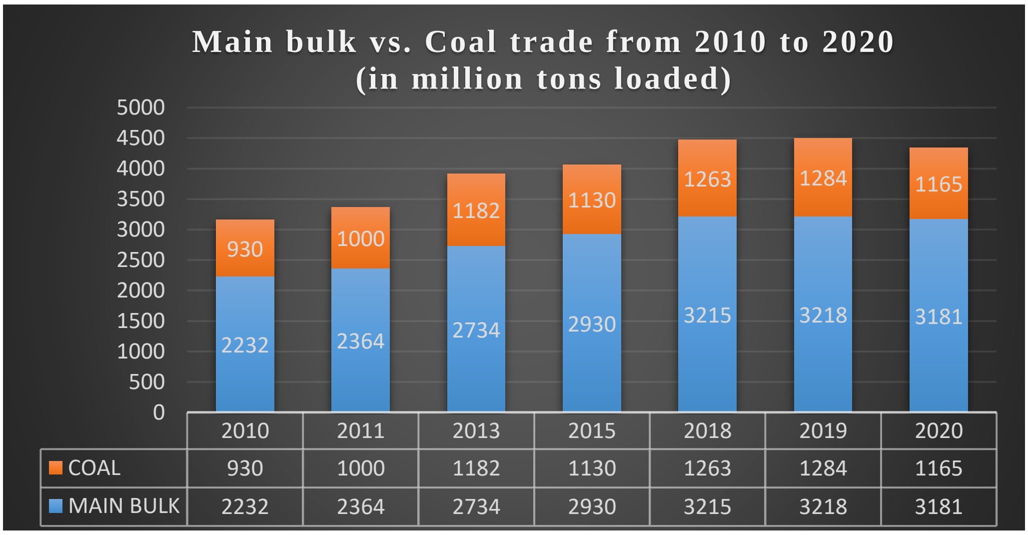
In India, coal production fell to its lowest level about 760 Mt with 9 Mt by %-1 in 2020 for the first time in last 20 years, and just the second time in history, following a substantial economic downturn in the second part of 2019 and Covid lockdowns owing mostly to lower coal-fired power generation offset by greater hydroelectric power. The economic rebound has outcomed in a continuous improvement in coal consumption since then, with a 6% increase in the fourth quarter of 2020. A reduction in hydro generation following the year's record-breaking production also spurred higher coal usage. In 2021, we predict a strong economic rebound in India, boosting GDP far beyond 2019 levels and raising coal demand by around 9% to 1.4 % beyond 2019 levels, according to our projections. As a result of this situation, coal storage at energy plants completed the year at record levels, with none of them reaching 'critical' levels for the first in years (IEA/OECD, 2020).

The US' production continues to decline, hitting 485 Mt in 2020, the lowest degree in four decades, continuing a declining trajectory that began at the turn of the century. Despite the fact that 2021 is predicted to be the first year of usage growth since 2013, coal consumption in the US is still down by -24 % to 485 million tons. The first monthly year-over-year increase in coal usage since November 2018 was spurred by rebounding electricity use and rising gas prices in December 2020. The power sector's coal usage is expected to increase by 10% from its lows in 2020, although need will not exceed that of 2019. Coal-fired electricity generation represents for 90% of the total amount of coal consumed in the US, and demand is anticipated to drop by one-third between 2018 and 2020 (IEA/OECD, 2020).

In 2020, Australia's coal output fell by 2% (-10 Mt), falling below the 500 Mt record established in 2017. Following a few years of rapid growth, Russia's output in 2020 was practically comparable to that of 2018, with a little -5 % decline (-20 Mt). Colombia's downward trend continued in 2020 (-41%), with Turkey overtaking Colombia as the world's 11th largest coal producer. (IEA/OECD, 2020) Similarly, in 2020, the E.U.'s coal production fell by 318.5 Mt, or 85 %, to its lowest level ever. Germany, Poland, and Greece are the primary drivers of this trend, with yearly decreases of -38, -10, and -9 Mt, respectively. In addition, Spain's coal output ceased in 2020. As a result of several nations announcing coal phase-out plans, this downward tendency is projected to sustain and increase.

In a growing number of E.U. countries, coal-fired energy generation is diminishing or becoming irrelevant. Carbon allowances continue to dissuade coal companies, with Austria and Sweden retiring their last coal-fired power plants in 2020, and Portugal retiring its last coal-fired power station this year. Two-thirds of all coal mined in the EU is used in Germany, Poland, and the Czechia. Gas and coal production prices are moving in the same range in Germany, where coal and gas rivalry is fierce owing to capacity constraints. As a result, even minor changes in fuel prices can have an impact on coal and gas's relative competitiveness, and hence coal demand. In light of this uncertainty, we predict a 4% rise in coal demand in 2021, owing mostly to a comeback in industrial use. This rise will still fall short of correcting the 18 % drop in demand expected in 2020 (Retrieved from. https://www.worldometers.info/coal). According to the current global Reserve/Output percentage, coal reserves represented for 139 years of current production in 2020, with the highest rates in North America (484 years) and the CIS (367 years). Finally, since 2010, coal traffic has accounted for 36% of all bulk commerce.

Figure 3: Main Bulk vs. Coal Trade from 2010 to 2020



Source: UNCTAD, 2021

Furthermore, for both exports and imports, the largest coal trade countries have shifted during the previous three decades. China now purchases one-fourth of all coal sold on the global marketplace, but its presence was minor in 2000. The E.U., contrastingly, was the world's greatest coal importer in 1990 and has progressively reduced its imports since then, from 35.4 % of global coal imports in 1990 to 6% presently. Viet-nam was the biggest surprise of the decade, shifting from supplier to buyer in 2005 and steadily rising requisition since then. Surprisingly, China has the highest overall imports (306 Mt), despite the fact that this only accounts for 25% of the country's entire coal supply. Other countries with lower import volumes have far higher dependency %ages, such as India and Japan, both of which have dependency %ages of over 30%. The OECD and the EU both rely on coal imports in equal proportions, with 18,8 % and 8,3 % of coal supply imported, respectively (IEA/OECD, 2020).

Despite the fact that coal exports from leading countries have declined as a result of the Covid 19 epidemic, Indonesia and Australia, with 32.6 % and 32.1 % of global coal exports, respectively, were the world's top exporters in 2020. Together with Russia, the world's third largest exporter, these two countries represent for 80 % of all coal exports (IEA/OECD, 2020).

Table 2: Major Coal Exporters (Mt) in 2020

No	Countries	2017	2018	2019	2020	Change	2020/2019
1	Indonesia	394	434	455	396	-59	% -13
2	Australia	379	382	393	390	-3	0
3	Russian Federation	190	210	217	188	-29	% -13
4	US	88	105	87	58	-29	% -33
5	S. Africa	71	70	81	62	-19	% -23
6	Colombia	103	84	72	30	-42	% -58
7	Canada	31	34	36	26	-10	% - 27
8	Mongolia	29	32	28	29	-1	0
9	Kazakhstan	29	27	25	24	-1	% 0
10	Philippines	6	5	14	-	9	-
	Rest of World	46	35	31	2	-29	% -93
	Total EU28	12	9	8	9	1	% 12
	Total OECD	512	532	524	527	3	0
	Total non-OECD	854	886	913	685	-228	% -25
Total	World	1.366	1.418	1.436	1.212	-224	% -16

Source: IEA/OECD, 2020

In 2020, Indonesia's exports declined by 13 % to 396 Mt, compared to the previous year's total. Other nations that had significant losts in exports were Australia, Russian Federation, US, South Africa, and Colombia. The US, on the other hand, had the greatest reduction in exports, with a fifth less than the last year (-21 Mt). Colombian exports fell by 29 Mt in 2020, a 33 % drop, due to Covid-19, a reduction in harvesting at one of the main mines, as well as supply problems that forced operations to be halted (UNCTAD, 2021).

As a supplier of imports, China and India were the two largest coal importers in 2020, with 306 and 210 Mt, sequentially; both had volumes than the last year, up +2 % and down -15 %. According to 2018 data, Viet-Nam saw the most significant increase in coal imports, effectively dublicating the volume to 52 Mt (+29 Mt, or 126

%). The E.U., far from Asia, reduced coal imports by 32%, from 134 million tonnes to 90 million tonnes (Retrieved from. https://www.worldometers.info/coal).

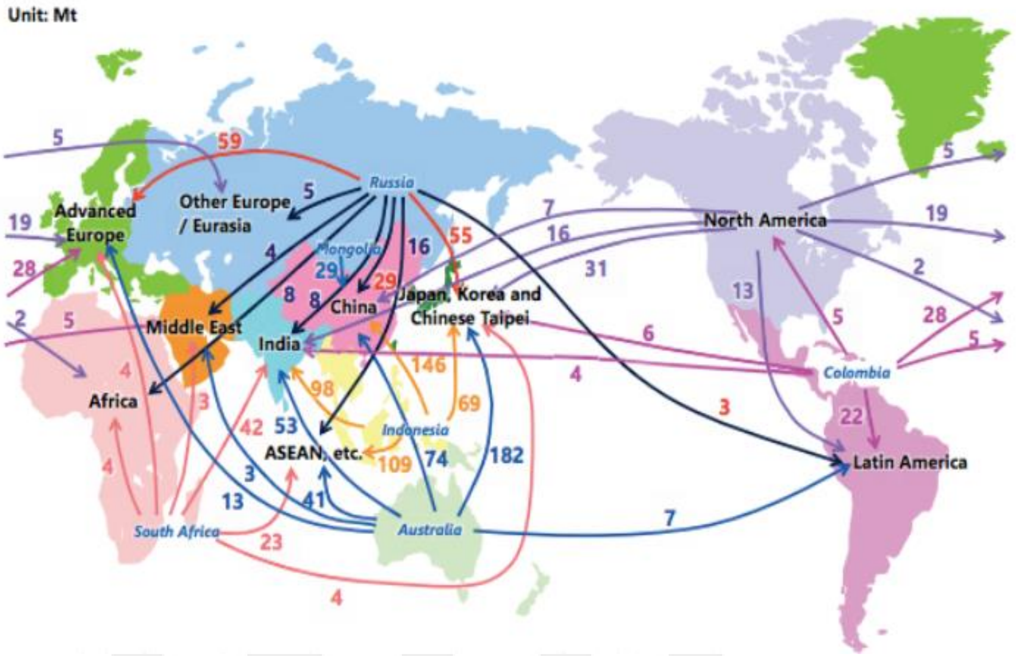
Table 3: Imports by Major Coal Importers, Mt in 2020

No	Countries	201	2018	2019	2020	Change 2020/2019	
1	China	284	281	298	306	8	% 2
2	India	210	223	247	210	-37	% -15
3	Japan	187	184	185	183	-2	% -1
4	Korea	139	136	130	123	-7	% -5
5	Chinese Taipei	68	67	67	63	-4	% -6
6	Viet Nam	14	23	44	52	8	% 18
7	Germany	51	45	41	29	-12	% -29
8	Turkey	38	38	38	40	2	% -5
	Rest of World	387	397	373	202	-171	% -46
	Total EU28	175	167	134	90	-44	% -33
	Total OECD	583	566	532	472	-60	% -11
	Total non-OECD	794	827	892	792	-100	% -11
Total	World	1.377	1.392	1.424	1.264	-160	% -11

Source: IEA/OECD, 2020

In addition, Thermal coal represented for 76% of global coal trade, with met coal representing for the remainder. The international (thermal) coal trading route is altering. Traditionally, trading was divided into two areas: the Pacific Basin, where Japan, Korea, and China are the leading importers, and the Atlantic Basin, where European nations imported the majority of traded coal. In the coal trade, South Africa and, to a lesser degree, Russia, connected the two basins. The Atlantic market has diverged from the Asian market, therefore this no longer depicts worldwide coal trade trends. For example, in 2019, India's coal imports were nearly twice those of the EU, indicating a definite shift to Asia and Europe's devaluation in international coal markets in Figure 4 (IEA/OECD, 2020).

Figure 4: Main Trade Flows in The Steam and Cooking Coal Market, 2020 (Mt)



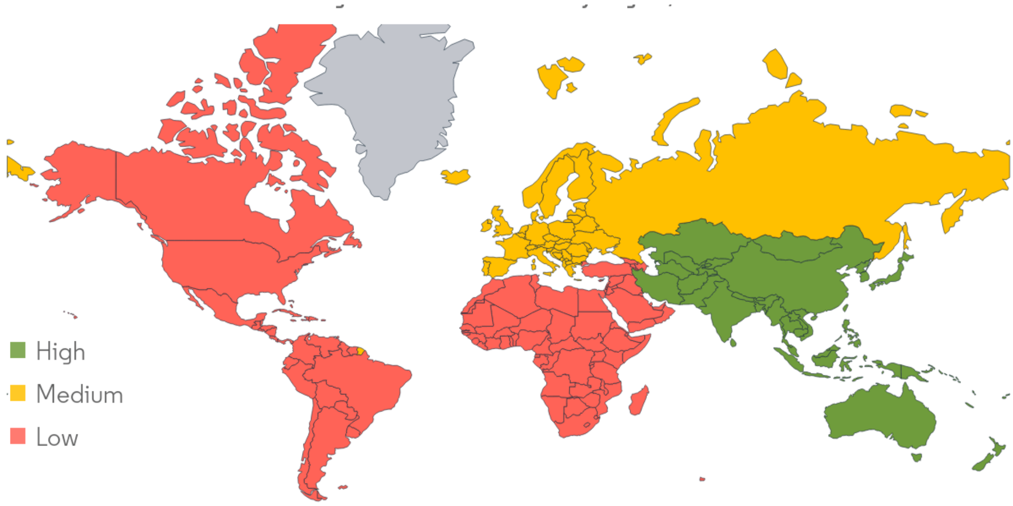
Source: Global Energy Supply and Demand Outlook, https://www.carbonbrief.org/mapped-the-global-coal-trade (28.11.2021)

Furthermore, by 2025, global coal consumption is expected to level out at roughly 7.4 billion tonnes. Over the next five years, trends are projected to differ by area. After a brief rise in 2021, coal continues to fall across Europe and North America. Given that the E.U.'s and the U.S. combined coal use presently accounts for roughly 10% of global coal consumption, additional decreases in both markets will have a limited worldwide impact (IEA 2021, World Energy Outlook 2021, IEA, Paris retrieved from https://www.iea.org/reports/world-energy-outlook-2021).

China's coal consumption has hit a low point, while our forecast for 2025 may need to be amended in light of the commencement of China's 14th Five-Year Plan. China's goal of being carbon-neutral by 2060 needs a long-term strategy to ensure a seamless transition for a country that burns 4 billion tonnes of coal per year. India and other South and Southeast Asian countries are predicted to increase coal consumption through 2025 as their industrial production grows and new coal-fired capacity is built (IEA 2021)

India's 2025 prediction is much lower than it was last year due to the outbreak. By 2025, ASEAN will have surpassed the US and the EU as the world's third-largest coal-consuming region. Various governments pledged to cut coal use in the next years (Korea, Japan), scale back planned coal growth (Viet-nam, Bangladesh, Philippines), and terminate coal development plans (Viet-nam, Bangladesh, Philippines) in 2020. (Egypt). Metallurgical or coking coal and steam or thermal coal are trade terms for various coals that refer to their eventual application instead of its coal quality (Steel production and power plant combustion, by oneself) (IEA, 2021).

Figure 5: Industry for Coal Trading – Growth Rate by Region, 2020-2025



Source: Mordor Intelligence, Jan 2021 https://www.mordorintelligence.com/industry-reports/coal-trading-market (28.11.2021)

1.1. MARITIME COAL TRANSPORTATION REGULATIONS

1.1.1. SOLAS (Safety of Life At Sea)

Maritime transportation is the lifeblood of intercontinental trade and a driver for civilisation throughout the World. The SOLAS Convention, in its several incarnations, is often considered to be the greatest of all treaty obligations dealing to the safeguarding of commercial ships. After the Sinking of the titanic in 1914, the first version was adopted, replaced by the second in 1929, the third in 1948, and the fourth in 1960. The unmentioned adoption mechanism is incorporated in the 1974 version, and determines the date on which a change will take effect on a specific date unless it is challenged by an agreed number of Parties before that date. As a result, the 1974 Convention has undergone various revisions and modifications. SOLAS, 1974, as revised, is the name given to the current Convention (IMO).

1.1.2. IMSBC Code (International Maritime Solid Bulk Cargoes Code)

The SOLAS was established to govern safety requirements for ships operating on international waterways. There are a slew of additional regional and international organisations that oversee shipping. Despite this, catastrophic accidents are recorded every year. The IMO established the International Maritime Solid Bulk Cargoes Code (IMSBC) to regulate the safe carrying of dry bulk Cargo (The IMSBC Code. 4 December 2008, by resolution MSC.268(85)).

The code, which was approved as part of the SOLAS treaty, gives specific information on the possible risks of solid bulk goods transported by ships. According to the World Coal Association, considerable attempts have been made within the IMO over the last decade to provide a more comprehensive evaluation of hazard evaluation for solid bulk cargoes in the framework of current maritime transport standards. Suppliers/shippers of solid bulk commodities, as well as vessels that must transport the cargo, must adhere to two crucial requirements (IMO,2008):

- International Convention for the Prevention of Pollution from Ships (MARPOL), which aims to protect the maritime environment against pollution.
- IMSBC Code, which intended to guarantee that solid bulk cargoes are transported safely.

The IMSBC's major goal is to encourage the safe transportation and handling of solid bulk cargoes by presenting knowledge on the threats in relation to the package of certain types of solid bulk cargoes (e.g. damage to the hull structure caused by inappropriate cargo allocation, loss or lessen of stability throughout a passage, chemical response of cargoes such as spontaneous combustion, emission of toxic or explosive gases, corrosion, and so on), as well as to educate the public about the hazards of transporting certain types of solid materials (Retrieved from: https://safety4sea.com/how-to-prevent-self-heating-of-coal-cargo. Access on 12.10.2021).

Solid cargoes are divided into three categories under the IMSBC Code:

- Group A – bulk materials that may liquefy,
- Group B – bulk materials possessing chemical hazards,
- Group B – bulk materials that are neither liable to liquefy nor possess chemical hazards,

The code addresses the dangers that come with transporting solid bulk commodities. Compounds known as "materials hazardous only in bulk" (MHB) represent a chemical concern when carried in bulk, unlike packaged harmful products (i.e. IMDG Code). These products represent a noteworthy danger when delivered in bulk and essential additional protections (IMO, 2008).

The IMSBC Code usually expect all coal cargoes to be designated as coal on the shipment notification since the IMSBC Code (the "Code") only has one COAL item, regardless of financial name for the kind of coal. The IMSBC Code recommend point all participants to this portion of the Code, which has a rather detailed set of suggestions for securely loading coal cargoes. Coal is commonly transported in bulk form, although certain kinds are very finely grained (known as 'fines') and may liquefy, necessitating the use of extra loading restrictions such as a TML Certificate and a Moisture Content (MC) Certificate. IMO has set recommendation for shippers to control their humudity control systems, and the Authoritative Authority at the Loading Port must now produce an auxiliary certificate stating that these processes have been approved. COAL SLURRY is another coal-related cargo that is made up of fine coal particles that have been cleansed from larger lumps. Because it might become liquid, it demands a TML and MC certificate before shipment (Retrieved from: https://safety4sea.com/how-to-prevent-self-heating-of-coal-cargo. Access on 12.10.2021).

According to the IMSBC Code, coal is a naturally, dense, flammable material comprised mostly of amorphous carbon and hydrocarbons. Spite of the fact that coal is known for its combustibility and capacity to self-heating, certain coal cargoes may be susceptible to liquefaction. The proposed changes to the IMSBC Code concern the requirements for categorizing coal cargoes as Group A, or liquefiable, as well as the chemical risks that apply to all coal cargoes, such as self-heating or methane emissions (IMO, 2008).

In terms of the hazard classification under the updated MARPOL Convention and the IMSBC Code, Caol Cargoes are classified as Group A and Group B by shippers. As a result, coal shipments may be subject to the same TML and moisture certification requirements as other Group A commodities including concentrates, nickel ore, and iron ore fines. Unless otherwise certified, Group A and B should be applied to all coal. Except they match the new standards outlined in the IMSBC Code, all coal shipments must be deemed liable to liquefy and pose a chemical danger (West of England.2008.Monitoring of Self-Heating Coal Cargoes Prior to Loading(Brochure)Luxembourg(Brochure)).

There are two more ways for shippers to declare that a coal cargo is not in Group A:

- If the particle size distribution of coal cargoes is less than 10 % less than 1 mm and less than 50 % less than 10 mm, they are excluded from Group A criteria. It's worth noting that the above uses the word "AND," implying that shipments that exceed any of these restrictions will not be exempt from Group A criteria. The corresponding size parameters for iron ore fines are different (and cover a broader range of cargoes).
- Alternatively, the competent body in the loading nation might set laboratory criteria for determining whether a coal shipment has Group A features. The results of the test procedures for Group A cargoes in Appendix 2 of the IMSBC Code would most likely be used to develop such criteria.

1.2. HAZARDS AND HANDLING OF THE COAL SHIPMENT

This study examines the potential risks and processes that may emerge during the handling of coal shipments using IMSBC Code requirement and circular announcement from the IMO, Classification Society (ABS, NKK, Lloyd's Register, and DNV-GL), and The P&I Clubs (North of England, Skuld, Northern Club, Gard, Steamship Mutual, and London P&I) who have given connected and appropriate notice on-board dry bulk cargo ships.

1.2.1. The Characteristics and Types of The Coal

Originally, coal is largely made up of carbon, hydrogen, and oxygen, with minor amounts of sulfur and nitrogen (The IMO, 2008).

Table 4 : General Information of the Group B (and A) Coal

REPOSITION ANGLE N/A	BULK DENSITY (kg/m3) 654 to 1266	S/F (m3/t) 0,79 to 1,53
DIMENSION < 50 mm	CLASS MHB	GROUP B (and A)

Source: The IMSBC Code, 2008

Methane, a flammable gas, may indeed be produced by coal. Sparks or naked flame, such as electrical or mechanical sparks, a lit smoke, can generate a flammable atmosphere in a methane/air mixture with a methane content of between 5% and 16%. Methane can concentrate in the top portion of the holds or other enclosed areas since it is lighter than air. If the cargo holds limitations are not adequately sealed, methane can leak into areas around the cargo holds (The Swedish Club,2018,A guide to the causes and prevention of cargo fires(Brochure)).

Coals might be oxidized, depriving the cargo holds of oxygen and raising CO_2 or CO levels. CO is a uncoloured, unscented gas that is somewhat less dense than air and has flammability limitations in air of 12 to 75 % by capacity. When breathed, it is dangerous because it has a 200-fold affinity for blood haemoglobin compared to oxygen. In addition, some coals may get overheated, resulting in spontaneous fire in the cargo holds. There's a chance that combustible and toxic gases like carbon monoxide will be generated. Also, several coals have a proclivity for reacting with water and releasing acids, which can result in corrosion. Gases that are combustible and harmful, such as hydrogen, are likely to be generated. Hydrogen is a transparent, tasteless gas that is substantially lighter than air and has flammability limitations ranging from 4 to 75 % by volume in air (UK P&I.2016 October. Carrying solid bulk cargoes safely. Retrieved from https://www.ukpandi.com/news-and-resources/articles/2016/carrying-solid-bulk-cargoes-safely/).

Brown Coal Briquettes: Brown Coal is a kind of coal that is brown in (Lignite) Briquettes are made by compressing brown coal particles that have been dried (The IMSBC Code, 2008).

Table 5 : General Information of the Group B Coal

REPOSITION ANGLE N/A	BULK DENSITY (kg/m3) 750	S/F (m3/t) 1,34
DIMENSION Largely < 50 mm	CLASS MHB	GROUP B

Source: The IMSBC Code, 2008

Threat: Briquettes are quickly sparked, susceptible to fires and explosions, and reduce oxygen supply in compartments.

This good is easily combusted, and it has the potential to heat up spontaneously, depleting oxygen in the cargo bay and the coal cargo is oxidized, resulting in dehydration and a rise in carbon dioxide in the cargo compartment. Also, in the cargo compartment, this cargo has the potential to heat up and suddenly ignite. It can be risky to develop combustible and harmful gases, such as carbon monoxide, by spontaneous heating. Carbon monoxide is a tasteless, unscented gas that is somewhat less dense than air and has flammability limitations in air of 12 to 75 % by size/mass. When breathed, it is dangerous because it has a 200-fold proximity for blood haemoglobin comparing to O_2. The proposed Threshold Limit Value (TLV) for The concentration of CO in the air is 50 parts per million (UK P&I.Carrying solid bulk cargoes safely(Brochure)).

Stowage and segregation: The perimeters of cargo compartments in which coal cargo commodities are transported must be fire and liquid impenetrable. Packaged cargoes of classes 1 (Division 1.4), 2, 3, 4, and 5 (see IMDG Code) and solid bulk goods of classes 4 and 5 must be "separated" from this cargo. It is prohibited to stow items of class 5.1 in packed form or solid bulk materials of class

5.1 up or down this cargo. Therefore, this cargo must be "isolated longitudinally from" commodities of class 1 other than Division 1.4. and this coal must’t be stored near any heat sources (Code of Federal Regulations. Title 46 148.155.Stowage and segregation for potentially dangerous materials).

1.2.1.1. Self-heating coals

Only once the heat of the cargo is less than 55°C will it be approved for loading, according to the COAL agreement in the Code. Both before and during the shipment, cargo temperature management will be required, if the importers or exporters claim that the coal has a signs of self heating (The Swedish Club, 2018).

If the shippers indicate that the coal has "no signs of self," it's a good idea to keep an eye on the heat of the coal cargo and prevent loading any coal with a heat above 55°C. It's most likely been mis-declared if the coal heat has already surpassed 55°C (The Swedish Club,2018).

Because self-heating activities are analogous to chemical processes in that the rate of reaction typically twice for every 10 degrees of heating rate, a maximum cargo temperature restriction is necessary. As a consequence, once coal reaches around 55°C and the velocity of self-heating processes becomes high enough, the coal may self-heating. There will be enough time to load, inspect, and restrict oxygen to prohibit self-heating processes and the coal from hitting the high heate necessary for ignite if the cargo heat is much less than 55°C (The Swedish Club, 2018).

The Code recommend against utilizing any 'normal' temperatures observed on floating barges or closed areas/silos because the Code does not specify that they are acceptable. If the coal has a signs of self heating and/or producing methane, this information ought to be included in the shipment statement. These qualities do not prevent coal from being conducted, but they have an impact on how it is managed and observed throughout loading and transportation (The IMSBC Code, 2008).

If the heat of the coal on any floating barge exceeds 55°C, the shipper must either drive bulldozers to cool the cargo or guarantee that the coal is not loaded. Crew policing, such as temperature monitoring on a regular basis, or local surveyors, if appointed, will be necessary. We also state that cooling coal by rotational and/or turning it over is conceivable, and we've done it previously, successfully cooling coal to a temperature below the 55°C restriction, allowing it to be loaded (UK P&I Club.2018.Carefully to Carry(Brochure)).

Before loading, monitor the temperature of the self-heating coals: The heat of the coal cargo should be confirmed previous to shipment, as per The Code. Some may wonder why such inspection is required if exporters or importers do not provide proof that the coal would self-heat. Nevertheless, there is a lengthy history of shippers lying or just not understanding why the information is needed or the implications if the cargo self-heating. Admittedly, if a fire breaks out in a ground-level stockpile, it's much easier to put out (CJA Maritime,Services.2010.A guide to the causes and prevention of cargo fires: Coal Cargo – Precautions Prior to Loading & During Voyage(Brochure)).

As a consequence, maritime experts recommend that before shipment, the heat of the designated cargo be inspected. Because majority of the coal in Indonesia is transported by barges, measuring coal cargo temperature readings prior to shipment to the vessel will almost probably necessitate inspecting the coal on the barges (Lloyd’s Register.2013. Carrying solid bulk cargoes safely(Brochure)).

A thermocouple gauge and thermometer are fantastic, but inserting one into coal can be difficult. An infrared (IR) thermal spot temperature device might be used instead if this is problematic or impossible. These are becoming more economical, and every coal-carrying ship may be equipped with one. Because these sensors are unreliable and can only detect surface temperatures, it is necessary to check the coal cargo under the surface, that is, after the grabs have unsettled it, and to assess the temperature of the stow's newly exposed surfaces. Shippers may also place heat sensors on loading carrier systems, which might be observed, provided access is given (The London P&I Club, 2018, Carriage of Coal Gas Monitoring and Ventilation(Brochure)).

Since cargo temperature observing may essential halting shipment, The findings of the coal cargo heat monitoring activity must be meticulously logged. Surface heats are a good position to commence, and if they're already over 55°C (the Code's maximum loading heat), the cargo is self-heating and won't fulfill the shipping criteria. The stowage on the floating barges (or on stockpiles if onshore) must be reachable from within the pile to obtain further temperature data, which necessitates excavating into the pile to reach the stow's interior sections.

Since self-heating in a stockpile of coal can be fairly limited, several pits would be excavated to estimate the heat across the stockpiling, transport boat, load, and stow. This method allows for the construction of a clear image of the heat profile of the mentioned cargo. If the temperature in the inner parts of the stowage proves to be over 55°C, it may be conceivable to operate an IR thermometer to measure the newly surfaces that have been exposed when a grab-system is withdrawn and, if required, prevent it from contacting the holds (West of England.2008.Monitoring of Self-Heating Coal Cargoes Prior to Loading(Brochure)Luxembourg(Brochure)).

1.2.1.2. Methane Emitting Coals

Because certain coals produce methane, a immensely combustible gas, the coal item in the Code beside specifies the safety preventions that must be taken when loading and transporting such material. Monitoring for methane becomes practicable only after such coals have been loaded, as the gas must be collected in the Cargo compartment and its existence can't be confirmed in the open air. Having an understanding of coal is critical to managing the risks, and the COAL schedule of the Code outlines the management for ship transport (Myers, D. Cooke, P. Croouch, N.2016.Carriage of coal cargoes: Self-heating and explosion risks.Skuld).

1.2.2. Hazards of The Coal

Coal has the ability to produce combustible atmospheres, heat up spontaneously, reduce oxygen levels, and corrode metal structures. It's possible that the coal will liquefy if it's primarily fine, less than 5 mm (The IMSBC Code, 2008).

1.2.2.1. Weather precautions

The following conditions must be met when a coal cargo may liquefy during transportation since its moisture content exceeds its TML and the coal cargo is handled on a vessel that is not specifically constructed or fitted to fulfill the standards of subsection 7.3.2 of this Code (West of England.2008.Monitoring of Self-Heating Coal Cargoes Prior to Loading(Brochure)Luxembourg(Brochure)):

1. During the sailing, the humudity concentration of the cargo must be kept below its TML.

2. Unless otherwise specified in this Itinerary, coal cargo shipments shall not be serviced while downpour,

3. During cargo shipment, all non-working hatches of cargo holds into which the cargo is loaded or will be loaded, should be closed unless otherwise stipulated in this specific schedule,

4. The cargo may be transported in the presence of precipitation if its real moisture content is below its TML and the genuine humidity levels is unlikely to be increased beyond the TML; and

5. During precipitation, coal cargoes in a cargo space may be unloaded if the complete quantity of coal cargoes in the cargo hold is to be unloaded in the loading port.

1.2.2.2. Special precautions

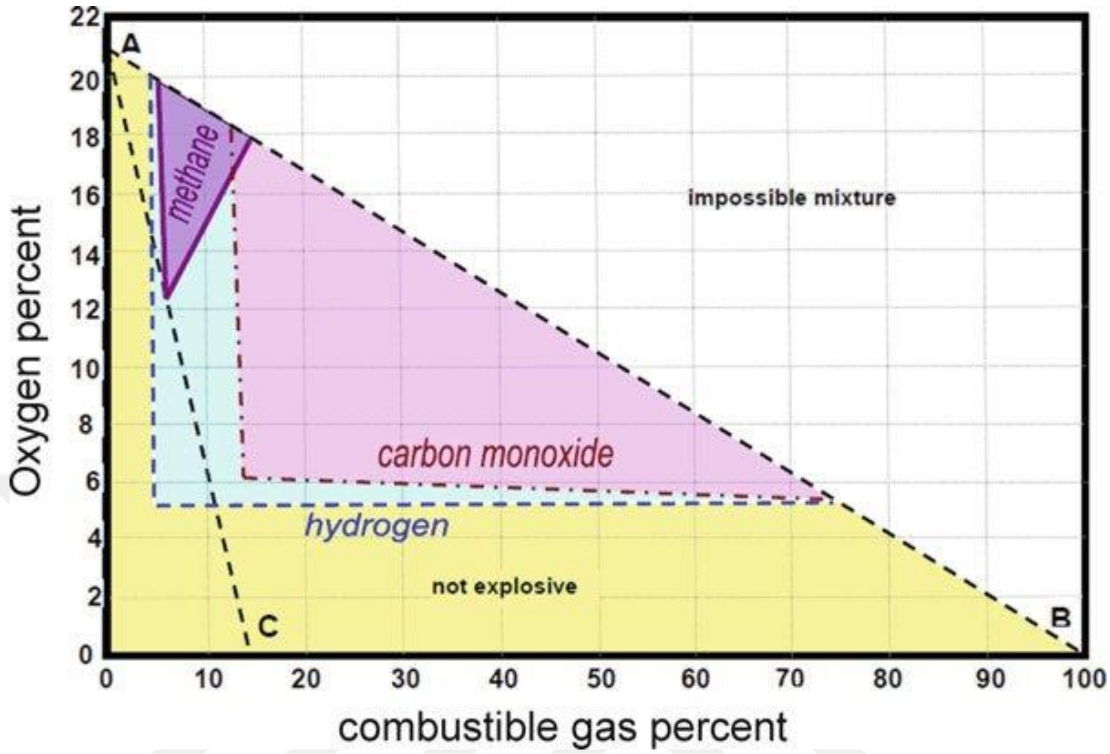
When carbon monoxide surveillance is carried out according to the established methods outlined below, it will ensure a trustworthy advance notice of self-heating inside this shipment. This enables for immediate consideration of preventative measures. A consistent rise in carbon monoxide levels found within a cargo compartment is clear evidence that self-heating is occurring. To facilitate the monitoring of the environment within the cargo compartment, all ships involved in the carrying of this cargo must have on board an equipment for detecting methane, oxygen, and carbon monoxide gas concentrations (UK P&I Club, 2018).

According to the manufacturer's recommendations, this device must be repaired and adjusted on a regular basis. Because of the low oxygen level, methane measurements collected in poorly ventilated. Cargo holds should be regarded with care. Proper measurement of catalytic sensors used for methane detection necessitates the presence of sufficient oxygen. Carbon monoxide and methane readings utilizing an infrared sensor are unaffected by this phenomenon. (UK P&I Club, 2018)

If the concentration is reduced from 100% to 1% as a result of this gradual dilution, the explosive range is defined as the concentration range of 5% to 15%. The combination might be ignited in this rangeAbove 15%, known as the UEL, methane air mixtures are not combustible, but it becomes flammable and volatile when combined with more air. Methane-air combinations never burn below 5%, known as the LEL (Kissell, 2006). Due to full combustion, the strongest explosion occurs when the methane concentration is 9.5 %. It indicates that all methane is burned with all available oxygen, leaving no methane or oxygen in the mine air following the explosion. Proper vessel firefighting and fire extinguisher procedures, as well as mechanical and/or natural hold ventilation systems, will ensure that methane passes through the combustible scope as quickly as possible, and that the volume of gas mixture in or beyond the explosive range is reduced to a minimum.

The Coward explosive triangle in Figure 6 illustrates that an explosion demands oxygen (greater than 12 % by mass) in addition to the amount of methane between the explosive range. If any of the triangle's elements are removed, the explosion will be turned out. (McPherson, 2015). Methane combustion is a dangerous occurrence in and of itself, but it becomes considerably more dangerous when the blast wave propels flammable dust into the air, where it might be sparked by the flame of the burning methane. In and of itself, methane ignition is a very dangerous occurrence. When a shock wave propels combustible dust into the air, the flame of burning methane might ignite it, making the situation much worse.

Figure 6: Coward Explosive Triangles



Source: McPherson, 2015

1.2.2.3. Some General Criteria for All Forms of Coal Cargoes,

Before shipment, the importer, exporter or her/his chosen official person must declare the master in writing of the coal cargo's specifications as well as advised safe loading and transportation measures. At a least, the cargo's contracting criteria for humidity and sulphur substance, and size, as well as whether the cargo is likely to emit methane or self-heat, must be specified (CJA Maritime Services, 2010).

Besides, the master must guarantee the following prior to actually loading (Coal Cargoes carriage at sea ,flammability hazards and preventive measures. Retrieved from https://bulkcarrierguide.com/coal-hazards-&-safety-considerations.html. Access: 19.11.2021):

- All holds and bilge are dry and clean. Any type of waste or past cargo remnants, together with detachable cargo battens, is removed; and

- All electrical lines and elements in hold areas and neighboring areas are in good working order. These wires and electrical components are either positively isolated or flammable.

The vessel must be properly equipped and have on board the necessary devices to measure the following without having to enter the cargo hold:

- Methane proportion in the atmosphere;
- O_2 levels in the atmosphere;
- CO proportion in the atmosphere; and
- PH value of holds bilge samples.

These devices must be repaired and gauged on a regular basis. Crew should be well trained in the usage of such devices. The processes for measuring gas are described in detail at the conclusion of the IMSBC Code. Also, it is proposed that techniques for detecting coal cargo heat in the range of 0°C to 100°C be provided, allowing heat to be recorded during cargo is being transported and without requiring access to holds. Moreover, in cargo holds and surrounding/closed areas, smoking and the use of lighters are prohibited, and relevant danger signs must be conspicuously placed. Igniting, chopping, scrapping, welding, or other combustible material are not allowed in the vicinity of holds or other nearby compartments except if the area has been accurately circulated and methane gas testing proves it is safe (Coal Cargoes carriage at sea flammability hazards and preventive measures. Retrieved from https://bulkcarrierguide.com/coal-hazards-&-safety-considerations.html. Access: 19.11.2021).

Before cast away from port, to avoid gas pockets forming and air infiltrating the briquettes' body, the ship's master must guarantee that the object's covering has been trimmed levels with the cargo compartment's limitations. Casings leading into the cargo holds must be marked and secured appropriately. The shipper is responsible for ensuring that the loading terminal provides the appropriate assistance to the master. The amounts of methane, oxygen, and CO in the atmosphere over each cargo holds must be continuously monitored. The tracking figures must be noted and logged. The monitoring frequency will be selected depending on the information given by the shipper and the information collected from the atmospheric analysis in the cargo holds. (Coal Cargoes carriage at sea flammability hazards and preventive measures. Retrieved from https://bulkcarrierguide.com/coal-hazards-&-safety-considerations.html. Access: 19.11.2021)

Unless otherwise indicated, surface circulation must be carried out in all cargo compartments conveying the coal for the first 24 hours after cast away from the shipment port. The atmospheric condition in the holds will be evaluated once from one control point per cargo holds during this time, and the ventilation will be switched off for a reasonable amount of time before the gas measurement. After the methane combinations measured within 24 hours after cast away from port are at an acceptable low level, the ventilation holes must be secured and the environment in the holds must be checked. Surface ventilation should be maintained, with the exception of a sufficient interval for gas measurement, and the cargo holds environment should be evaluated if methane concentrations detected within 24 hours after cast away from port are not at an acceptable low level. This technique must be followed until methane concentrations are reduced to an acceptable level. The environment in the regarding areas will be checked on a daily basis in either case. If considerable methane concentrations are detected in unventilated cargo holds, the requisite specific measures for coals releasing methane must be taken (The London P&I Club, 2018).

As far as is reasonably practical, the master should ensure that any gases produced by this cargo do not concentrate in neighboring enclosed places. The captain on board is responsible for ensuring that surround working spaces such as storerooms, carpenter's shops, passageways, the duck keel, and other similar locations are examined for methane, oxygen, and carbon monoxide on a regular basis. These locations need to be thoroughly ventilated. During the transportation with this cargo, periodic hold bilge testing must be conducted out in a methodical manner. If pH monitoring shows a corrosion concern, bilges must be emptied out often throughout the journey to minimize the buildup of acids on tank tops and in the bilge system. The master must notify the shipper if the goods acts differently during transportation than what the Cargo declaration indicates. The shipper will be able to monitor the activity of coal shipments using these information and evaluate the master's report in light of prior transportation experiences (West of England. Coal Cargoes – Know the Dangers(Brochure)).

Before to load a Coal: If the goods has a signs of self heating or methane emission, shippers must submit Cargo/shipper declaration. If it doesn't, double-check with the shippers, because both of these characteristics are widespread in Indonesian coals, with self-heating being more common. The master of the vessel must take measures and actions while interacting with coal cargo during loading, unloading, and throughout the voyage (CJA Maritime Services, 2010).

During the transportation, all coal shipments will be monitored. For each hold, this will take the form of temperature and gas data. As previously indicated, all boats transporting coal must have sufficient gas monitoring devices for the entirety of the transportation, and this device must be in good working condition and have an the latest calibration certificate prior to loading. Because the Code mandates gas monitoring for coal and other related commodities, Before loading commences, understanding that how vessel's multi-gas detector operates is critical (CJA Maritime Services, 2010).

A gas sample is vacuumed down a sampling drain-pipe in the Cargo compartment headspace, through the gas sampling opening, and over the instrument's gas sensors in certain multi-gas detectors. Others don't have this function, thus sucking headspace gases through the meter requires the use of a latex hand-pump in the shape of a bulb inserted amongst the sample tube's end and the multi-gas detector. Before taking the next reading, make sure the meter comes back to normal gas ratings in fresh air, i.e. oxygen 20.9 %, carbon monoxide 0 %, and LEL 0 %. Dust and moisture should be kept out of the gas meter since they might destroy the sensors, therefore an in-line filter can assist (West of England. Coal Cargoes – Know the Dangers(Brochure)).

Access to the something where through the gas sample ports allows for precise monitoring of oxygen (O_2), methane (CH_4), and carbon monoxide (CO) levels without having to open the hatch covers. It's also vital to know which gases are being examined and why they're being checked (The IMSBC Code, 2008)

Most multi-gas meters onboard ships won't operate for hydrocarbons or other flammable gases at low oxygen tension - In reality, they won't operate at all if the oxygen level is less than 12 %. This is the case because most gas analyzers employ flame detectors, which demand oxygen to function properly and give correct hydrocarbon/flammable gas measurements (The London P&I Club, 2018).

Furthermore, there are two critical difficulties that must be addressed before and during the loading of the coal. To begin, the Coal Cargo must be trimmed. Trimming the cargo lessens the risk of it moving and reduces the amount of air that enters the container. If air enters the cargo, it may cause it to heat up spontaneously. To reduce these dangers, loads must be cut to a reasonable amount as needed. Furthermore, if there is any worry about stability, the master has the power to propose that the cargo sholud be flat level based on the information available and bearing in mind the ship's characteristics and the intended itinerary. Second, if the bulkhead among the holds and the engine room is not isolated to the IMSBC Code's class A-60 requirement, this cargo must be handled "away from" the bulkhead (The IMSBC Code, 2008).

1.2.3. Handling of the Coal Cargoes

Over than a billion tonnes of coal cargoes are carried out by sea every year (IEA, 2020). Coal is a crucial source of energy and a chemical raw resource that is delivered in substantial volumes across the world. Shipping coal as a cargo, on the other hand, entails a the quantity of dangers, and it should be carried out in compliance with all legal standards.

Considering its beginnings as a carbon - containing sedimentary rock formed over time by erosion and weathering exerting pressure on organic material remains (ISO 11760:2018 (en)), coal may take several forms and refers to a wide range of cargoes. As a consequence, the characteristics of coal and the risks associated with it differ remarkably based on the nature of coal being carried as Cargo. The level of geologist "coalification," which changes the features of the original organic matters by transforming it into a stiffer, drier, harder, and more carbon-rich material, is referred to as "coal rank" (U.S. Geological Survey). Low-grade coals, such as brown coal, are more able to self heating, whereas high-grade coals, such as anthracite, are more prone to create methane (What are the types of Coal?.Retrieved from https://www.usgs.gov/faqs/what-are-types-coal. Access: 18.11.2021).

What all coal shipments have in mind is that specific precautions must be taken during shipment and controlling while transportation. The following qualities of coal are the most important in terms of its shipment at sea and must be considered. Some coals have the potential to (The London P&I Club, 2018)**:**

- Release methane (CH_4), which can generate a flammable or explosive environment if a spark or flame is used to ignite it. If the cargo area isn't gas-proof, CH_4 will build up in the upper layer of the space and may leak into nearby locations.
- Deplete oxygen (O_2) in cargo holds and surrounding areas, resulting in a rise in carbon dioxide (CO_2) in the cargo holds;
- If handled with too much moisture, it will liquefy (as explained below).

Because coal is a highly hazardous bulk product, it should always be operated, transported, and unloaded in accordance with the IMSBC Code. The IMSBC Code comprises a presented timeline for coal carriage and stowage, as well as information on the risks associated with coal carriage, such as asphyxiation and seafarers' contact to dangerous gases, as well as the safety safeguards that must be taken. Both ship and onshore management/company manager should be aware of and follow these guidelines. If members have any questions, they should seek expert counsel or confirmation / state letter from the corresponding Flag State (The IMSBC Code, 2008).

1.2.3.1. During Loading

The seller or its nominated agent must alert the master in writing of the cargo's specifications and advised regarding safe methods for loading and carrying the cargo before coal cargo operation. At a minimum, the moisture and sulphur ingredients, and size of the cargo ought to be specified in the contract (Gard P&I, 2015.Loading of Coal Cargoes(Brochure)). Before loading, this cargo must be kept for 7 days. This decreases the danger of spontaneous combustion during transportation, storage, and handling. The master must ensure the following before loading this Cargo (Gard P&I, 2015):

- The cargo holds weather deck enclosures have been assessed for their integrity. On board, these sorts of equipment are locked and secured.
- All electrical lines and devices in cargo compartments and nearby areas are in good working order. Such cables and electrical parts are either positively separated or safe to use in a combustible and/or dusty environment

Smoking and the use of naked flames are forbidden in cargo compartment and nearby places, and appropriate danger signs must be posted prominently. Igniting, chopping, scrapping, welding, or other combustible material are not permitted near holds or other nearby compartments. In order to reduce the creation of dust and particles, this cargo should not be lowered more than one meter during loading. Wherever practicable, individual cargo areas should be loaded without stoppage. In a cargo holds hatch cover that has been unsecured for more than six days (or fewer in temperatures over 30°C), hot spots can form. Also, before departing from port, the master ought to be convinced that the surface of the material has been trimmed flat with the cargo hold's borders to prevent gas pockets developing and air invading the briquettes' body. Casing leading requires the aid of the loading terminal.

After the commodities have been placed into the cargo holds, all cargo holds must be closed and secured as soon as feasible (Gard P&I, 2015).

Ventilation: During the transportation, the cargo compartments carrying this cargo must not be circulated.

1.2.3.2. During Carriage:

According to IMSBC Code, once the coal has been loaded and has met the carrying criteria of the IMSBC Code (the "Code"), It is critical that this cargo be allowed for commencing operation only when the heat of the coal cargoes does not exceed 55°C. The cargo's observing and controlling during the transportation becomes crucial at this point. Regardless of whether the coal was loaded at heat lower than 55°C, this does not rule out the possibility of issues developing during the carriage (The IMSBC Code, 2008).

Any gases generated by the coal cargoes should not be permitted to gather in nearby enclosed places, among others store rooms, carpenter's shops, passageways, tunnels, duckkeel and so on, to the extent possible. Such areas must be properly ventilated and methane, oxygen, and carbon monoxide levels must be measured on a regular basis. The hatches shall not be reopened or the cargo holds aired or accessed during the transportation, unless in an emergency. Methane, oxygen, and carbon monoxide levels in the atmosphere from the cargo surface to hatch cover for all cargo holds must be measured on a regular basis. The observation frequency will be selected depending on the information given by the seller and the readings collected from the atmospheric analysis in the cargo holds. The monitoring must be done at least twice a day and at a time that is as near to the same as possible. The inspection information must be noted and logged. If there are any signs of considerable self-heating throughout the shipment, the seller or receiver may demand more regular monitoring (The IMSBC Code, 2008).

Access to the upperspace of the cargo via the gas sample ports allows for reliable monitoring of oxygen (O_2), methane (CH_4), and carbon monoxide (CO) levels without actually opening the hatch covers. It's also crucial to understand which pollutants are being examined and why (The IMSBC Code, 2008):

- Oxygen (O_2) levels should have been dropping in a self-heating coal. Self-heating is impossible without O_2.
- Carbon monoxide (CO) is a gas that is created when self-heating/combustion emerges in the presence of low oxygen levels. This unscented gas is known as a "silent killer" since it adheres to haemoglobin in the blood and causes suffocation.
- Methane (CH_4) is a gas that is emitted by some coals; a rising grade specifies that the coal is producing CH_4 and should be continuously observed. Ventilation is necessary if the levels increased to 20 % of the LEL.

It's worth noting that most onboard multi-gas detectors may not be dependable for hydrocarbons or other combustible pollutants when oxygen grades are low in fact, they will not function effectively below roughly 12 % O_2. Because most of them are ignition sensors, they require oxygen to work and provide accurate hydrocarbon/flammable gas readings. The following considerations must be made (The London P&I Club, 2018):

- The oxygen concentration in the enclosed compartment will drop out of a high of 21% to a range of 6 to 15% over the course of a few days. If the oxygen level does not drop below 20% or rapidly rises after a dip, the cargo holds are likely not securely secured and are at risk of spontaneous combustion,(The American Club.2015 November. Coal Cargoes: Self/over-heating and Emission of Flammable Gases(Brochure))
- In a safe, well-closed cargo holds, carbon monoxide levels will rise to values ranging from 200 to 2000 parts per million,
- A sudden increase in carbon monoxide levels in this cargo of around 1000 ppm over a 24-hour period might indicate spontaneous combustion, especially if it comes with an increase in methane values.
- The methane contents of briquette cargo is typically minimal, less than 5 ppm, and poses little danger. A quick and sustained rise in methane levels beyond 10 ppm, on the other hand, indicates the formation of spontaneous combustion in the cargo holds,
- Because temperature control inside the temperature pipes are positioned inside a hold but on the outskirts, any heat measurements can only give a broad estimate of the heat of the coal near the pipe and cannot tell you what the temperature of the cargo is like farther in the cargo holds. As a result, gas gauging are the primary and most accurate model for cargo observing throughout transportation.

The temperature of the coal cargo in a well-sealed cargo holds is generally 5 to 10°C higher than the temperature of sea water, with the difference attributable to natural diurnal breathing of tiny amounts of air into the cargo holds. It is critical to examine the cargo holds seals for air leakage. Unexpected ignition is evidenced by a fast increase in temperature of around 20°C over the course of 24 hours.

Systematic hold bilge testing must be performed on a regular basis. If the pH measurement shows that there is a corrosion risk, the master must keep all bilges dry during the transportation to minimize the formation of acids on tank tops and in the bilge system. When the cargo's behavior during the transportation deviates from what was described in the Cargo Declaration, the master must notify the shipper. Furthermore, such declarations will qualify the shipper to preserve track of the cargo's progress, allowing the master's information to be examined in context of past shipment expertise. When the master suspects the cargo is self-heating or spontaneously igniting, the following measures must be done. At the loading port, communicate with the vessel's agent. The DPA of the shipping company will be alerted as soon as possible (UK P&I Club.2018).

If the master determines that access is required for the ship's or passengers' safety, do not enter the cargo holds or open the hatches. When a ship's crew enters a cargo holds, re-seal it as soon as they leave. Increase the number of times you check the cargo's gas composition and temperature, if possible. To receive expert guidance, send the following information to the ship's owner or nominated agent at the loading port as soon as feasible (The American Club.2015 November. Coal Cargoes: Self/over-heating and Emission of Flammable Gases(Brochure)):

1. The total number of cargo holds in question;
2. The outcomes of the analyzing carbon monoxide, methane, and oxygen concentrations;
3. The heat of the coal cargo, placement, and technique used to collect data, if available;
4. The date and time of the gas analyses (checking procedure);
5. The amount of cargo in the cargo hold(s) in question;
6. The cargo specification as indicated in the shipper's declaration, as well as any particular precautions stated in the declaration;
7. Any additional pertinent remarks or measurements taken by the master.

1.2.3.3. During Discharge

The major issues with unloading a self-heating coal commodities are connected to as a matter of fact that even a small area of burning, burning coal produces a substantial cloud of smoke. This smoke builds up in the hold's headspace and is discharged all at once when the hold covers are opened, giving the impression that the situation is worse than it is. Receivers are frequently concerned about this, and some coal stations have rejected to unload the commodities depending of whether the cargo hatch cover had been opened or not, allowing additional oxygen to enter the cargo holds to sustain further self-heating/ignition. As a result, we propose that the hatch covers be opened only when the cargo will be discharged directly. Until then, they should be tightly sealed to limit oxygen exposure (The London P&I Club, 2018).

The simple solution is to let the fire burning or burning cargo extracted; however, this requisites that the location be reachable and that accessing the hold to remove it is safe when it comes to CO_2 emissions monoxide levels. Although limited sprinkling of clean water to humudify such patches is regarded as a temporary solution, greater water usage should be prohibited since any significant increase in the coal cargo's humidity will reduce the coal's calorific value. Furthermore, if the hot spot is not eliminated but is exposed to air, it will re-ignite within hours or even days. If at all feasible, any water used to extinguish fires should be fresh water rather than saltwater, because chloride contamination in receivers can cause corrosion in power plant boilers when the coal is eventually burned (UK P&I Club.2018)

Receivers and Terminal Operators in port terminals wherein coal is transported to conveyor systems could be apprehensive to transfer hot coal over their belts for adversely affecting them, such as melting the rubber or, worse, igniting them. Because coal-fired power plants rely on a constant procurement of coal, any detriment to the carrier systems that leaves it unusable for an extended period of time will be of great interest to the Receivers, notwithstanding the possibility of such detriment happening being minimal. Furthermore, water used in firefighting might impair the cargo handling qualities of particular coals, making them 'cohesive' and hard to release into carrier lines when wet (UK P&I Club, 2018)

When a self-heating coal cargo is unloaded, it's vital that the cargo compartments are unloaded entirely and on time, because partially discharged cargo holds maintain a larger reservoir of oxygen, which may be used to power the self-heating activities in any existing cargo stowage. This could also trigger 'hot spots' to ignite or re-ignite within the material. Certainly, the master and crew have no influence over whether or not the terminal shuts down unload for whatever cause, but there have been several occasions when partly unloaded cargo holds have burnt whilst vessel stayed at the anchorage waiting for discharge to be finished. If this occurs, the only thing that can be done is to try to minimize the cargo's accessibility to oxygen as often as practicable by shutting off all ventilation systems and the like, while analyzing the headspace gases. If the vessel has performed all necessary to prevent self-heating inside the stows by blocking cargo access to oxygen throughout the trip, therefore the cargo burning after discharge is due to the coal's intrinsic nature. Regrettably, as a consequence of this, charges against the vessel will not always be eliminated (The Swedish Club, 2018).

Finally, Receivers may object to the smoke caused by coal burning, partly because it has the potential to limit stevedore personnel' entrance to cargo spaces, mainly because to environmental concerns. It is critical to maintain that once release begins (in a problem coal), it is completed, and that partially released cargo compartments are not left open (The Swedish Club,2018). Extra caution is required while unloading hot, methane-emitting coal and other materials since opening the hatches lets oxygen to enter the holds, which might cause an explosion if combined with the methane. Prior to beginning the discharge procedure, it will be necessary to seek expert guidance (The IMSBC Code, 2008).

Despite the fact that the gases appear to be blasted out through the hatch cover vents, oxygen is permitted into the cargo holds. It's also conceivable that an inert gas will be injected directly to the holds just before they're opened. The flammable gases will be pushed out of the system through a secondary open vent, lowering the risk of an explosion. This is something that should only be considered with the assistance of a expert (The IMSBC Code, 2008).

It may be necessary to have firefighting experts on standby to help in the case of an issue as well as to shower the cargo with water after it arrives on land. By spraying a tiny amount of fresh water into the problem region, the grabs may be able to remove the patch. When the discharge reaches the grabs' limitations, however, the gas levels may prevent employees, such as the bulldozer driver, from accessing the holds (The IMSBC Code, 2008). Chemical cargoes, on the other hand, require the ship's care for a different reason. Delivering the cargo as pure as possible and in good condition at the loading port is one of the most critical components. Both physical and chemical specialties of cargo must be properly preserved in order to maintain cargo purity.

In December 2008, the IMO established the obligatory IMSBC Code, which replaced the prior recommendatory Code of Practice for Solid Bulk Cargo (BC Code). In 2011, Brazil recommended the creation of a working committee to investigate the flaws in the new code's test techniques. This fresh study resulted in amendment 3/2015, which took effect on January 1, 2017. The building of a new program for iron ore fines, as well as confirmation of the modified P&F test to determine the TML, were the most significant aspects of the change.(Modified Proctor/Fagerberg Method for Coal.2014 November)

The three existing tests listed above were examined in a controlled, methodical, and transparent context as part of the IMSBC Code review. For evaluating iron ore fine cargoes, all three were shown to have limits (Modified Proctor/Fagerberg Method for Coal.2014 November):

- With a particle size constraint of 7mm, the flow table test was subjective (New IMSBC Code requirements aim to control liquefaction of coal cargoes, Gard. Retrieved from http://www.gard.no/web/updates/content/26655235/new-imsbc-code-requirements-aim-to-control-liquefaction-of-coal-cargoes. Access 24.01.2020).
- The input vibrational energy in the penetrated table test has no resemblance with the actual conditions inside a cargo hold.
- The most reliable method was discovered to be the Proctor Fagerberg Method (P&F).

However, there was a 5mm size restriction. Furthermore, the usage of a 350g hammer to input energy was deemed overwhelming when compared to the original hold situations (New IMSBC Code requirements aim to control liquefaction of coal cargoes.Gard.Retrieved from http://www.gard.no/web/updates/content/26655235/new-imsbc-code-requirements-aim-to-control-liquefaction-of-coal-cargoes. Access 24.01.2020).

After determining that the P&F test was the most consistent and objective of the current procedures, considerable testing was carried out to improve its suitability. The coal TML technique is a modified P&F procedure that incorporates a unique methodology for dealing with lumps larger than 50 mm in the material, and therefore a different Proctor hammer and cylinder than existing P&F procedures (such as those suited for iron ore fines). Drying heaters, unlike the other TML test methods, should have controlled movement or use an inert gas. At least in the medium future, adequate TML est facilities are unlikely to be commonly accessible in commercial coal laboratories (New IMSBC Code requirements aim to control liquefaction of coal cargoes.Gard. Retrieved from http://www.gard.no/web/updates/content/26655235/new-imsbc-code-requirements-aim-to-control-liquefaction-of-coal-cargoes. Access 24.01.2020).

This procedure demonstrates how to calculate the Transportable Moisture Limit (TML) for coal cargoes with a official top size of 50 mm in the laboratory. The approach is based on an adjustment to the Proctor/Fagerberg general bulk material test, which may be found in Appendix 2 of the IMSBC Code (New IMSBC Code requirements aim to control liquefaction of coal cargoes.Gard. Retrieved from http://www.gard.no/web/updates/content/26655235/new-imsbc-code-requirements-aim-to-control-liquefaction-of-coal-cargoes. Access 24.01.2020).

The following are significant changes to the original test in the IMSBC Code:

- Sample preparation to make it easier to examine 0 x 50 mm coal by reconstituting it to -25 mm;
- Use of a test cell with a diameter of 150 mm; and
- Formation of samples with a hammer similar to the P&F "D" energy hammer

1.3. LITERATURE REVIEW ABOUT SELF-HEATING/IGNITION ON COAL CARGO

According to industry experts SOLAS, the IMSBC code book is presently regarded as the most essential guidance for the escalation event induced by wrong operations in coal transportation. The BC Code was initially established by the IMO in 1965 and has been amended by the Subcommittee on Containers and Cargoes on a regular basis since then. The BC Code has formed part of Chapter VI of the 1974 SOLAS Agreement since 1991. The BC Code was then updated/revised over the years, and in 2008, it was already being utilized as a fundamental source as the IMSBC Code (SOLAS 1974).

On December 4, 2008, the IMSBC Code was established by resolution MSC.268(85), and it went into force on January 1, 2011, when the SOLAS Convention required it. The SOLAS Agreement, as modified, covers a wide range of maritime safety issues and, in Chapter VI, contains necessary provisions for the shipment of solid bulk shipments. These rules are expanded upon in the IMSBC Code (The IMSBC Code, 2008).

The IMSBC Code, which substitutes the BC Code, has the predominant objective of producing critical shipment and shipping of solid bulk cargoes easier and better documentation on the threats connected with specific kinds of solid bulk cargoes along with specifications on how to ship solid bulk cargoes (The IMSBC Code, 2008).

The most prevalent threats associated with the handling of solid bulk shipments are construction destruction from inadequate cargo placing, cargo chemical reactions, loss or decrease of stability during a travel, and self-heating/ignition. As a conclusion, the main aim of the IMSBC Code is to create secure shipment, stowing, and delivery of solid bulk cargoes easier by giving information on the hazards connected with various types of solid bulk cargoes as well as enlightenment on how to transfer solid bulk cargoes effectively. The Code incorporates the processes and requirements that must be met, as well as the safeguards that must be performed, when cargo operations such as loading, discharging, trimming, and carrying solid bulk commodities by sea, assuring conformity with the statutory SOLAS Convention requirements (UK P&I.2016 October. Carrying solid bulk cargoes safely. Retrieved from https://www.ukpandi.com/news-and-resources/articles/2016/carrying-solid-bulk-cargoes-safely/).

Cargoes have been carried in bulk for over a century. However, in recent years, the range of bulk goods transported by sea has increased, accounting for a significant portion of worldwide maritime trade. Every year, vast quantities of coal, concentrates, cereals, fertilizers, livestock feed, minerals, and iron ores are shipped by sea in bulk. Throughout the overwhelming amount of these cargoes run smoothly, there have been a few significant incidents that have resulted in sea pollution and the losing of not only the vessels, but also life.

One of the key problems to risk evaluation in maritime transportation is self-heating/ignition during coal cargo shipment. Self-heating/ignition, one of the most major problems in coal transportation, has been studied in greater depth, particularly on mines, and there are few examples in the literature in maritime transportation. So there was no comprehensive literature identified because to commercial pressures, P&I club expenses, one of the key obstacles in risk assessments in the maritime sector. Table 6 lists some of the most important research on self-heating/ignition in coal transportation.

Table 6: Self-heating/ignition in Coal Cargo Transportation in Maritime and Mines,

Author	Journal	Contribution & Output
GholamReza Emad Heydar Zare (2013)	The 15th Maritime Industries Conference(MIC2013) 29-31 October 2013 – Kish Island	They investigated at the stages of coal spontaneous heating, as well as the internal and environmental elements that influence coal spontaneous heating. They also discussed the primary tactics that needed to be used in order to execute Prevention, Detection, and Control. Finally, they addressed in their article how controlling the code's application is a critical aspect in preventing mishaps and fires.
H. Nalbandian (2010),	IEA CLEAN COAL CENTRE	The research covered techniques for determining the potential for coal to self-heat, as well as self-heating in stockpiles, during shipment, keeping in bunkers, and in the mills themselves. As a result of some coals' proclivity to self-heat, spontaneous combustion can occur. Spontaneous ignition is defined as an oxidation process without the forces exerted heat such as a spark or a pilot flame, and in which the

		deviation of the institutional temperature profile from flat is entirely due to the material's own heat extricate as a result of chemical response.
Fukuchi and others, (1998)	Journal of the Society of Naval Architects of Japan	They looked into how much methane gas is created when coal is carried in the holds of a ship and how much of it can cause ignition. Gas buildup in the cargo holds is dependent on coal qualities and features, according to simulations. According to the authors, hold ventilation alone may not be an effective method of limiting methane gas development and, as a result, spontaneous combustion, depending on the coal type and susceptibility to create methane.
Querol Aragón and others (2009)	13th International Multidisciplinary Scientific GeoConference SGEM 2013	They address laboratory-scale experimental methodologies for characterizing coal's proclivity to self-heat. Classical approaches, thermal analysis, activation energy, and isothermal heating are the various methodologies they deployed.
Minton Treharne & Davies Group (2008)	Minton Treharne & Davies Group (2008) *LP bulletin*	The business has recently encountered a number of issues with the loading of hot coal at offshore loading facilities. Many of the issues stemmed from extensive storage conditions on shore and/or long barge transit durations. Discharging rejected 'hot' coal from the barge to the original loading point proved difficult. The paper also emphasizes that with careful attention to detail and expert assistance, a hot cargo may be stabilized and transported to the discharge port without having to be pulled out of the ship's holds.
Nelson and Chen (2007)	The Geological Society of America	They study at the many sorts of Scottish coals. According to them, it has been argued that transporting materials at ostensibly supercritical conditions is safe if

		the projected shipping period is smaller than the assembly's time to ignite. If the projected ignite time exceeds the shipping time, which is a practical outer limit of three weeks, there is no realistic risk. According to their estimates, neither of these coals must be supplied as a 3 m cube component if the coal is supercritical. But, the projected igniting period for two of the coals is significantly longer than any transportation time, therefore they may be considered safe to transport.
M. Onifade, B. Genc (2020)	International Journal of Mining Science and Technology	Academics, research institutions, and business are all conducting study on unforced burning of coal and coalfields fires across the world. The commonly used spontaneous combustion methodologies for predicting coal's spontaneous combustion hazard were reviewed within this framework. Despite the widespread use of various methodologies, no one method has emerged as the gold standard for estimating the likelihood of spontaneous combustion. A range of experimental methodologies and mathematical models have been developed to explain the interconnection of such processes. Regrettably, there is no one experimental technique or model that fully addresses the complex physical and chemical relationships that drive coal self-heating and unforced burning. The fundamental constraint of all scientific approaches and models is that no universal model for predicting coal's spontaneous combustion hazard exists at this time.
Ran Vijay Kumar Singh	Procedia Engineering The 9th Asia-Oceania Symposium on Fire	His objective is to better understand the causes, mechanisms, and technological developments associated with spontaneous

	Science and Technology	heating, especially the development of various chemicals for mitigating fire in coal mines. He goes on to say that in order to deal with current fires and prevent future fires in Indian coal mines, the surveillance, appraisal, prevention, and control of mine fires in the Jharia coalfield should be priority.

Source: Created by author

CHAPTER TWO
RISK ANALYSIS TECHNIQUES

In recent years, risk analysis methods for maritime transportation have gotten a lot of attention, to the point that international organizations have issued guidelines on how to deploy certain risk analysis and management tools.

Because of the nature of the job, maritime transportation entails a variety of risks, which might have serious implications. As a result, every activity taken on board a ship is extremely hazardous. To increase maritime safety in maritime transportation, threat risk factors ought to be kept under control to the greatest extent possible. The probability of a hazard/failure happening and the severity of the outcomes can be used to define risk. Risk assessment is important in the maritime sector since it helps to improve safety. The IMO issued FSA (Formal Safety Assessment) recommendations in 2002 as part of the MSC (Maritime Safety Committee) and MEPC (Maritime Environment Protection Committee) circulars. By undertaking a risk analysis, the recommendations aim to increase safety at sea. Similarly, the ISM code specifies the risk evaluation that is essential in chapter 1 article 1.2.2.2 – segment objectives. Each organization, in accordance with the code, must examine all known threats to the crew, as well as the maritime ecosystem and the ship. The ISM Code specifies risk assessment procedures and processes that are used by shipping businesses (The ISM Code, 1993). DPAs (Designated Persons Ashore) and safety officers are particularly interested in the risk assessment of on-board processes and plans under the HSEQ department.

The four steps of risk assessment include threat evaluation, outcome analysis, estimation of the possibility, and risk prediction (Curcuru et al., 2013). According to Rasche (2001), no particular risk evaluation method should be utilized unless relevant hazards have been identified. The two forms of risk assessment methods are qualitative and quantitative approaches (Tixier, 2002). The quantitative measurement of occurrence and intensity is required for quantitative hazard analysis. This technique is useful when the risk is high, comprehensive research are justified, and relevant data is applicable. Qualitative risk evaluation is more acceptable once threats are minor and a limited number of items may include the whole range of outcomes and probability.

Risk analysis methodologies have been offered for the forecasting and mitigating of catastrophic events. Some risk analysis methodologies used in maritime transportation include the Hazard and Operatability Study (HAZOP), bow-tie method, functional hazard analysis, Failure Modes and Effect Analysis (FMEA), what-if analysis, outcomes analysis, and ALARP (As Low as Reasonably Practicable). Because bow-tie (the combination of FTA and ETA) is a organized and disciplined approach of anticipating risk, various risk evaluation methodologies are used to create FTA and ETA feedback (Lees, 1996).

The FTA and ETA are rational and pictorial explanations of conceivable configurations of breakdowns that are used to assess the possibility of the an unintended occurrence as well as the likely consequences of that occurrence. In sea transportation, complication rates of parts of the system are inexact, inadequate, or unclear. Fuzzy sets approaches are used to address these issues and constraints. As a result, in the FTA and ETA (bow-tie) risk evaluation methodologies, which interact with unclear, comparatively incomplete, ill-defined, and erroneous data, fuzzy sets and possibility theory are applied.

The focus is to create an integrated model that incorporates fault tree and event tree analysis, with bow-tie evaluation to check out the risk of self-heating/ignition accidents in coal cargo carriers (Villa et al.,2016). Using the experts opinions, the probability of the root causes acquired after the literature study and experts opinions were computed, and fault tree analysis was performed by establishing a fault tree. Then, to migrate to the bow-tie system, the dynamic analysis was conducted utilizing the fault tree pass approach.

2.1. THE BOW-TIE ANALYSIS

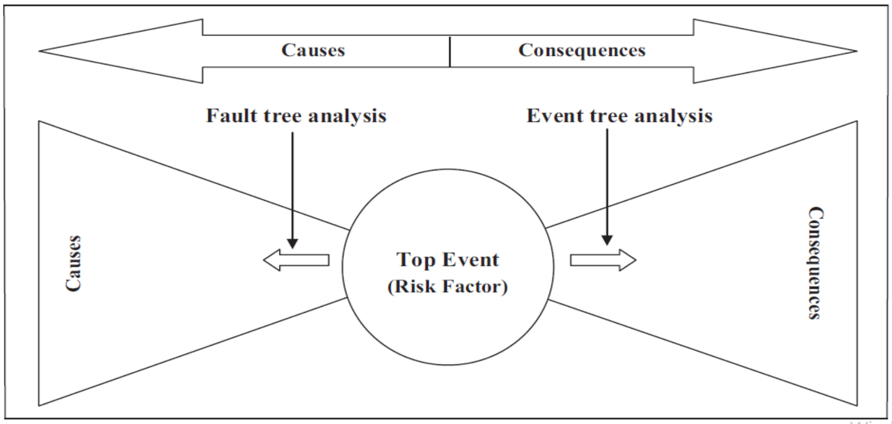
A bow-tie is a useful graphical hazard assessment approach that combines a variety of reason - result models (Visser, 1998). It concentrates on a bad action and employs a fault tree and an event tree to uncover the possible reason and outcomes of the negative occurence. The fault tree depicts the relationships between the accident and its causative factors, while the event tree depicts the accident and its possible repercussions (Mokhtari et al., 2011). There is a scarcity of statistical information in the maritime transport industry, the bow-tie technique will be used in this research in a fuzzy sets environment to deal with the ambiguity of maritime experts judgment.

Bow-tie analysis is a reliable hazard evaluation method that may be accustomed to connect a set of reasons and effects. The strategy is very easy to use for analyzing hazards. The bow-tie is a graphic representation of possible dangers. FTA and ETA are used to emphasize on the reasons and repercussions of an occurence (Mokhtari et al., 2011). The bow-tie graph is an effective instrument for reviewing previous instances and determining likely causes (Mokhtari et al., 2011). While the method is both proactive and reactive, it has been used by a number of academics to analyze risks in various sectors such as petrochemicals, aviation, and off-shore drilling (Purton et al., 20104; (Khakzad et al., 2013), (Shahriar et al.,2012).

It has shown that it is capable of giving an acceptable standard of simplifying of the causal factors in order to condense vast amounts of details into a small number of typical situations that can represent the plurality of incidents. A fault tree may be used to show the relationship between an accident and all probable causes in an accident scenario (Feasibility of storybuilder software tool for major hazards intelligence.Retrieved from: www.hse.gov.uk Access 08.10.2020).

At the same time, an event tree may be used to show the link between an accident and its several probable outcomes. As shown in Fig. 7, fault and event trees could be combined in the shape of a bow-tie graph, with the central event representing 'the discharge of a dangerous substances. Because the reasons and effects of accidents are inextricably interrelated, this approach is particularly beneficial for accident evaluation. Furthermore, it offers the user with a simplified categorization framework that allows the user to stock and summarize the often diverse information provided in incident reports using a a collection of standard criteria. A large amount of researchers have developed a threat evaluation model and software solutions using the bow-tie framework to control occupational hazards (Wang et al. 2007, The quantification of occupational risk The development of a risk assessment model and software.2008. Retrieved from https://www.rivm.nl/bibliotheek/rapporten). Thus, the bow-tie evaluation is a proactive and reactive approach that aims through the danger and its control in a systematic manner. It employs the Hazards and Effects Management Process approach (Edwards et al. 1999, Zuijderduijn et al.1999). It may be used to show how well a maritime facility's safety management system works and to do gap analysis (The Application of Bow-ties in Maritime Safety Management.2006. Retrieved from https://www.scribd.com/document/211476669/BowTie-TechPaper1). The bow-tie design may be accustomed to show how the relevant safety management system component criteria are satisfied in terms of hazard and risk element coordination and monitoring (ABS, American Bureau Shipping.2019.Thesis Bow-tie, Solution for the management of risk.2007.Retrieved from www.absconsulting.com.Accessed on: 08.01.2019, Trbojevic et al.,2000, Cockshott 2005).

Figure 7: A Bow-tie Diagram



Source: Storybuilder, White Queen BV, the Netherlands, 2008.Retrieved form http://www.storybuilder.eu/catalog.htm Accessed 07.10.2021)

2.1.1. The Bow-Tie Applications in Maritime Field

The Bow-tie method is a well-known strategy for addressing the major sources and impacts of hazard. Nevertheless, due to a shortage of information, when determining maritime risk, the bow-tie approach is rarely utilized. The method was utilized by Mokhtari et al. (2011) to conduct a causal risk assessment of maritime ports and offshore terminals In addition, bow-tie drawings have the benefit of providing a clear, linear visual depiction of the threat, which includes reason and outcome scenarios as well as linkages between different system elements. They also enable for the detection of dangers and/or repercussions that aren't being appropriately controlled, as well as the investigation of mitigation options. The capacity to integrate a range of characteristics on a single representation, among others environmental factors, human behavior, and mechanics, adds to their versatility. As a consequence, bow-tie drawings could be an extremely effective tool for depicting and maintaining a current, actual risk management process (Sotiralis et al. 2019). Table 7 lists some of the most important research on Bow-Tie analysis in maritime transportation.

Table 7: Bow-Tie Analysis in Maritime Transportation,

Author	Journal	Contribution & Output
Panagiotis Sotiralis, Konstantinos Louzis and Nikolaos P Ventikos (2019)	Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability	Using the bow-tie method, they employing the bow-tie method, they investigated into the function of vessel examinations in maritime mishaps. Their goal is to figure out how omissions during the testing process impact the growth of different sorts of accidents. They looked at over 600 accident reports over a 25-year period (from 1991 to 2015), selecting 100 incidents for research that were either directly or indirectly connected to ship investigation problems, and generating several bow-tie drawings, including a passengers ship F&E. General cargo ship structural failures, as well as passenger ship fires. The fundamental result of their study is that examination omissions are a key factor in the incidence of maritime incidents such as construction collapses and explosions, which have serious effects for the sake of people's health, the ecosystem, and property. According to the IMO SI, over 60% of constructional defects (which accounted for 50% of all accidents in the dataset) more than 30% of blasts

		resulted in overall outcomes of Level 4 seriousness. The truth of the matter that 24 % of the disaster incidents entailed luxury boats, which are a safety related vessel type due to the huge amount of people onboard, and 24 % embroiled bulk carriers, which are a over widespread vessel kind with a massive international fleet, emphasizes the seriousness of the problem.
Kambiz Mokhtari, Jun Ren, Charles Roberts, Jin Wang (2011)	Journal of Hazardous Materials	They used the bow-tie technique in conjunction with the FTA and ETA methodologies to assess is among the most significant running risks. They investigated at the running threat factors in harbours and offshore terminals using Fuzzy Set Theory, which was geared to the reasonableness of unpredictability generated by imprecision or vagueness and dealt with the ambiguity of human judgement.They discovered that BE No:2, i.e. BE2 (Pilot uninformed of ship's behavior), is the most important in the FTA, and that "Repercussions as a result of pilot-related mistakes with no consequences" has the greatest event probability point.
Emre Akyuz, Ozcan Arslan, Osman Turan (2020)	Applied Ocean Research	They selected cargo liquefaction on seagoing vessels as an example because the effects of cargo liquefaction are exceedingly harmful for the seafarer, vessel, and maritime ecosystem owing to the free surface effect, which represents a significant risk to vessels if the goods on board liquefies. According to the research results, the BE6 (Incorrect declaration of the cargo's average moisture content before loading), BE14 (Incorrect cargo identification), have a significant impact on the TE. Loss of life (3.29E- 02) has the greatest event chance in the case of cargo shifting that creates vessels to list or capsize owing to cargo liquefaction, according to the probable effects of cargo liquefaction and occurrences probability. The second most likely scenario is a vessel isolated with substantial harm (2.75E-02) owing to cargo liquefaction, as the cargo movement may force the

		vessel to list but not capsize.
Seher Suendam Arici, Emre Akyuz, Ozcan Arslan *(2020*)	Ocean Engineering	In their investigation, they nominated collision/contact throughout STS activity as the Top Event. They sought advice. Due to a shortage of data in maritime transportation, a number of maritime experts share their thoughts on every BE that might result in a collision/contact event while the STS activity. The FT graph was then constructed using twenty-six BEs and ten IEs. After assessing the event of the TE and grading the MCSs depend on their caunted objectives (V–FIM), the following significant system failures were identified: (BE17, Failure to follow manoeuvring plan -BE1 Failure to take the appropriate steps to prevent the mutual effect -BE12, Failure to measure close quarter situation appropriately). The sequences of events from the top event through the numerous alternative outcomes were then thoroughly examined. Lastly, the data demonstrate that during STS operations, the consequence event (C6 – Near Miss, 2.17E-01) has the highest relationship with collision/contact accidents.
Vladimir M. Trbojevic, Barry J. Carr (2000)	Journal of Hazardous Materials	Because no laws for maritime activities are created, and the harbours and shipping sector are only getting started with safety standarts used in other sectors, a step-by-step technique for improving port safety has been designed. A step-by-step procedure for improving the safety of maritime activities at a port has been given. Threat familiarization and qualitative risk appraisal are conducted in order to identify hazard boundaries that are or must be in ways that avoid dangers from being emitted; measures to control these dangers are therefore designed and implemented into the SMS. The hazard management method is qualitative, and the technique may be thought of as a "broad brush" risk evaluation. In addition, high-risk regions are explored in greater depth, and a threat side view for port activities is

		developed. This stage is quantitative, and one of the benefits of quantitative evaluation is that it considers both the likelihood and the effects of a wide range of potential incidents.
Panagiotis Sotiralis, Konstantinos Louzis and Nikolaos P Ventikos (2019)	J Risk and Reliability	The method employed in this article entails determining the fundamental causes and effects of accidents that may be related to inspection concerns and then merging this information in bow-tie diagrams. The generated bow-tie graphs offer valuable insight into the function of a lack of examination techniques in the growing of maritime accidents and the possible consequences. Additionally, the generated graphs may be carried out to investigate the threat of examination concerns by creating generalized accident situations with every conceivable a mixture of many components that explain all potential paths, from origins to effects. To summarize, omissions made while the examination program are a key element in the event of maritime incidents like constructual collapses and blast, which have serious effects for human health, the maritime ecosystem, and wealth (i.e. the cargo and the ship)
Abdul Aziz, Salim Ahmed, Faisal Khan, Chris Stackb, Annes Lind (2019)	Reliability Engineering and System Safety	F&E, propulsion engine failure, power failure, and maneuverability failure were all designed as potential failure situations. To portray these situations, the second phase involves developing analogous bow-tie models based on vessel construction and process data. To measure risk, they analyzed fault info for various parts gathered from the ship's service diary and incident logs, as well as the number of instances and fault %age of the safety challenges. The suggested model was confirmed using performance log from the vessel, a single-engine ice-breaker bulk carrier that mostly navigated in the Canadian subarctic area. Their approach represents a big step forward in the development of a systematic and realistic risk evaluation methodology for maritime ships. The

		framework might be a valuable tool for managing vessel safety in terms of quantitative risk, allowing for more efficient resource allocation through prioritizing and the avoidance of unwelcome occurrences.
Gizem Elidolu, Emre Akyuz, Ozcan Arslan, Yasin Arslanoglu (2022)	Engineering Failure Analysis	Their research focuses on static electricity, which is among the most dangerous hazards onboard and may result in massive blasts if a discharge comes into touch with surrounding combustible gases or air mixtures. The top event in a bow-tie structure was judged to be a static electricity-related F&E and catastrophe. The combustible environment in a tank, running faults, technological faults, and dangerous behaviors, which encompass obvious human faults, were all regarded intermediate events in the fault tree diagram. Experts identified and assessed possible event series in event tree analysis. The most likely outcome was discovered to be economic disruption, which could be kept to a minimum by taking prompt action to limit the spread of fire following an explosion.
Leszek Smolarek (2016)	Journal of KONES Powertrain and Transport	In his study, he tries to adapt the Bow-Tie concept to maritime transportation. Many technological systems and processes have discovered the advantages of employing Bow-Tie diagrams for risk assessment. Barrier diagrams, a method of visualizing the connections between the causes of a failure's event, the escalation of such events to a variety of possible findings, this technique is demonstrated by the controls that prevent the change from happening and the preparatory procedures in place to mitigate the repercussions.
Cui Wengang, Fan Houming, Yao Xi, Yang Yu, Ma Mengzhi (2016)	International Conference on System Reliability and Science Transportation Management College	Their paper employs the fuzzy bow-tie type to assess the oil spill danger of tanker mooring and stowage operations, fuzzy numbers to determine the phenomenon chance of oil spill threat factors, analytic hierarchy process to quantify the mass rates of oil spill consequences, and eventually threat rates of oil

	Dalian Maritime University	spill occurence.
Selçuk ÇEBİ, Esra İLBAHAR (2018)	Journal of ETA Maritime Science	They aimed to develop a comprehensive approach for addressing this gap in the literature and assessing occupational incidents and accidents in shipyards. As a result of this research, an unique risk assessment technique has been added to the literature. The proposed method was developed using well-known techniques as the bow tie method, fuzzy AHP, and fuzzy inference mechanism. The following are the main hazards, as established by the findings of the shipbuilding where the proposal was filed, that do not pose a disastrous risk: Working with an unsafe vehicle is hazardous to one's health and safety. There is a shortage of machine safety and equipment. Chemicals, gases, and dusts are only a few examples. Failure to adhere to OHS policies, Failure to follow the instructions of the manufacturer, Because to a lack of suitable equipment, There is a lot of joking in the workshop.
Mehmet Kaptan (2021)	Ocean Engineering	He wants to improve maritime safety in terms of operations by using quantitative risk analysis to describe anchor losses that happen throughout anchorage activities. In his work, he employed the fuzzy bow-tie technique to assess faults in anchoring operations (AHO) and their effects. According to the findings of his research, BE16 (deep water) is the most important base effect of anchor losses.
Michael Stein (2020)	Proceedings of 8th Transport Research Arena TRA 2020	After completing a mixed-method study, he presents operations without manned within the framework of well-accepted risk management frameworks - the Swiss Cheese Model and a related Bow Tie evaluation. This study combines unmanned inspections in maritime operations into the sphere of risk management, using well-accepted frameworks of SCM and BTA. A broader understanding of port safety/security, unmanned systems, general risk management, and learning from occurrences is

		offered based on extensive literature review. He does, however, say that unmanned technology can already provide a trustworthy and significance service while cutting inspection costs. He underlines the significance of future research based on standardized drone systems in order to gain a better knowledge of the technology and help in its incorporation into ordinary business operations.

Source: Created by author

2.2. FTA – FAULT TREE ANALYSIS

Fault tree analysis (FTA) was established by H.A. Watson in 1962 at Bell Laboratories on an assignment from the US Air Force Ballistics Systems Division to investigate the Minuteman I Intercontinental Ballistic Missile (ICBM) Launch Control System (Ericson 1999, Rechard 1999, Winter 1995, Benner 1975). Fault trees have subsequently achieved widespread acceptance, and reliability experts frequently employ them as a failure analysis tool (Ricky 2011). Years after the publication of the first reported application of FTA in the 1962 Minuteman I Launch Control Safety study, Boeing and AVCO extended FTA utilize to the whole Minuteman II system in 1963–1964. At a 1965 System Safety Symposium in Seattle, hosted by Boeing and the University of Washington, FTA gained a lot of attention. (Delong 1970) Around 1966, Boeing commenced using FTA for commercial airplane design (Eckberg 1964, Hixenbaugh 1968).

The graphical representation of the rational arrangements of reasons connected with an unfavorable occurrence or scenario is known as FTA. It's frequently used in risk assessments and incident investigation to address the root cause causes of bad outcomes (Kristiansen, 2004; Ugurlu et al., 2012, 2015; Kose et al., 1998; Celik et al., 2010; Tanaka et al., 1983; Ringdahl, 2005;). FTA is divided into two phases: qualitative and quantitative techniques. The qualitative technique begins with a detailed framework that includes, its elements, and subdivisions.

An FTA commences with a set accidents or breakdown (top event) and analyzes the causes of the incident in order to discover the root cause of the mishap (basic event). A fault tree can anticipate an accident or risky elements ahead of time, as well as the potential repercussions of an mishap. As a result, this is extremely useful for safety management. Because of the benefits described above, FTA has been extensively recruited in a variety of fields, including transportation, chemical industries, nuclear power, aviation, and human services.

The following step is to create a fault tree for unfavorable situations. The last events (root causes), primary occurence, middle occurences, and logic gates are the key aspects of an FT (Antao and Soares, 2006). When creating the FT, the link between the defects is detailed using rational gates and symbols. The top event in the FT is characterized as an accident. The reason of the top event represents FTA. The logical link between the causes is developed once the events have been defined and built.

In most circumstances, the first event is reliant on the contemporaneous actions of the second stage. The logical relationship between the reasons is established throughout the third step of FTA. Once a thorough fault tree (fault frequencies or probability values) is provided, the fault tree may be created and quantitative data can commence (Ugurlu et al., 2015; Tanaka et al., 1983). The qualitative stage tries to comprehend and analyze FTA by drawing on the expertise, understanding, and research of experts (Harrald et al., 1998).

Identifying and correcting whether they might do incorrect is critical to creating solutions that help effectively. In risk and durability research, FTA is the most widely employed approach for causative analysis (Rausand, 2004). FT therefore provide excellent foundation for both qualitative and quantitative evaluation analysis, according to the International Crisis Management Association (ICMA, 2014), since they have both rational (Boolean algebra) and deterministic bases.

2.2.1. Symbols and Elements of Fault Tree Diagrams

A fault tree is a form of directed acyclic network that has two types of nodes: events and gates. An event is an occurring inside the system, usually a single-component subsystem failure. Simple events (basic events) and intermediate events (events triggered by one or more other events) are two types of events (intermediate events). The top event is the event that simulates the breakdown of the system under examination and is positioned at the top of the fault tree (Robert at el., 2005).

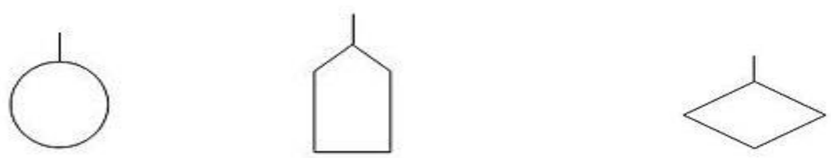
Although there are several fault tree analysis symbols in use, they are typically classified into three categories: event symbols, gate symbols, and transfer symbols. The events in the error trees are represented by event symbols, which indicate whether the mistakes are normal, independent, conditional, or contributory. Also, Door symbols are used to connect higher-level events with lower-level occurrences by rationally describing the essential functional relationship. Door symbols are used to connect higher-level events with lower-level occurrences by rationally describing the essential functional relationship (Robert at el., 2005).

Gates and events are associated with lines in FT diagrams. In a fault tree, the AND and OR doors are still the most commonly utilized gates. Take into account occurrences, input events, that can lead to another event, the output event, to demonstrate the application of these gates. If one of the occurrences triggers the output event to occur, an OR gate is used to link two input occurrences. Alternatively, if both are required for the output event to occur, an AND gate is used to combine the input and output events. The FTA symbology is shown in Figure 8 with the meanings described (Patil et.al 2013).

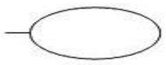
2.2.1.1. Event Symbols

Primary and intermediate events are represented by symbols. Initial events do not progress any further on the fault tree. A gate's output includes intermediate events. The emblems for the events are listed below (Patil et.al 2013):

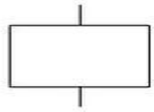
Figure 8: Event Symbols



Basic event External event Undeveloped event



Conditioning event



Intermediate event

Source: Patil et.al 2013

The following are the most common event symbols (Patil et.al 2013):

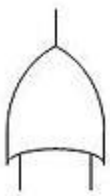
- **Basic event** - A system component or element has failed or has made an error
- **External event** - generally supposed to take place
- **Undeveloped event** - an occurrence about which there is inadequate knowledge or which is of no relevance
- **Conditioning event** - circumstances limiting or affecting logic gates

To allow extra area to enter the occurrence description, an intermediate event gate can be placed just above a major event. FTA is a bottom-to-top technique.

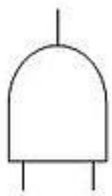
2.2.1.2. Gate Symbols

The link between input and output occurrences is represented by gate symbols. The symbols are drawn from those used in Boolean logic (Patil et.al 2013):

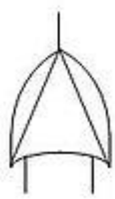
Figure 9: Gate symbols



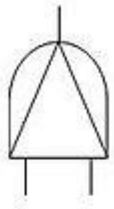
OR gate



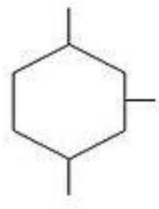
AND gate



Exclusive OR gate



Priority AND gate



Inhibit gate

Source: Patil et.al 2013

The following is how the gates work (Patil et.al 2013):

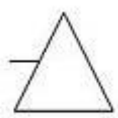
- **OR gate -** whether any input happens, the output arises.
- **AND gate -** the output is only active though all inputs are active
- **Exclusive OR gate**: if just one of the inputs happens, the output happens.
- **Priority AND gate -** the output is produced if the inputs are received in the order indicated by a qualifying event.
- **Inhibit gate** - if the input meets an allowing condition indicated by a qualifying event, the output happens.

2.2.1.3. Transfer Symbols

The inputs and outputs of associated with fault trees, such as the fault tree of a component to its network, are connected via transfer symbols. NASA compiled a detailed report on FTA based on real-world examples (Vesely et al. 2002).

Figure 10: Transfer Symbols

Transfer in



Transfer out

Source: Patil et.al 2013

Qualitative analysis assesses a fault tree's minimal cutsets, common mode fails, and the prominence of elements that might result in an undesirable situation. The quantitative study of a fault tree assists in evaluating the frequency of an occurrence depending on the breakdown probabilities of system elements and key causes (Vesely et al., 1981). NASA (National Aeronautics and Space Administration, 2002) recommended eight procedures for FTA consideration (Zhang *et al*. 2014).

- Find out what the FTA's goal is,
- Describe the FT's most important event,
- Specify the extent of the FTA;
- Specify the FTA decision;
- Outline the FTA's ground rules,
- Assemble the tree;
- A review of the FTA; and
- Analyzing and reporting the findings

In this way, the benefits of FTA may be summarized as follows (Benefit of fault tree analysis.Retrieved from https://accendoreliability.com/benefits-of-fault-tree-analysis.Access on 18.10.2021):

- It instructs the analyst to look for failures in a logical manner.
- It highlights the features of the system that are important for identifying the potential failure process.
- It presents a pictorial aid that allows individuals in charge of system administration to perceive the hazard; these people aren't usually involved in system design improvements.
- Giving a method for analyzing system dependability,
- Enabling the evaluation to focus on one specific system breakdown at a time
- Empowering the evaluation with true insights into system behavior and allowing the evaluation of human and other non-hardware breakdown reasons.

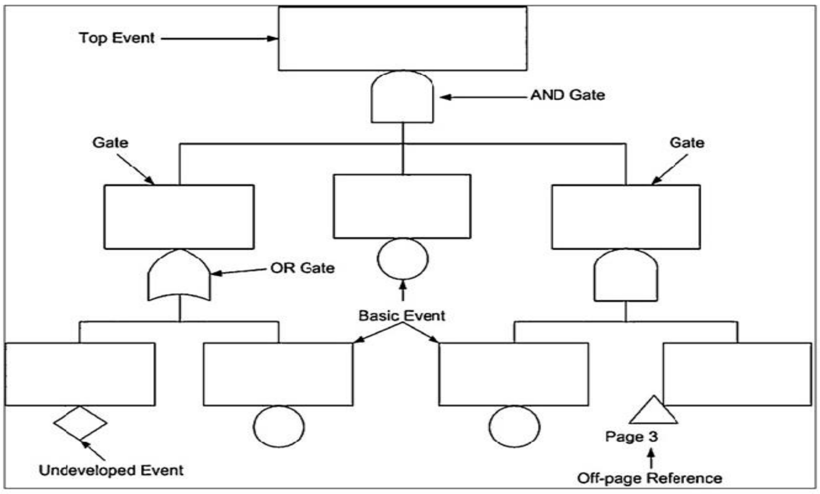
FTA has a number of drawbacks, including focusing just on one sort of problem in a system (several fault trees are required to manage numerous modes of faults), requisiting a certified analyst, and being an costly and time-consuming thread evaluation.

FTA's forecast accuracy is determined on the accuracy of component failure data. In an ideal scenario, the probability of failure of the top-event is calculated using correct values derived from the breakdown probability values of the system's main components. In reality, though, unclear system and element activity, a system's environment in which it operates, and an inadequate parameter estimation create challenges when estimating the actual failure probability of fundamental sections (Ferdous et al., 2009). Cut sets are also groupings of objects that trigger a top fault when they are together. A minimal cut set is a set of occurrences that would not result in a top fault if any of them were deleted. This information assists in detecting failures that should be avoided in order to maintain system security, as well as directing efforts to prevent a top fault event (Ortmeier and Schellhorn, 2007).

2.2.2. Presentation of a Simple Fault Tree Analysis

A typical fault tree is made up of the top event, the basic events, and the logic gates. The essential Fault Tree Analysis symbols are depicted in Figure 8. The two most common types of events are the top event and the basic event. The basic event denotes the status of the system component, whereas the top event denotes a system state that is undesirable. In FTA, logic gates clarify the connections between the basic and top events. The OR logic gate shows that the outcome is in a failed state if at least one of the sources is in a failed state. An intermediate event in a logic gate reflects a system state that is either directly or indirectly related to the top event (Dokas et al. 2009).

Figure 11: Standard Fault Tree Symbols



Source: Wang, 2004

2.2.3. Qualitative and Quantitative Evaluations of Fault Tree Analysis

FTA is a systematic method for determining the qualitative and quantitative dependability of complex systems. FTA provides failure probability estimates for top events (TE) based on generic data. In other words, it estimates the chance of TE failure using accurate figures.

So a Fault Tree is a rational equation, the chance of the top event can be figured out by assigning probabilities to each fundamental event and employing probability calculation procedures and Boolean algebra properties (Aldwinckle, 1984).

When the occurrences are independently and the probabilities are minimal, an OR gate that sums the probabilities of the occurrences can be used to predict the likelihood of the output occurrence. The chance of a gate's outputs event can be estimated as the combination of the probabilities of the input events under the same conditions. The likelihood of a gate's output occurrence can be estimated as the product of the likelihood of the occurrences under the same conditions. When the probabilities rise, however, the prediction of the top event probability becomes less reliable and more timid, even if the occurrences are independent.

The probability values of the beginning occurrences (root causes) are established in the second, quantitative step, and the minimal cut sets have been determined. The minimum cut set indicates the smallest number of reasons necessary for an accident to occur. At this point, the research concentrates on the accident or fault combinations that have the highest incidence of occurrence. The aim of this qualitative fault tree research is to examine the logic relationships between each basic event or their variations with the top event, and then to determine the fault tree's minimal path sets, minimal cut sets, and structural important coefficient for each basic event. As a result, preventative and control actions are conduct with more urgency.

In respect of analytical techniques, we differentiate between qualitative FTA, which examines the structure of the FT, and quantitative FTA, which assesses values such as the chance of faults of the FT. In the qualitative area, cut sets are an important indication that shows which combinations of system problems contribute to system breakdowns. A system vulnerability may be indicated if a chopped set has too few pieces. Path sets and common reason failures are two more qualitative measures we consider.

2.2.4. Calculation of MCSs and the Likelihood of TE Failure

A minimal cut set (MCS) is a collection of simple things that form the foundation of the FT. An MCS can be used to specified the structural vulnerability of a system. It implies that the system gets riskier as the number of MCSs increases. BEs are undesirable events in the system, and the TE will happen if all BEs under the MCS execute. Detecting MCSs is also crucial from a risk standpoint. The relevance of each MCS to the probability of the TE is represented by the MCS ranking. The calculation and evaluation of MCSs are critical for gaining an understanding of operational dangers. The sensitivity analysis, or defining the MCSs contribution to TE probability, is carried out via the optimization phase. The Vesely-Fussell Importance Measure Method can be used to rank these sets (V-FIM) (Wu et al.,2013, Arici et al., 2020). The Vesely-Fussell Importance Measurement (V-FIM) approach may be used to rank the MCSs. To put it another way, the vulnerability of TE's probability is estimated by evaluating MCSs based on their TE probability commitment and relevance level (Ünver et al., 2019). In this work, V-FIM is used to investigate sensitivity.

The important degree estimations in this thesis were also performed using the FV-I approach. **Eq. (1)** applies to this strategy.

$$I_I^{FV}(t) = \frac{Q\dot{I}\,(t)}{QS(t)} \quad \textbf{(1)}$$

Where I_I^{FV} (t) represents the magnitude of MCS_i, $Q_i(t)$ represents the occurrence probability of MCS I and $Q_s(t)$ represents the likelihood of occurrence of TE owing to MCS**.**

Because it is among the most important elements of the FTA, the FT graph incorporates several MCS (minimum cut set). The MCS is used to measure the system's structural vulnerability. The MCS can be visualized using the equation below **Eq. (2)**.

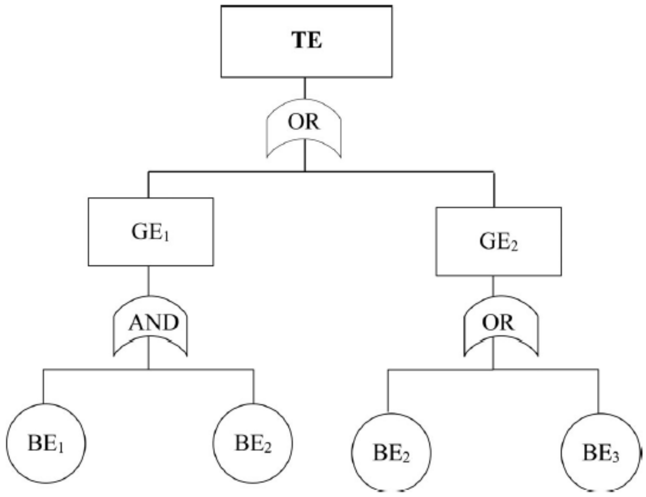
$$T = MCS_1 + MCS_2 + \ldots.. + MCS_N = \bigcup_{i=1}^{nc} MCS \quad \textbf{(2)}$$

In light of the foregoing, the event frequency of TE can be computed using **Eq. (3).**

$$\begin{aligned} P(T) &= P(MCS_1 \cup MCS_2 \cup \ldots.\cup MCS_N) \\ &= P(MCS_1) + P(MCS_2) + \ldots.(PMCS_N)\text{-}(P(MCS_1 \cap MCS_2) \\ &+ (P(MCS_1 \cap MCS_3) + \ldots(P(MCS_i \cap MCS_J)\ldots)\ldots \\ &+ (-1)^{N-1P(MCS_1 \cap MCS_2 \cap \cdots \cap MCS_N)} \end{aligned} \quad \textbf{(3)}$$

At the moment that a fault tree comprises fundamental events that occur multiple times, the most common methods for calculating the TE probability use the minimal cut sets (MCs). A MC is made up of a series of basic events. The TE is certain to arise if all of these events occur; however, if any of the essential events do not arise, the TE will not occur. Assume that the MCs in a fault tree are represented as MC I n.

Figure 12: Example of a Fault Tree Structure



Source: Abad et al. (2019)

FTA can be employed both qualitatively and quantitatively. Qualitative analysis is applying Boolean algebra to obtain minimal cut sets (MCSs). An MCS is the smallest combination of BEs that result in a TE (NASA, 2002). In other words, an MCS represents the top event in terms of the basic events. To illustrate qualitative fault tree analysis, consider the fault tree structure shown in Figure 12. Boolean algebra rules are used to obtain the MCSs of the tree are as shown in **Eq. (4)-(7).**

$$TE = GE_1 \cup GE_2 \quad \textbf{(4)}$$

$$GE_1 = BE_1 \cap BE_2 \quad \textbf{(5)}$$

$$GE_2 = BE_2 \cup BE_3 \quad \textbf{(5)}$$

$$TE = (BE_1 \cap BE_2) \cup BE_2 \cup BE_3 \quad \textbf{(6)}$$

$$\mathrm{MCS}_1 = BE_1 \cap BE_2,\ MCS_2 = BE_2,\ MCS_3 = BE_3 \quad \textbf{(7)}$$

Equation (7) shows that the fault tree has three minimal cut sets: BE1 \ BE2, BE2, and BE3: The occurrence of BE1 and BE2 at the same time will lead to the occurrence of the TE, while BE2 and BE3 are adequate by themselves to cause the TE to arise. After determining the MCSs, quantitative analysis can be performed to assess the probability of occurrence of the TE. To quantify the fault tree, the probability of occurrence of the BEs must be defined. Thereafter, using Boolean algebra, the probabilities of the MCSs and the TE can be obtained.

2.2.5. Fault Tree Analysis in Maritime Transportation: A Review of the Literature

There are many different sorts of maritime catastrophes, but collisions, capsizes, foundering, breaking apart, grounding, stranding, and fire or explosion are all common (Abbassi et al., 2017; Akten, 2006). “"Human error, mechanical and structural failure, and environmental elements are all major sources of risks, accounting for varied proportions of the total (Karahalios, 2015; U_gurlu et al., 2015). The Major Hazard Incident Data Service (MHIDAS, 2002) database analyzed mechanical failure, impact failure, human error, instrumental failure, services failure, violent response, external events, and upset processing characteristics as likely causes of generalized tragedies.

Furthermore, any accidents or events involving coal cargo that originate from ships may result in substantial expenditures for the shipping company and P&I clubs of the vessels, as well as total loss. Despite the fact that likely accidents and/or occurrences have major consequences, the essential safeguards are not taken academically.

Unfortunately, there are few and important procedures in place to prevent cargo, ship, and environmental accidents and/or incidents in the sector, which are insufficient and result from systematic cause and effect analysis.

In addition, Bulk cargoes are shipped in quite large and unpackaged amounts. Maritime dangers and disasters may increase as the number of ships grows. Akten (2006) despite increased safety regulations and greater technology, noted that shipping is and always will be plenty with hazards. Celik et al. (2010) different viewpoints on the topic of reducing shipping accidents include system complexity and automation, human mistakes, human-centered system design, and potential design-based failures. As a result, worldwide maritime administration has made enormous efforts to improve shipping security (Hetherington et al., 2006). Notwithstanding this, current statistics studies show that there are still a lot of disasters out there (Baltic Sea Maritime Incidence Response Group (MIRG), 2017; Darbra and Casal, 2004; Eleftheria et al., 2016; Roberts et al., 2012).

Coal cargoes transported by bulk carriers, in particular, are combustible, explosive, poisonous, corrosive, environmental pollutants, and hazardous to human health. Cargo handling, berthing-unberthing, hold cleaning, and STS cargo transferring are all high-risk tasks for coal carriers. Due to mining and manufacturing, transportation, friction, weather conditions, and smoulding, these processes cause self-heating/ignition, resulting in methane emissions. Despite the fact that risk assessment is critical for coal cargo carriers operations, there has been little study on the subject to far. Table 8 lists some of the most important research on FTA in maritime transportation.

Table 8: FTA in Maritime Transportation,

Author	Journal	Contribution & Output
Ugurlu Ozkan, Basar Ersan, Kose Ercan (2012)	5th International Conference on Maritime Transport	They examined at F&E statistics from the GISIS (Global Integrated Shipping Information System) system for oil tankers. Risk evaluations were conducted in their study utilizing the FTA (Fault Tree Analysis) tool for occurrences such as F&E in oil tankers, and they built an FTA. Human mistake is the primary cause of F&E incidents. As a result of the FTA investigation, the majority of the incidents were human caused, which included the use of inappropriate equipment, a lack of hot work procedures, and the accumulation of explosive gases. The main causes of human mistake are a lack of training and experience.
Özkan Uğurlu, Ercan Köse, Umut	Maritime Policy &	They looked at maritime incidents and accidents for collisions and groundings in oil tankers using the

Yıldırım & Ercan Yüksekyıldız (2015)	Management	FTA approach between 1998 and 2010. They obtained GISIS-registered collision and grounding statistics (Global Integrated Shipping Information System). They carried out FTA, which is divided into two stages: qualitative and quantitative methods. They developed FTA for grounding and collision, as well as analyzing 26 maritime incidents to develop FT for grounding.
Özkan Uğurlu (2016)	International Journal of Industrial Ergonomics	Using Fault Tree Analysis, he investigated F&E incidents that happened in tankers carrying dangerous liquid cargoes between 1999 and 2013, discovering 13 root causes and five causative variables (FTA). He claimed that the most fundamental root causes of F&E fatalities in tankers hauling hazardous liquid cargoes includes hot work, electric arcs, static electricity, and combustible gas buildup, and that VWP and LRA are the major causative elements of F&E fatalities. In his research, he discovered a link between education, experience, and a lack of safety awareness when evaluating causal elements. As a result, a fundamental issue in enhancing safety in the maritime sector is a lack of certified seafarers. The quality of training offered to seafarers must be enhanced in order to avoid F&E mishaps.
D. Wang et al. (2013)	Journal of Loss Prevention in the Process Industries	He conducted FTA to perform a research on Crude oil tank F&E (COTFE), and the COTFE fault tree was created. According to their research, there are 43 BEs and 392 MCSs in the COTFE tree that may be contributing to the incidents. The results in their study indicate that: 1) the fuzzy approach's COTFE occurrence probability value is about 12% lower than the conventional approach's value; 2) the fuzzy approach's COTFE occurrence probability value is about 12% lower than the traditional approach's value; and 3) the fuzzy approach's COTFE occurrence probability value is about 12% lower than the 2. In contrast to standard FTA, the fuzzy

		FTA gives precise details about the involvement of the linguistic rating scale (H and VH) to the COTFE probability. 3) There is a small change in the most essential BEs, but a large difference in their ranking. Breathing valve maintained open since broke down, fire work, and gauge hatch regularly open are also among the top three BEs, according to their research.
Emre Akyuz, Ozcan Arslan, Osman Turan (2020)	Applied Ocean Research	They performed the bow-tie approach in a fuzzy logic framework to complete a full risk assessment. The fuzzy logic technique copes with the ambiguity and inaccuracy of maritime experts judgements, whereas the bow-tie method analyzes probable causes and repercussions of errors. The issue of cargo liquefaction on vessel was chosen as a case study because the repercussions of cargo liquefaction are exceedingly severe for the seafarers, vessel, and maritime environment. They constructed an FTA diagram, and the likelihood of the top event (cargo liquefaction) occurring was predicted to be 1.63E-01 (0.163). BE6 (Incorrect declaration of the average moisture content of the cargo before loading), BE14 (Incorrect cargo identification), are all strongly influenced by the qualitative evaluation of the fault tree.
Cheliyan and Bhattacharyya (2018)	Journal of Ocean Engineering and Science	They carried out FTA to do a probabilistic faults evaluation of oil and gas leaks in a subsea production system. Due to the uncertainty of the fault data, the researchers took a fuzzy approach to it, resulting in the fuzzy fault tree analysis (FFTA), a method that uses maritime expert elaboration and fuzzy set theories to determine the failure probabilities of intermediate and top events by identifying the fault tree's minimal cut sets. In a fault tree analysis of a subsea production system, the fuzzy set theory was carried out to quantify the 'probability of the leakage,' which is the top event (X 41-Leakage in offshore pipeline system), and

		this probability was computed as 0.017825 and 0.01777 (C 1 to C 19), indicating that the higher order terms have marginal impact.
H. Kim et al. (2005)	Korean J. Chem. Eng	Internally caused significant mishaps were characterized in their study as six major occurrences that resulted in a substantial discharge of natural gas, and the failure rates of these events were computed using other resources of process equipment reliability data due to a shortage of membrane type-specific data. They calculated the gross failure rates for six top events depending on the risk evaluation of 100,000m3 membrane-type LNG holding tanks in Korea, which might result in a large amount of LNG discharge as a result of the FTA. According to the current investigation, the membranetype holding tank has an acceptable degree of failure rate with a gross mechanical failure value of 8.81068.8×10−6.
Sunaryo and Mochamad (2017)	Procedia Engineering	Primary data was gathered through on-the-spot occurrences of container handling operations at the berths of three container terminals at Tanjung Priok Port in Jakarta, Indonesia's largest and busiest port, as well as interviews with port operators and supervisors who worked at the terminal quays. Secondary data was gathered from the port authority, including accident data, container throughput, and the types of loading and unloading operations. Worker struck by collapsing hatch cover or container; worker slips, trips, or falls; and truck slammed by berth crane are threats with a very high degree of risk. Uncertain SOPs, corroded components, harsh weather, a cluttered operating room, inappropriate employee recruiting and training, and unclear legislation are the most typical primary causes.
A. Blokus, B. Kwiatuszewska-Sarnecka	Proceedings of the 2018 IEEE	They conducted FTA to perform a study on the reliability of the Crude Oil Transfer System in the Oil Port Terminal. In their work, they detail the

(2018)		crude oil transfer procedure in the oil port terminal, as well as its analytical characterization. Additionally, the possible reasons and circumstances of oil spill accidents and occurrences are examined, with an emphasis on oil overflow and leakage. The relevance of the human component for the safety of crude oil transport in oil port terminals is demonstrated through Fault Tree Analysis. They emphasized that when trying to examining the safety of crude oil transfer in a port terminal, A technique that emphasizes on the examination of the safety and dependability of technical software, along with the safety of oil transfer in accordance with human aspect, i.e. the system's correct administration and operating, can be introduced.
Ahmed Ali Baig, Risza Ruzli, and Azizul B. Buang (2013)	International Journal of Chemical Engineering and Applications	Their study examines the literature generated in the previous decade on current changes in the zone of risk evaluation utilizing Fault Tree Analysis (FTA). They also discussed the basic approach for FTA, its use in many sectors, and the changes that have been implemented throughout time to address the method's shortcomings. As a consequence of their study, a quick overview of the uses and improvements made to FTA to create it more reactive and effective is provided. The downsides of FTA were examined, as well as the improvements that were taken to address these issues.
Pedro Antao, C. Guedes Soares (2006)	International Journal of Automation and Computing	They employed FTA to carried out a study on Fault-tree Models of Ro-Pax Vessel Accident Scenarios. The goal of their project is to investigate risks associated with Ro-Pax vessel accidents. The terminal casualty occurrences picked are based on the vessel's accident and incident records. Human factors, navigation aids, manoeuvrability, and system failures are the most important influences on collisions, while there are additional occurrences

		or weights that might influence the result of a collision. The basic events connected to human variables are the main elements towards the unintentional occurrence, as shown by the fault tree and following sensitivity analysis. This contribution is greater for groundings and collisions, where an increase in the starting likelihood results in a nearly 90 % shift in the chance of these terminal events occurring. This impact is less pronounced in the case of fire and capsize.

Source: Created by author

2.3. ETA - EVENT TREE ANALYSIS

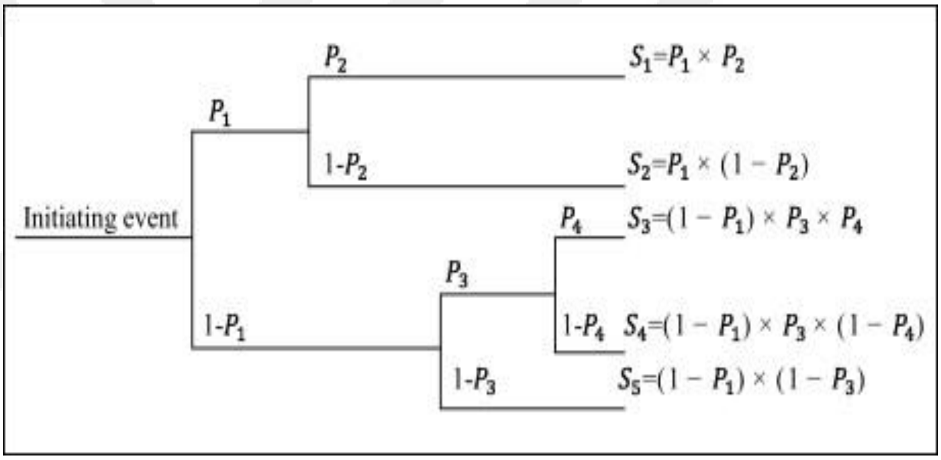
Event Tree Analysis is a widely employed approach for determining the repercussions that may arise as a result of the existence of a potentially dangerous events (Andrews et al., 2000). It was initially used in nuclear risk evaluation, but it is now used in a variety of sectors, including chemical processing, offshore oil and gas production, and maritime transportation. The frequency of every one of the consequences may be anticipated by quantifying the event tree graph. The initiator is the potentially dangerous trigger event. The inductive, or forward logic, approach of event trees considers all potential answers to the beginning event as it progresses across the page from left to right. Furthermore, by offering a risk assessor with the chance of happening, the use of ETA as a tool in risk evaluation can assist to avert unfavorable consequences (Kabir et al.,2018).

The term "Event Tree" was created in the time of the WASH-1400 nuclear power plant safety research (approximately 1974), when the WASH-1400 team required an alternative to FTA since the fault trees were too huge. The UKAEA first used ETA in its design offices in 1968, but not under the term event tree. The goal was to employ whole system risk analysis to improve the design of a 500MW Steam Generating Heavy Water Reactor (Clemens et al., 1998). ETA was able to reduce the information into a more understandable format in this investigation. Event tree analysis is a hazard approach of deriving options and consequences in a chronological order that evolved from decision tree analysis. This method employs a "event tree" graph to demonstrate the logical connection between predicted accidents and their causes (Wang et al.,2000). Through the qualitative and quantitative evaluation of the event tree, users can uncover the primary reasons of accidents and propose trustworthy remedies so as to achieve the aim of forecasting and enhancing safety (Ericson, 2015). In an event tree, qualitative evaluation point outs the various outcomes of an commencing event, and quantitative evaluation calculates the tree's final event probability or frequency (likelihood). To predict the final event likelihood or frequency, quantitative evaluation of an event tree customarily uses crisp probabilities of occurrences **(**Kenarangui, 1991; Lees, 2005; Ferdous, 2006). In actuality, obtaining accurate estimation of event probability is hard and costly because, in the vast majority of instances, these predictions are the consequence of an expert's insufficient knowledge, incomplete information, lack of data reliability, or incorrect interpretation of a failure mechanism. These unavoidable concerns introduce uncertainty into the ETA and reduce the credibility of the evaluation process as a decision-making tool.

The purpose of event tree evaluation is to figure out how likely something is to happen undesirable effects after a given starting event. Specific knowledge about a network must be utilized to interpret intermediate events, accident scenarios, and initiating events in order to create an event graph. The starting event is at the top of the event tree, and the consequences follow in a binary (success/failure) order. Each occurrence generates a path that leads to a number of successes or failures, and It is possible to compute the total likelihood of that route happening. ETA can be used to predict the likelihood of intermediate events failing, 1 = probability of success (ps) + probability of failure (pf) can be used to compute the probability of success (Ericson, 2015).

To determine the result event likelihood or recurrence, quantitative evaluation of an event tree traditionally employs clear probabilities of occurences. The branch probabilities have been considered as precise values in traditional Event Tree Analysis, as explained by (ABS, Risk Assessment Applications for Maritime and Offshore Oil and Gas Industries 2000, Ferdous et al.,2009). This allows for a rapid examination, each branching or route of the event tree is filled with precise probabilities. In Figure 13, which is an example of a typical event tree, the resultant event rates, which are plain figures, are indicated. Pn represents the Success/True/Yes likelihood of the *nth* occurrence inside the same column, whereas (1 Pn) represents the Failure/False/No probability of the same occurrence. Within the shown event tree, S_n is also the computed result event occurrence for the *n*th outcome event. This form of assessment, as per ETA (ABS, RASs for Maritime and Offshore Oil and Gas Industries 2000), can preserve (1) qualitative descriptions of potential pitfalls (configurations of events creating various challenges from causative factors) and (2) quantitative forecasts of occurrence frequencies or probabilities, which can help demonstrate the relative importance of various failure sequences.

Figure 13: Sample of a Conventional Event Tree



Source: Ferdous et al.,2009

From the initial event, the event tree diagram depicts all potential paths. The begining event appears as a diagonal line on the left side that branching vertically. The vertical branch represents the accomplishment or faults of the first event. To embody the accomplishment or faults of the first event, a linear line is drawn on the top and bottom of the vertical branch, and an explanation (usually success or failure) is documented with a tag that reflects the path, such as 1s where s signifies a success and 1 is the event number, or 1f where 1 is the event number and f signifies an inability (Figure 13). This method is carried out again and again until the desirable result is obtained. The result probability equation is created after the event tree diagram has come to the end phase for all routes (Clemens et al.,1998, Ericson, 2015).

How to conduct an Event Tree Analysis (Ericson,2015):

1. Create a system definition: Identify who needs to be engaged and where the lines should be drawn.
2. Determine the possibility of an accident: Conduct a system evaluation to identify potential dangers or accident circumstances in the system's construction.
3. Determine the events that set off the chain of events: To specify beginning events, do a risk evaluation.
4. Determine what happens in the middle: Determine the responses that apply to the given circumstance.
5. Create an event tree graphs
6. Calculate the chances of an event failing: Whereas if failure probability cannot be determined, fault tree modeling can be used to estimate it.
7. Determine the likelihood of a specific result: Determine the risk by calculating the total probability of the event routes.
8. Assess the possibility of outcome: Determine the appropriateness of each path by assessing its risk.
9. Suggest preventative action: If a path's consequence risk is unacceptable, make design adjustments to reduce the risk.
10. Demonstrate the ETA: On the event tree charts, define the whole procedure and adjust as needed for incoming knowledge.

2.4. FUZZY LOGIC AND FUZZY SET

We are not always aware of and understand our thoughts precisely. Many etiquette rules are hazy and unclear. The modified set theory was created in order to more exactly model these circumstances. The term "fuzzy set theory" was used by L.A. Zadeh to describe this notion (Borovicka, 2014).

Fuzzy set theory was designed to engage with inconsistencies or mistakes in human decision-making because regular probability techniques alone are insufficient to describe difficulties (Zadeh, 1965). Subjective judgements and language expressions can be converted into quantifiable and statistical data using this approach (Khan and Sadiq, 2005). Experts judgment can be expressed in normal language, such as minimal, moderate, or high, and it can be used with any other decision-making procedures (Türkoglu and Mentes, 2014; Castigla and Giardina, 2013). A membership function A(x) in fuzzy set theory relates each component x in X with a real integer in the interval (0, 1) for a fuzzy subset A in X (Zadeh, 1965). The function A(x) indicates if x is a member of the fuzzy set A (Castigla and Giardina, 2013). Various shapes can be used to represent membership features parameters, but triangle and trapezoidal membership features are the most common (Barua et al., 2014; Wang et al., 2004).

2.4.1. Fuzzy Set

Also, Zadeh (1965) offered a set of fuzzy numbers to deal with ambiguity or inaccuracies in human decision-making. Fuzzy sets are thought to represent an expansion and reduction of traditional number sets. The traditional set provides accurate membership because the fuzzy set contains items that address inaccurate membership properties (Wu et al.,2018, Wu et al 2019). In practice, fuzzy sets theory will be used whenever a human's judgement is imprecise in making a choice. The linguistic factors are used to transform a decision-opinion maker's into reasonable understanding (Akyuz et al.,2015,B.Sahin 2017). The principle may be used to any approach that allows experts to express their judgement in normal language, such as lower, moderate, high, extremely high, and so on (F. Castiglia et al.,2013).

The following is a diagram showing the conceptual description of fuzzy sets. A membership function A(x) is coupled with each element x in X with a real number in the interval (0, 1) to characterize a fuzzy subset A in X. The membership of x in the fuzzy set A is illustrated by the equation A(x). Fuzzy sets have membership functions that are either triangular or trapezoidal. The membership function A(x) is represented as the following formulae, and the triangular fuzzy set numbers are specified as triplets x1, x2, x3 (E.Akyuz, 2016).

$$(x) = \begin{cases} \dfrac{x-a}{b-a}, a \le x \le b \\ 1, \quad b \le x \le c \\ \dfrac{d-x}{d-c}, c \le x \le d \\ 0, otherwise \end{cases}, where a < b < c < d \tag{8}$$

$x1$, $x2$, $x3$, $x4$ may be claimed that the trapezoidal fuzzy sets numbers are demonstrated. As a result, the continuity equation may be used to characterize the membership function A(x).

2.4.2. Calculating Possibility from Experts Judgement

Operational data on the composition of seafaring works is difficult to come by, and much of it is undisclosed. The maritime experts' judgements are utilized to handle data issues (Lavasani et al.,2015). Because Basic Events (BEs) play a key role in initiating chains of events, experts provide their opinions on each BE. Judgement of the maritime experts, on the other hand, may differ due to differences in expertise, schooling, administrative and intellectual expertise, and so on. This is referred to as a diversified group of experts. The degree of significance at this level influences the experts's judgement. Experts' weighting scores are essential to improve evaluation accuracy and prevent research from being questioned. In light of the foregoing, experts judgement is utilized to determine the likelihood of each basic occurrence. Experts language phrases provide a convenient approach to transform possibilities to probabilities (Hsu et al.,1994).

Maritime experts' language statement is translated into a set of ambiguous numbers (Kuzu et al.,2019, Sahin,2017). Figure 12 depicts fuzzy grading and membership functions in this context. As a result, Table 16 depicts linguistic concepts as well as trapezoidal fuzzy values (Chen et al.,1992). For this study, the conversion scale number seven was selected as the best match. Maritime experts' viewpoints are not always aligned, and their perspectives on a particular quality may differ. As a result, incorporating the dominating element is crucial. Table 10 provides the weights of maritime experts who responded to the survey dependent on their profiles. Table 14 contains language judgements based on the experiences of maritime experts.

Expert assessments are frequently employed to ensure practical answers to threat evaluation in the maritime transport sector leading to a shortage of operational data (Lavasani et al., 2015). Experts weights in on the BEs that make up the fault tree's sub-events and the starting point for the error chain. The relative significance of the experts' comments on each quality is prone to change since they have various qualifications, schooling, and understanding. Yuhua and Datao (2005) designed an expert weighting rating to illustrate the relative quality of experts, hence improving the assessment's overall accuracy. Expert judgements given in language terms can be utilized to calculate the chance of each BE in light of the aforementioned. For non-homogeneous teams of experts, Hsu and Chen (1994) presented an expert elicitation methodology.

As a result, this study integrated the perspectives of a group of experts, including academicians, DPA, operation managers, deck superintendents, masters, and chief officers, who have necessary experience and expertise with Coal Cargo operations such as loading, unloading, and carriage, among others, so as to minimize potential risk and promote maritime safety throughout the previously stated operations.

Hsu and Chen (1996) suggested a method for eliciting information from a non-homogeneous group of experts, which they called "group experts elicitation." SAM (Similarity Aggregation Method) is a mechanism for transforming fuzzy numeric equivalents of verbal ideas. The following are the basic phases of the SAM approach.

2.4.3. Collecting Obtained Possibilities:

The possibilities are gathered in the first phase of SAM. Assume that each experts, (k = 1, 2,..., M), explains his/her judgement on a given feature in comparison to a specific environment using a preset set of linguistic variables. The experts' language phrases are then transfigured to fuzzy numbers. The following are the details of the equations (Lavasani et al.,2015, Senol et al.,2015):

2.4.3.1. Calculating the Degree of Agreement:

In the sub-step, *Eu* and *Ev* identifies each maritime experts pair and *Su v* (*R˜u*, *R˜u*,) serves views of maritime experts where *Su v* (*R˜u*, *R˜v*) (0, 1). In this context, *A*¯ = (*a*1, *a*2, *a*3, *a*4) and *B*¯ = (*b*1, *b*2, *b*3, *b*4) are two trapezoidal fuzzy numbers in general. Using the similarity function of S, **Eq. (9)** is used to determine the degree of similarity between two fuzzy integers.

$$S(\check{A}, \check{B}) = 1 - 1 / 4 \sum_{i=1}^{4} \mathrm{I}\ a_i - b_i\ \mathrm{I} \qquad \textbf{(9)}$$

where *S* (*A*˜ , *B*˜) (0, 1).

The higher the resemblance between the two fuzzy values of A and B, the larger the value of S (A, B).

2.4.3.2. Calculate Average Agreement (AA) Degree AAEu of the Experts:

In the second sub-step, an **Eq. (10)** is used to calculate the maritime experts' average agreement degree.

$$AA(E_u) = \frac{1}{M-1} \sum_{u \neq v}^{M} S\left(\widetilde{Ru}, \widetilde{Rv}\right) \qquad \textbf{(10)}$$

2.4.3.3. Assess the Degree of Relative Agreement (RA), RA(Eu) of the Experts:

Eq. (11) is used to evaluate the degree of relative agreement between maritime experts.

$$RA(E_u) = \frac{AA(Eu)}{\sum_{u=1}^{M} AA(Eu)} \tag{11}$$

2.4.3.4. Predict Consensus Coefficient (CC) Degree, CC (Eu) of the Experts:

The maritime experts' consensus coefficient level is predicted using the formulae below. **Eq.(12)** E_u: (u = 1, 2,…,M)

$$CC(E_u) = \beta . w(Eu) + (1- \beta). RA(E_u) \tag{12}$$

where $\beta (0 \leq \beta \leq 1)$is a relaxation factor.

2.4.3.5. The Comprehensive Result of The Maritime Experts' Judgements:

The SAM's final sub-step is to combine the results of the maritime experts' judgements (AG). The preceding **Eq. (13)** is used to calculate the result.

$$\widetilde{R_{AG}} = \sum_{u=1}^{M} CC(E_u) X \widetilde{R_u} \tag{13}$$

2.4.4. Defuzzifying of Aggregated Experts Judgement (Fuzzy Possibility)

The collected maritime experts judgement must then be defuzzified in the second phase. Under fuzzy sets, triangular or trapezoidal fuzzy numbers are turned to assigning numerical values using **Eq (14)**. The centre of area (COA) approach is employed for defuzzification in this case (Lavasani et al.,2015).

$$X^* = \frac{\int u_i(x) x dx}{\int u_i(x)} \tag{14}$$

The fuzzy possibility is represented by X*, the integrated membership function is defined by ui(X), and the result variable is represented by X.

2.4.5. The Transition from Possibilities to Probabilities:

Maritime experts judgements are used to translate possibilities into probabilities. Onisawa (1988) proposed a formula for transfiguring fuzzy failure possibilities to fuzzy failure probability. The fuzzy possibility (FPT) rate is derived from the levels of fuzzy possibility (FPs). The equations below are utilized. The error value of a typical human function is considered to be and the error rate's lower limit is 5 in the equation. FPS and K, which is specified as a fixed amount, may be used to compute the fuzzy failure rate (FFR). (Swain et al.,1983) The safety criteria depend on the lowest limit of the error frequency and fault rates of a routine is represented by K, which is a constant. **Eq.(15)-(16)** may be used to compute it.

$$Pr = \begin{cases} \frac{1}{10^k}, FP \neq \ 0 \\ 0, \ FP_s \ = 0 \end{cases} \tag{15}$$

$$K = \left[\left(\frac{1-FPs}{FPs}\right)\right]^{1/3} \times 2.301 \tag{16}$$

Leading to a shortage of probability data for BEs, maritime experts judgment is employed to evaluate the likelihood of a BE. Expert language phrases provide a convenient approach to transform possibilities to probabilities. Table 9 (Weighting scores of non-homogenous experts) illustrates weighting scores for maritime expert in this situation because they are a diverse group (non- homogenous) (Senol et al.,2015). Maritime experts' language statement is translated into a set of ambiguous numbers (Kuzu et al., 2019, Sahin et al.,2017). Figure 10 depicts fuzzy evaluation and membership functions in this context. Table 13 (Linguistic words and trapezoidal fuzzy numbers of possibilities) shows linguistic variables and trapezoidal fuzzy quantities of possibilities (Chen et al., 1992). The exchange rate number seven was determined as the best fit for this research.

CHAPTER THREE

RISK ASSESSMENT OF COAL CARGO OPERATIONS IN MARITIME TRANSPORTATION: PROBABILISTIC APPROACH

In this section, the risk assessment of coal operations carried out during transportation or port conditions, as well as the probabilistic relationship analyses between the variables that cause self-heating/ignition accidents, are investigated using fuzzy bow-tie analysis. The research's subject, goal, and model, the qualitative and quantitative methodologies employed in the study, the sample of study, the data collecting tool, the data gathering procedure, the analyses, and the results were all analyzed in this context.

3.1. SUBJECT OF RESEARCH

Coal was the fuel that ignited Europe's and ultimately America's Industrial Revolutions. By the late 1890s, the U.S. had overtaken over as the largest coal producer. After becoming the world leader since the commencement of the formal industry in the 1500s, Britain is presently placed second. Germany came in third, highlighting its expanding manufacturing would in compared to continental adversary France. Coal's supremacy in energy consumption peaked in the early twentieth century, thereafter which oil and natural gas gained over. By the late twentieth century, China's fast economic growth, rising demand for power, and enormous coal reserves had pushed it to the top of the world's coal output.

In addition, in terms of the threat categorization under the updated MARPOL Convention and the IMSBC Code, Caol Cargoes are classified as Group A and Group B by shippers. As a result, coal shipments may be subject to the same TML and moisture certification requirements as other Group A commodities including concentrates, nickel ore, and iron ore fines. Unless otherwise certified, Group A and B should be applied to all coal. Unless they match the new standards outlined in the IMSBC Code, all coal shipments must be deemed liable to liquefy and pose a chemical danger.

In addition to the information provided in the chapter 2, the coal load has several threats that may arise owing to its structural features; it is possible to experience loss of life, pollution, and total loss in the event of probable self-heating/ignition. Factors such as fire and the fact that the facilities that can be used for intervention are not readily available in the immediate vicinity, according to port operations, have caused the maritime sector to view these operations as high risk and the need to take extreme caution by presenting risk management.

Furthermore, coal cargoes are certainly one of the most dangerous commodities transported by sea, requiring exceptional competence in terms of handling, stowage, and transportation. BC code contains extensive guidelines for the safe shipment and carrying of coal cargo. It asserts that coal may heat up on its own and that particular coals are prone to self-heating, which could result in spontaneous combustion. Because such shipments can be combustible, explosive, poisonous, corrosive, pollutant of the environment, and hazardous to human life, they always necessitate extremely cautious and skilled handling.

Chemical cargoes, on the other hand, require the ship's care for a different reason. Delivering the cargo as pure as possible and in good condition at the loading port is one of the most critical components. Both physical and chemical specialties of cargo must be properly preserved in order to maintain cargo purity. Due to the reasons listed above, the problem of the research was determined as "Self heating/Ignition of Coal Cargoes during Maritime Transportation and Shipment and its Effects on the ship".

3.2. OBJECTIVES AND SCOPE OF THE STUDY

Risk is defined by the American Bureau of Shipping (ABS,2014) as a result of combining the probability of risky occurrences occurring and the magnitude of severity and disaster that these events can generate. SOLAS aggrement is one of the IMO's main pillars, including rules aimed at ensuring the safety of commerce ships. The SOLAS convention's principal goal is to establish minimal criteria for the safe handling of ships and to promote operational safety at sea through codes like ISM, IMDG, and MARPOL.

Maritime dangers and disasters may increase as the number of ships grows. Despite increased safety regulations and enhanced technology, according to Akten (2006), shipping is and always will be full with hazards. As a result, worldwide maritime organizations have made major efforts to improve shipping sector safety (Hetherington et al, 2006; O'Neil, 2003), yet according to AGCS (2020) and EMSA (2020), recent data results suggest that there are still a substantial number of maritime incidents.

Self-heating/ignition on board, particularly on coal cargo-based vessels, is a major problem for the maritime industry and its employees, since it threatens the cargo, crew, ship, and maritime environment. In order to determine the suitable response approaches, it is important to create an accurate and exact estimation of the degree of Self-heating/ignition. For officers who are alone at sea, conducting a risk analysis and planning ahead of time is particularly crucial in order to decrease the chance of self-heating/ignition and not being exposed to dangers in this way. Accidents are usually occured by a complex interaction of several contributing elements. It is vital to establish underlying causes and their linkages in order to avoid and explain such tragedies.

Despite a significant effort in recent decades to reduce the number of maritime casualties and accidents, the figures remain inadequate. Self-heating/ignition in a coal carrier appears to be one of the most disastrous disaster types on board. Identifying the dangers and risks particular to coal cargo carriers and producing an efficient risk assessment to evaluate them is also a key step in preventing self-heating/ignition on board.

The primary goal of this thesis is to use fuzzy fault tree analysis (FFTA) to specify and appraise the root causes of self-heating/ignition in Coal Cargo vessels. Event Tree is used in a fuzzy sets environment to enable empirical evaluation and illustration of operational problems throughout loading, unloading, and transportation. Furthermore, it emphasize an undesirable occurrence and use both a fault tree and an event tree to construct the likely sources and effects of the undesirable occurence separately.

This work also addresses a gap in the literature by being one of the few studies on modeling and analyzing the amount of self-heating/ignition on board owing to coal cargo activities in dry bulk carriers. According to some research, technical variables were shown to be a significant influence in self-heating/ignition incidents, according to accident datas, Schroder et al. (2011) on the other hand, discovered major gaps in the identification and assessment of organizational elements.

3.3. RESEARCH METHODOLOGY

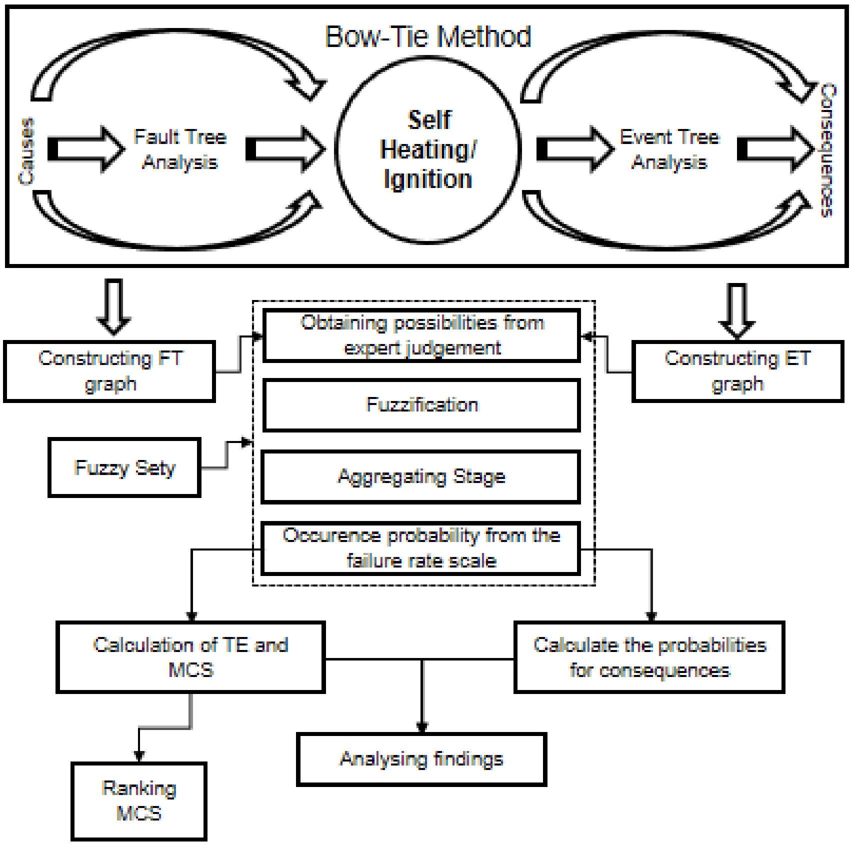
The research model and processes are mostly addressed in this part. The data collecting instruments utilized in the study were detailed after information on the research model and procedure was provided. Following that, the selection procedure for the experts whose opinions were sought was discussed, as well as the sample methods employed.

3.3.1. Model of the Research

There are two aspects to the research model: qualitative and quantitative research. Firstly, in the context of qualitative study, expert views were gathered in addition to the literature review, and the fundamental causes of the self-heating/ignition peak occurrence in bulk carriers transporting coal while loading, unloading, and transportation were attempted to be determined. With these root causes gathered, a fault tree was formed, basic and intermediate events that led to the peak event were identified, and the links between them were schematized using logical gates. Then, under the observation of six maritime experts, the initial step in quantitative risk evaluations is to create an FT graph based on the BEs and TE. When the TE (self heating/ignition) has been recognized, the FT is finished. Using Boolean algebra principles and the fault tree topology, qualitative FTA may be used to determine the MCSs of the probable change. The MCSs illustrate the TE in terms of its underlying causes and indicate the various methods in which the change can take place. Then an ET graph was created to accomplish quantitative risk analysis utilizing the bow-tie technique by first handling the starting event, which was determined to be self-heating/ignition during coal cargo operations. The likelihood of the outcomes were determined based on these experts' assessments.

Bow-tie analysis is a reliable risk analysis method that may be used to connect a set of causes and effects. The strategy is very easy to use for analyzing hazards (J.P. Visser et al., 1998). The bow-tie is a graphic representation of possible dangers. To stress on the causes and effects of an occurrence, it comprises of FTA (Fault tree analysis) and ETA (Event tree analysis). The bow-tie diagram is a useful tool for identifying probable causes and analyzing previous mishaps (K. Mokhtari et al.,2011). Because the precise value of probability is ambiguous and human error information shortages is one of the major problems to risk evaluation in the maritime sector, Fault Tree and Event Tree Analysis are combined in this study in a fuzzy sets setting. The methodological structure of the comprehensive approach is depicted in Figure 14.

Figure 14: The Integrated Methodology's Conceptual Framework



Source: Created by author

3.3.2. Implementing the Data Gathering Tool

Expert perspectives were solicited in two phases of the study's qualitative and quantitative methods. A semi-structured interview form was conducted to describe the root causes, discover the variables relevant to the thesis's subject, and expose the correlations between the variables in the qualitative process, which is the first step. First, a literature assessment of self-heating/ignition incidents that happened in shore and maritime facilities handling bulk coal was conducted as part of the data gathering tool development. In addition, accident reports involving bulk carriers were investigated. The questionnaire for the semi-structured interview given in Annex 1 was constructed as a draft using the variables gathered from all of these methods. The draft questionnaire was acquired from to one academician and five practitioners (masters) as maritime experts with sufficient Expertise in the transportation of dry bulk Cargo and this discipline, particularly coal and ore cargoes such as nickel ore, iron ore, mineral, and so on. Also, the questionnaire was refined based on their feedback. Academicians and practitioners provided feedback on the substance of the variables, the language utilized, and the question forms during this procedure. The second step of qualitative study revealed the relationships between the variables with the semi-structured interview form.

To overcome this risk, the thesis concentrates on carrying out a risk evaluation for self-heating/ignition owing to coal cargoes shipment on-board dry bulk carriers in order to improve maritime safety by using fuzzy logic into the bow-tie study. Expert judgement can be an alternate to data imbalance, which is one of the main obstacles for quantitative risk evaluation in maritime traffic (Rausand and Hoyland, 2004). To conduct quantitative FTA and ETA, the proposed framework employs fuzzy set theory. The challenges associated with a lack of empirical findings in self-heating/ignition owing to coal cargoes shipment can be solved in this fashion. Under the guidance of six maritime experts, an ET graph was created to carry out quantitative risk evaluation utilizing the bow-tie technique by first addressing the starting event, which was determined to be self-heating/ignition during the coal cargo handling and storage operation. The likelihood of the outcomes were determined based on these Experts' assessments. Their linguistic judgement of each result is shown in Table 20. Following that, the odds of each outcome were estimated. The final bow-tie, which contains the FT and ET graphs and depicts the chance of each outcome occurring, is shown in Figure 15.

3.3.3. Expert Selection and Sampling

Expert judgment can be used instead when there is a lack of data, which is one of the main obstacles for quantitative risk evaluation in maritime trade traffic. So, Expert judgements were employed in the thesis to choose the accident factors, determine the correlations between the variables, and create the final FFTA model.

The corporate information of these Experts, their responsibilities, the expert profile and the weighting scores Experts are all included in Table 10 & 11 & 12. In this regard, the Experts in the research considered the following factors when making their decisions:

- Have a minimum of 1st officer and/or Master's level experience on bulk carriers,
- Being in charge of the operations and/or inspector of ships in companies that operate bulk carriers,
- Having worked as a expert in bulk carrier accidents,

The procedure of estimating the a priori probability of underlying causes and the quantitative process of the study were repeated, this time with Expert advice. The weight coefficients of the Experts were taken into account while collecting Expert views derived using fuzzy set theory, and a single average value was obtained. Using the clarifying approach, these values were converted into quantifiable numbers, and the likelihood of the conflict peak occurrence was estimated using fault tree analysis. The important issue here is to pick both diverse and homogeneous groups of experts (Ford & Sterman, 1998). Workers and experts can create a heterogeneous group, but only workers can form a homogeneous group. As a result, the recruitment of an Expert group is both necessary and challenging. In decision-making situations, a varied group of experts appears to be more realistic than a homogeneous one (Helvacioglu & Ozen, 2014). As a result, a diverse collection of experts with relevant Expertise and experience in the maritime industry was used in this thesis. Six experts, including a DPA, fleet manager, master, P&I surveyor, and academic professor, were hired to voice their ideas for the sent questionnaire in order to form a varied group.

3.4. THE BOW-TIE ANALYSIS

The Bow-tie analysis identifies the possibility for major disasters inside the system or sector. The important event is represented in the bow-tie designs in the center. The fault tree approach is shown on the left side of a bow-tie analysis to determine the hazard's sources, while the event tree method is shown on the right side to discover the danger's impacts (De Dianous and Fi´evez, 2006; Shahriar et al., 2012). The method's core methodology is straightforward, combining cause and effect studies on a single chart.

Because there is a shortage of statistical information in maritime transportation, the bow-tie technique will be used in this research in a fuzzy sets environment to deal with the ambiguity of expert judgment. The following is a description of how the bow-tie technique and fuzzy sets are combined.

3.4.1. Fault Tree Analysis

The number of failures of self-heating/ignition on coal cargo carriers is strongly influenced by the situation of the coal in cargo holds, stowage condition and area in harbour or storage area/pile, mode of transportation, loading and handling system in port or anchorage, coal characteristics and origin, weather conditions, and the enviromental situation. Self-heating/ignition can appear in a variety of ways, posing a threat to sailors' lives, cargo, vessels, society, the maritime environment, and the industry.

The much more essential reasons and hidden dangers can be determined, including the probability of a mishap, using qualitative FTA evaluation. The FTA, in contrast, is a close combination of mathematics and expert competence. For the formulation and investigation of the fault tree, a strong mathematical foundation and significant Expert competencies are necessary. FTA is a deductive reasoning method in which tree diagrams are used to show the logical relationship between prospective accidents and their causes.

Quantitative FTA in the traditional sense necessitates the precise probabilities of occurrences. However, in the maritime industry, having access to such precise figures is not always achievable since historical data on the likelihood of change causes or outcomes is often missing, partial, or inaccurate. Quantifying FTA using inaccurate data adds to the analysis' uncertainty and creates a misleading sense of accuracy, undermining the process' overall confidence (Ferdous et al. 2009; Abdelgawad and Fayek 2011).

3.4.1.1. Conduct a Qualitative FTA

The process of developing a qualitative research model comprises steps such as determining the research topic and its variables, as well as constructing an error tree structure based on the link between the variables and consulting experts.

3.4.1.1.1. Identifying Hazards of Coal Cargo Handling

By reference to the author's expert viewpoints, the fundamental causes, namely basic events, were defined as shown in Table 9 below, taking into consideration the expert interviews listed in Table 9, literature review and accident reports getting from shipping companies. The expert work group was instructed to determine BEs and identify the logical link between the root causes. Expert weigh in on the BEs that make up the fault tree's sub-events and the starting point for the error chain. However, each expert's viewpoint on the case's underlying causes may vary. As a result, the importance of each expert from various perspectives influences judgments. Experts' differing perspectives on the same event can be attributed to a variety of factors including educational attainment, experience levels, and disparities in fields of expertise.

In addition, this step involved a review of existing literature to determine the variables that led to the self-heating/ignition aboard ship owing to coal cargoes shipment, as well as an analysis of accident reports, which are helpful in identifying possible hazards in the maritime industry. The parameters in the documents and literature were then corrected and upgraded after engaging maritime professionals interviews. This was performed by a semi-structured online or face to face interview with six experts, which yielded 23 basic occurrences. The detected root causes are labeled with the letters 1, 2..., and 23.

Table 9: Basic and Intermediate Events for Self-heating & ignition.

FTA definition	Potential failures	Definition
TE	Self – Heating & Ignition	When coal is exposed to the atmosphere, exothermic chemisorption of oxygen occurs, proceeded by the creation of oxide layer and, to a lesser extent, oxidation of the coal, culminating in the emission of different gases.
IE_1	Not Comply wıth IMSBC Code	It refers to the ship's and shipper's non-compliance with the IMSBC Code.
IE_2	Characteristic of Coal	It refers to the classification of coal based on where it is produced.
IE_3	Before Loading Failure	Before loading coal, it detects erroneous activities.
IE_4	During Loading and Transportation Failure	During loading and transportation of the coal, it detects erroneous activities.
IE_5	Geographical Location of The Type of Coal	It refers to the geographical location of the type of coal based on where it is produced
IE_6	Moisture Content	It depicts the moisture content of coal based on its characteristics.
IE_7	Third Party Failure	Prior to loading coal on a bulk carrier, It demonstrates the failure of a third party such as surveyors, P&I and related person
IE_8	Charecteristic of Pile	It refers to the classification of coal pile based on where it is produced
IE_9	Assess Self – Heating	During loading and transportation of the coal, evaluate the self-heating/ignition coal by ship crew
IE_{10}	Surface Oxidation	During loading and transportation of the coal, it describes that occur surface oxidation in the cargo hold
IE_{11}	Improper Loading	During loading and transportation of the coal, It refers to a ship that has not performed a proper loading process
IE_{12}	Poor Cargo Monitoring	During loading and transportation of the coal, It mentions to a ship that has not execute a proper cargo monitoring process
IE_{13}	Hold Integrity	During loading and transportation of the coal, it signifies a breakdown of the integrity of the hold

IE_{14}	Ventilation	During loading and transportation of the coal, it determines whether or not the coal load in the hold is being properly ventilated.
IE_{15}	Tightness of Hatch Cover	During loading and transportation of the coal, it denotes the failure of the hatch cover to seal
BE_1	Not to Carry Out Can Test	The cause for this occurrence is "not to carry out can test" by not complying with the IMSBC code before loading in a self-heating/heating coal-carrying bulk carrier.
BE_2	Commercial Pressure by Third Parties	It establishes the "Commercial Pressure by third parties" for non-compliance with the IMSBC rules prior to loading self-heating coal on a bulk carrier.
BE_3	Inaccurate Decleration	It states that self-heating in coal-carrying bulk vessels is caused by "inaccurate decleration regarding coal characteristic" performed by third parties before to loading.
BE_4	Inproper Temperature Control by Surveyor	It attributes the incident on a self-heating coal-carrying bulk carrier on "improper temperature control by the surveyor" before to loading.
BE_5	Open Yard Storage	It is determined that the cause of this incident on a self-heating coal-carrying bulk carrier is the open yard storage of the coal cargo prior to loading.
BE_6	Barge Storage	It is because the coal load is carried on the floating barge preparatory to loading in a self-heating coal-carrying bulk carrier.
BE_7	Overreliance	This occurs on a self-heating coal-carrying bulk carrier due to the ship's officers/personnel becoming over reliance during transportation or loading.
BE_8	Lack of Knowledge	This occurs on a self-heating coal-carrying bulk carrier due to the ship's officers/personnel becoming lack of knowledge during transportation or loading.
BE_9	Improper Equipment	The usage of inproper equipment by the ship's officers/personnel during transportation or loading is the cause of this incident in a self-heating/ heating coal-carrying bulk carrier.
BE_{10}	Lack of Experience	The lack of experience of the ship's officers/ crew during transportation or loading is the cause of this incident on a self-heating coal-carrying bulk carrier.
BE_{11}	Hatch covers not being closed in Time	It specifies that the cause of this incident on a self-heating coal-carrying bulk carrier is the ship's officers/personnel failing to close the holds in a timely manner during transportation or loading.
BE_{12}	Fire Damper/Mushroom Ventilation Failure	This incident occurs when the ship's hold integrity is interrupted during transportation or loading owing to fire damper/mushroom ventilation failure in a self-heating/heating coal-carrying bulk

		carrier.
BE_{13}	Rubber Package Failure	The failure of the ship's hatch cover seal owing to the hatch cover rubber package during transportation or loading is the cause of this incident on a self-heating/heating coal-carrying bulk carrier.
BE_{14}	Heavy Weather	It specifies that the cause of this incident onboard a self-heating coal-carrying bulk carrier is the breakdown of the hatch cover seal while transportation owing to heavy weather conditions.
BE_{15}	Inaccurate Trimming	It specifies that the source of this incident in a self-heating/heating coal-carrying bulk carrier is inaccurate trimming owing to wrong loading during loading operation.
BE_{16}	Delays During Loading	This incident is caused by delays during loading owing to improper loading of the ship during loading on a self-heating coal-carrying bulk carrier.
BE_{17}	Improper Ventilation	It specifies the reason for improper ventilation during transportation or loading on a self-heating/heating coal-carrying bulk carrier.
BE_{18}	Not Ventilating After Interruption	It specifies when a self-heating/heating coal-carrying bulk carrier fails to ventilate when the loading process is interrupted during loading.
BE_{19}	Size of Particle Failure	The coal particle size, which varies based on the geographical features of the coal load, is defined as the source of this phenomena in a self-heating coal-carrying bulk carrier.
BE_{20}	Air Gap Between Particles Failure	It specifies that the air gap between particles, which varies based on the geographical features of the coal load, is the source of this occurrence in a self-heating/heating coal-carrying bulk carrier.
BE_{21}	Coal in Stockpile	In a self-heating coal-carrying bulk carrier, it determines the moisture content of the coal in the stockpile based on the geographical features of the coal load.
BE_{22}	Coal in Barge	In a self-heating coal-carrying bulk carrier, it defines the moisture content of the coal in barge based on the geographic location of the coal.
BE_{23}	Coal in Closed Area	In a self-heating coal-carrying bulk carrier, it specifies the moisture content of the coal in a closed area based on the geographical region of the coal load.

Source: Created by the author.

3.4.1.1.2. Constructing FT Diagram

The FT graph is drawn in the first phase to assess the likelihood of TE (top event). The TE is critical to the system and has disastrous effects for crew, commodities, and the environment. The chance of TE is calculated using a risk analysis. A block diagram is used to represent the system's failure from TE to BE (basic events).

The author used expert opinions mentioned on Table 12 to categorize root causes in the process of building the fault tree structure. The procedures that were utilized to investigate the reasons of P&I Clubs (North of England, Skuld, U/K, Gard, London Steam Ship, Standar Club, West of England P&I), Classification Societies (ABS, Class NK, Bureau Veritas, RINA, TL, Lloyd's Register, and DNV-GL), and IMSBC Code regulations and circular statement maritime accidents were used to naming and classifying root causes. Also, the semi-structured technique was employed in the first step to detect the design change's underlying causes (BEs). The semi-structured approach is a methodology for confirming risk by employing a prepared semi-structured that mainly depends on expertise (Hong et al. 2009). The expert task group was then requested to utilize OR or AND gates to identify the logical link between the main causes. The experts gave the participants a chance to go through their replies again in the second step and make any required changes. After applying the modifications, the experts came to an agreement in the third step and confirmed the fault tree's graph. Figure 15 illustrates the generated fault tree for the specified modification in the thesis.

The Det Norske Veritas - Maritime Systematic Cause Analysis Technique is being employed to categorise the variables in order to reach intermediate events after determining the basic events. Table 7 illustrates 23 fundamental events and 15 intermediate events that are organized together. In this study, the TE is described as a self-heating/ignition that could cause serious harm or death to a seafarer, vessel and also maritime environment. The fundamental execution approaches for the fault tree technique were discussed in depth with them prior to the professionals interviews. The professionals were then encouraged to share the logical relationship between the key reasons using OR or AND gates.

The unwanted occurrence, namely the peak event, has been determined as "self-heating/ignition" during the loading, unloading, and transportation of the coal cargoes procedures that are the topic of the investigation. Not comply with IMSBC Code and Characteristic of Coal were then separated from this peak event. The

"AND gate" connects these two primary events to the top event. Using fault tree analysis' logic gates, the model was developed by grouping 23 root causes and intermediate events between these primary events. All of the connections between events in the model employ the "OR gate." 18 of the 23 root causes are classified as failures to NOT COMPLY WITH THE IMSBC CODE, while 5 are classified as failures to CHARACTERISTIC OF COAL.

The primary event of not complying with IMSBC Code is separated into two intermediate events: Before Loading Failure and During Loading and Transportation failure. Third-Party Failure and Characteristic of Pile Failure are all divided into sub-intermediate events under Before Loading Failure and Not to Carry Out Can Test and Commercial Pressure by Third Parties are mentioned as basic events under Before Loading Failure. The root causes of Inaccurate Decleration and Inproper Temperature Control by Surveyor are mentioned as basic events under Third Party Failure. The root causes of Open Yard Storage and Barge Storage are mentioned as basic events under Characteristic of Pile.

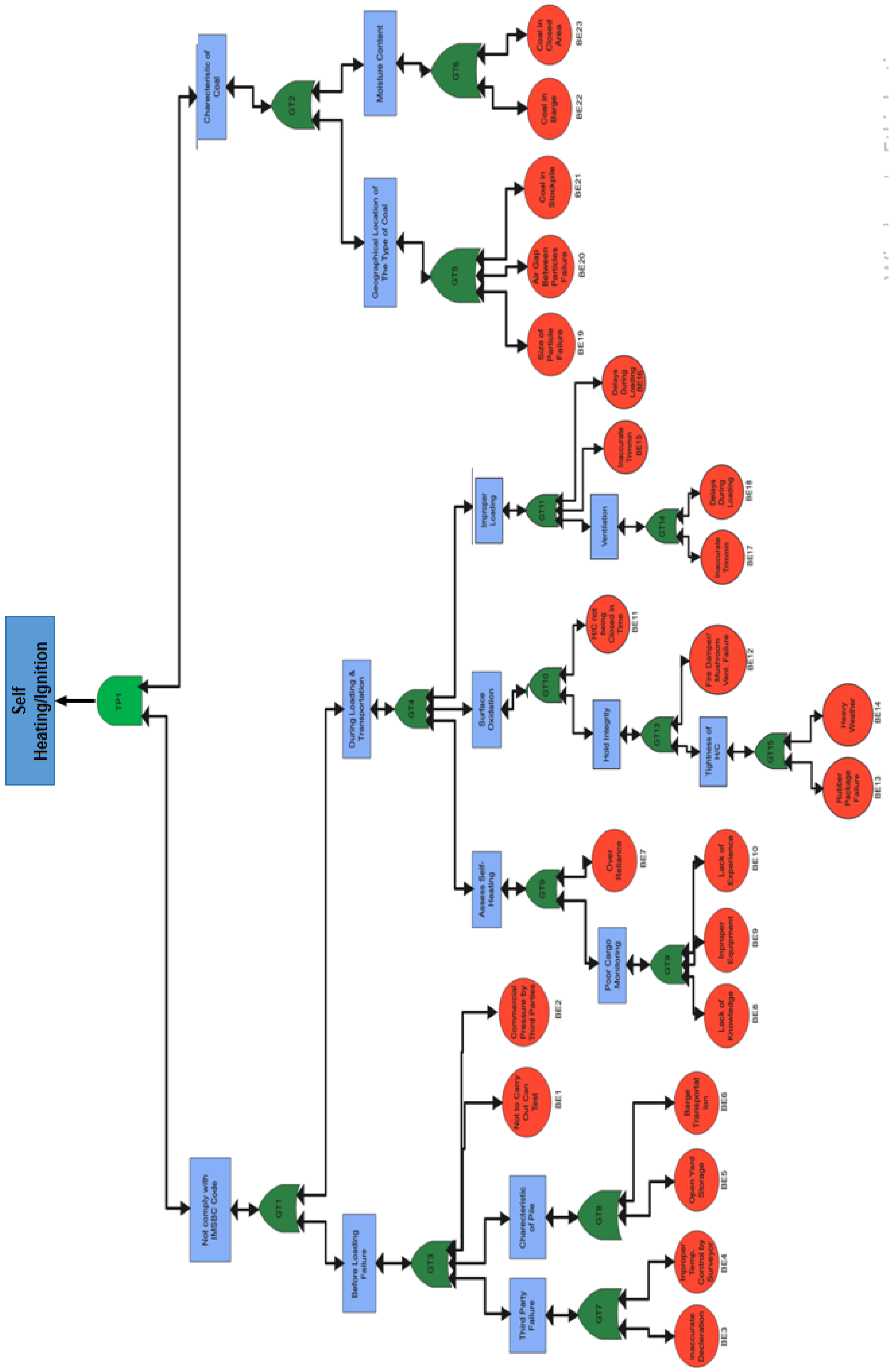
Assess Self Heating, Surface Oxidation, and Improper Loading are all divided into sub-intermediate events under During Loading and Transportation failure. The root cause of Overreliance is mentioned as basic event and Poor Cargo Monitoring is mentioned as sub-intermediate event under Assess Self Heating. Lack of Knowledge, Improper Equipment, and Lack of Experience are mentioned as basic events under Poor Cargo Monitoring.

Hatch Covers not being Closed in Time as basic event and Hold Integrity as sub-intermediate events are divided into two events under Surface Oxidation. Likewise, Tightness of Hatch Cover as intermediate events and Fire Damper/Mushroom Ventilation Failure as basic events are divided into two under Hold Integrity. In addition, Rubber Package Failure and Heavy Weather are basic events under Tightness of Hatch Cover. Furthermore, Inaccurate Trimming and Delays During Loading are basic events and Improper Ventilation is sub-intermediate events under Improper Loading. In addition, Improper Ventilation and Not Ventilation After Interruption are sub-Intermediate events under Ventilation.

The second primary event of Characteristic of Coal under Self-heating/Ignition is seperated into two intermediate events: Geographical Location of

The Type of Coal and Moisture Content. Size of Particle Failure and Air Gap Between Particles Failure are mentioned as basic events under Geographical Location of The Type of Coal. Also, Coal in Stockpile, Coal in Barge and Coal in Closed Area are mentioned basic events under Moisture Content.

Figure 15: Fault Tree Structure



Source: Created by author

3.4.1.2. Conduct Quantitative Fuzzy FTA

Quantitative FTA is used to accomplish a second goal of this thesis, which is to determine the likelihood of an understudy change (P (TE). To add fuzzy logic, we'll take three stages that are based on the technique described in Abdelgawad and Fayek (2011) and Abad et al. (2019). The fuzzy technique is conducted to first assess the fuzzy probabilities of BEs and PE, which are specified in linguistic variables instead of numerical values, using the fuzzy approach. Linguistic variables are phrases used in natural language to describe an unknown value. Linguistic variables and their fuzzy numbers can be utilized to indicate the chance of BEs occurring. Knowledge acquisition is a typical strategy for constructing fuzzy membership functions for linguistic variables. Experts are required to judge the membership values of each specific component in a fuzzy set that most clearly communicate the meaning of that linguistic variable in this technique (Klir and Yuan 1995).

The maritime experts in this thesis were shown the common application procedures of FTA approach, and FTA drawings were made under their observation. The diagrams may be used to qualitatively and quantitatively analyze the causes and results of self-heating/ignition. The qualitative technique categorized the causes of self-heating/ignition, derived failure probability estimates using fuzzy logic implementations in accordance with maritime experts opinion, and built a logical connection between the causes. Minimum Cut Sets (MCS) were found in the quantitative manner, and the likelihood of occurrence of the combinations that led to self-heating/ignition was assessed. The maritime experts in this thesis were picked from a group of people who shared the same interests as the researchers. Diverse disciplines of research, backgrounds, and experiences may be found among maritime experts (Cheliyan and Bhattacharyya, 2018). As a result, it would be fair to assess the experts' perspectives on FTA analysis based on their expertise and knowledge. The opinions of maritime experts were weighted in this thesis depend on their expert status, competency, and maritime background.

Priori probability values of the root causes were attempted to be identified in the form of numerical data employing fuzzy set theory and expert views once the fault tree structure was established.

3.4.1.2.1. Determine the Membership Functions of Linguistic Variables

Quantitative FTA necessitates calculating the likelihood of MCSs occurring. Due to a lack of accurate data, linguistic variables can indeed be utilized and converted to fuzzy numbers to represent the likelihood of occurrence and the level of uncertainty in each estimate. Linguistic variables are phrases used in natural language to express an unknown rate in Figure 13. Linguistic terms and related fuzzy numbers can be utilized to indicate the chance of BEs occurring. Knowledge acquisition is a typical strategy for constructing fuzzy membership functions for linguistic variables. Trapezoidal fuzzy numbers are the easiest to grasp and operate of the several types of fuzzy numbers accessible. As a result, we describe the variety of different linguistic variables using trapezoidal fuzzy numbers. For the trapezoidal fuzzy set numbers (a, b, c, d), this equation can be described in chapter 2.4.1. (Badida et al., 2019).

3.4.1.2.2. Calculating Possibilities from The Expert Opinions

Data source on the nature of maritime activities is difficult to come by, and much of it is undocumented. The Experts' judgements are utilized to identfiy data difficulties (Lavasani et al.,2015). Because BEs play a key role in initiating chains of events, Experts express their opinions on each BE. Expert judgement, contrarily, isn't always comparable because they have varying levels of skill, education, institutional and intellectual expertise, and so on. A diverse collection of experts is what this is referred to as. The Expert's assessment is influenced by the degree of relevance at this stage. Experts' weighting scores are essential to improve evaluation accuracy and prevent research from being questioned. In light of the foregoing, Expert judgment is utilized to determine the likelihood of each basic occurrence. Expert language phrases provide a convenient approach to transform possibilities to probabilities.

3.4.1.2.3. Experts Selection and Experts Weight Coefficient Calculation

While determining the Experts whose opinions will be consulted in the process of determining the probabilities of the root causes in the network structure; 6 different experts were selected, paying attention to the fact that they had carried out coal transportation operations on ships of different types and tonnages, on which they worked as ship master, operations manager. The information and interview dates of the selected Experts are presented in Table 10.

Table 10: Expert Profile Attanded Survey

Maritime Expert	Position	Years Maritime Experienced	Educational Level	Shore-based Service Time
1	DPA & Operation Manager & Master	11-15	Bachelor	6 – 10
2	Superintendent / Master	11-15	Bachelor	≤ 5
3	Superintendent / Master	11-15	Bachelor	≤ 5
4	DPA & Operation Manager & Master	≥ 16 years	Bachelor	16-25
5	Academician & Master	11-15	PhD	11-15
6	P&I Surveyor / Master	≥ 16 years	School level	16-25

Source: Created by the author.

The interviews were done at various times, both face-to-face and online, to avoid being affected by each other's comments while expressing the experts' viewpoints. Each interview lasted roughly 2-3 hours in total, with a 45-minute break in between (due to the Covid-19 epidemic, which affected the whole world at the time of the interviews, the interviews were held outdoors and by taking the necessary pandemic precautions). Each expert was educated on the goal of the study, the model development procedure, the construction of fault tree and event tree structures, and the application of bow tie evaluations before the interviews. Before requesting for probabilistic root cause evaluations, details on each root cause and its history was provided.

In this study, the weighting coefficients of each maritime expert were established in Table 11, taking into consideration the weight requirements stated in Table 12, while evaluating the impacts of experts on probability, that is, their weights.

Table 11: Weighting Scores of Non-Homogenous Experts

Group	Classification	Score
Expert position	Academician	5
	DPA & Operation Manager	4
	Superintendent	3
	Master	2
	Chief officer	1
Sea service time	≥ 16 years	5
	11-15	4
	6-10	3
	3-5	2
	≤ 3	1
Education Level	PhD	5
	Master	4
	Bachelor	3
	HND	2
	School level	1
Shore service time	≥ 26	5
	16-25	4
	11-15	3
	6 – 10	2
	≤ 5	1

Source: Created by the author

Table 12: Weights of Maritime Experts Participated to Survey.

Maritime Expert	Weighting Factor				TW	Weighting Score
1	4	5	3	2	14	0,175
2	3	4	3	1	11	0,1375
3	3	4	3	1	11	0,1375
4	4	5	1	4	14	0,175
5	5	4	5	3	17	0,2125
6	4	3	3	3	13	0,1625

Source: Created by the author

3.4.1.2.4. Using Experts Opinions to Determine Root Cause Probabilities

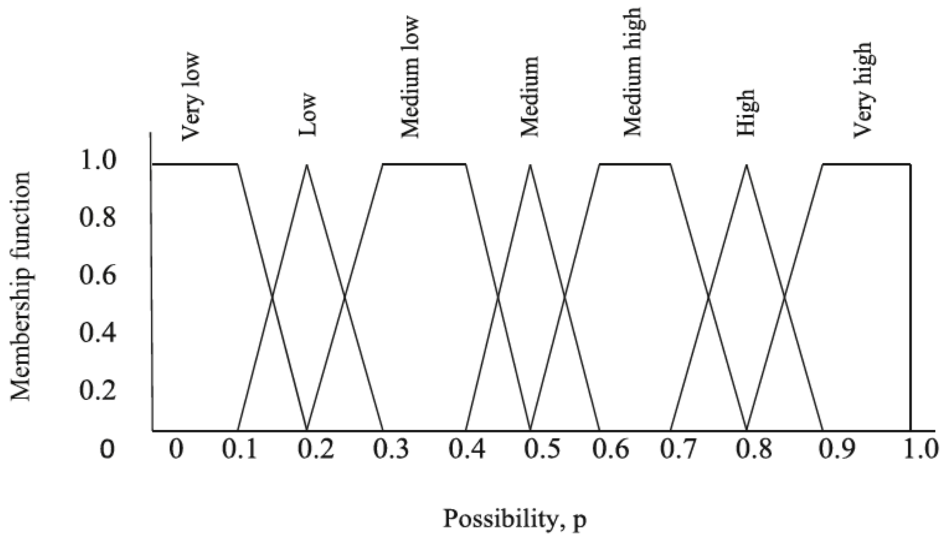
The author prepared questions prior to soliciting maritime expert opinions in order to assist the expert's response to the potential of each underlying cause. A numerical approximation approach was used to transform the maritime experts' language statements into fuzzy numbers. Expert views on fundamental occurrences with uncertain failure rates were obtained using the references maritime probability fuzzy language phrases (Wang et al., 2013; Lavasani et al., 2015; Yazdi et al., 2017; Li et al., 2020). The language judgements of expert assessments of the basic events on the fault tree are shown in Table 14.

Table 13: Probability Fuzzy Language Terms

Linguistic terms	Fuzzy numbers
Very low (VL)	(0.0, 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, 1.0)

Source: Created by the author

Figure 16: Fuzzy Rating and Membership Functions



Source: Arıcı et.al (2020)

Table 14: Linguistic Judgments of Maritime Experts for BE Possibilities.

	M.Exp 1	M.Exp 2	M.Exp 3	M.Exp 4	M.Exp 5	M.Exp 6
BE_1	VL	VL	ML	VL	L	ML
BE_2	MH	H	H	H	VH	M
BE_3	M	H	H	MH	H	M
BE_4	MH	L	MH	L	ML	MH
BE_5	H	M	M	MH	M	MH
BE_6	MH	M	M	MH	M	H
BE_7	MH	MH	H	H	MH	MH
BE_8	ML	M	ML	MH	M	MH
BE_9	M	M	L	ML	M	MH
BE_{10}	MH	MH	H	H	M	M
BE_{11}	MH	M	H	M	MH	H
BE_{12}	ML	M	ML	ML	L	M
BE_{13}	H	MH	MH	M	MH	H
BE_{14}	H	ML	M	H	H	MH
BE_{15}	VL	ML	M	VL	L	M
BE_{16}	M	M	MH	M	H	MH
BE_{17}	H	MH	VH	H	H	H
BE_{18}	MH	M	MH	MH	H	H
BE_{19}	H	MH	H	H	MH	VH
BE_{20}	VH	H	H	VH	H	H
BE_{21}	VH	H	MH	MH	VH	H
BE_{22}	MH	M	MH	H	MH	M
BE_{23}	ML	M	M	ML	ML	MH

Source: Created by the author after Experts evaluations

3.4.1.2.5. The Aggregate Result of The Experts' Judgements

The use of linguistic variables in probability assessment enables experts to offer responses that are comfortable within a certain range, but these verbal expressions must be transformed into equivalent fuzzy numbers in order to collect numerical data. Because each maritime experts have a distinct perspective at this stage, it is vital to integrate the maritime experts opinions correctly, taking the expert weight coefficients into consideration.

Hsu and Chen proposed a method for soliciting expert opinions from diverse groups of experts. SAM is a technique for translating verbal concepts into fuzzy numerical counterparts. **The Eqs. (9)–(13)** are used to compute the aggregated opinion of maritime experts. As a result, BE9 - Improper Equipment Failure has a similarity function and a similarity value, as shown in Table 15**.** In addition**,** the mean agreement (AA), relative agreement (RA), and consensus coefficient of maritime experts are shown in Table 15. Because six maritime experts are regarded to be similar, is nominated as 0.5 in the computation (Lavasani et al.,2015, Senol et al., 2015).

Also, for each BEs, the similarity value reflects the link between each maritime expert's view and the viewpoints of other maritime experts (Arici et al, 2020). For example, Table 15 shows the aggregate computation of expert views for the root cause of " **BE9-Improper Equipment Failure**":

Table 15: Calculation of the variable "BE9-Improper Equipment Failure"

Expert 1	VL	0	0	0.1	0.2		
Expert 2	VL	0	0	0.1	0.2		
Expert 3	ML	0.2	0.3	0.4	0.5		
Expert 4	VL	0	0	0.1	0.2		
Expert 5	L	0.1	0.2	0.2	0.3		
Expert 6	ML	0.2	0.3	0.4	0.5		
S (E12)	1	S (E26)	0.725	AA (E1)	0.865	AA (E4)	0.865
S (E13)	0.725	S (E34)	0.725	AA (E2)	0.865	AA (E5)	0.865
S (E14)	1	S (E35)	0.85	AA (E3)	0.805	AA (E6)	0.805
S (E15)	0.875	S (E36)	1				
S (E16)	0.725	S (E45)	0.875	CC (E1)	0.173	CC (E4)	0.173
S (E23)	0.725	S (E46)	0.725	CC (E2)	0.154	CC (E5)	0.192
S (E24)	1	S (E56)	0.85	CC (E3)	0.148	CC (E6)	0.161
S (E25)	0.875						
Weight of expert 1		0.175		RA (E1)	0.171	RA (E4)	0.171
Weight of expert 2		0.138		RA (E2)	0.171	RA (E5)	0.171
Weight of expert 3		0.138		RA (E3)	0.159	RA (E6)	0.159
Weight of expert 4		0.175					
Weight of expert 5		0.213					

Weight of expert 6	0.163			
$\tilde{R}_{AG}$ Aggregation	0.0809	0.1309	0.2118	0.3118

Source: The author used aggregate calculation formulas to generate this figure.

3.4.1.2.6. Defuzzifying Possibilities Obtained

The consolidated maritime expert judgement is defuzzified in this stage. Under fuzzy sets, triangular or trapezoidal fuzzy numbers are turned to fresh numbers. In this study, the centre of area (COA) method is conducted for defuzzification. The use of the center of gravity clarification calculation is considerably convenient than other ways among the various strategies that may be utilized in the clarification process (Leekwijck at al.,1999).

Equation (14) is then used to integrate maritime experts judgements. Defuzzification is used to transform fuzzy numbers into discrete values after the aggregated results have been obtained **(Eq. 15)**. Table 16 illustrates the defuzzified failure possibilities expert judgements for each BE.

Fuzzy numbers were defined and a single numerical figure was produced for each root cause in Table 16.

Table 16: Aggregated Expert Judgments and Defuzzified Failure Possibilities for Each BE

BE	Aggregated expert judgements on failures				Defuzzified possibility
BE1	0.081	0.131	0.212	0.312	0.18586
BE2	0.638	0.738	0.774	0.855	0.75757
BE3	0.567	0.667	0.685	0.785	0.67586
BE4	0.317	0.417	0.485	0.585	0.45119
BE5	0.482	0.582	0.616	0.716	0.59924
BE6	0.481	0.581	0.616	0.716	0.59830
BE7	0.563	0.663	0.732	0.832	0.69735
BE8	0.369	0.469	0.534	0.634	0.50188
BE9	0.340	0.440	0.473	0.573	0.45618
BE10	0.529	0.629	0.662	0.762	0.64531
BE11	0.531	0.631	0.667	0.767	0.64906
BE12	0.244	0.344	0.395	0.495	0.36964

BE13	0.550	0.650	0.701	0.801	0.67719
BE14	0.553	0.653	0.683	0.783	0.66798
BE15	0.175	0.241	0.291	0.391	0.27631
BE16	0.486	0.586	0.618	0.718	0.60205
BE17	0.686	0.786	0.815	0.900	0.79569
BE18	0.556	0.656	0.706	0.806	0.68089
BE19	0.648	0.748	0.798	0.882	0.76838
BE20	0.734	0.834	0.867	0.934	0.83997
BE21	0.672	0.772	0.840	0.904	0.79534
BE22	0.501	0.601	0.653	0.753	0.62474
BE23	0.308	0.408	0.477	0.577	0.44267

Source: Created by the author using the center of gravity approach utilizing defuzzing method formulas

3.4.1.2.7. Failure Probabilities Calculation

The final stage in determining root cause probabilities is to compute likelihood of failure from defuzed failure probabilities. The options are then converted to probabilities dependent on expert judgement. To execute this, Onisawa (1998) suggested a method for converting fuzzy failure possibilities to fuzzy failure probability. The fuzzy probability rate (FPT) is obtained from the fuzzy possibility rates (FPs). The equations below are utilized.

Equations (15) and (16) were used to convert the probabilities derived from the expert's language phrases into numerical probability values for each BE. Table 17 shows the probability values derived from the possibilities.

Table 17: Probabilities of Failures Obtained from Possibilities

Basic Events	Probabilities of failures	Basic Events	Probabilities of failures
BE 1	0.00017	BE 12	0.00178
BE 2	0.02668	BE 13	0.01594
BE 3	0.01581	BE 14	0.01504
BE 4	0.00350	BE 15	0.00067
BE 5	0.00972	BE 16	0.00990
BE 6	0.00966	BE 17	0.03447
BE 7	0.01811	BE 18	0.01632
BE 8	0.00517	BE 19	0.02865
BE 9	0.00363	BE 20	0.04742
BE 10	0.01304	BE 21	0.03439
BE 11	0.01335	BE 22	0.01144
		BE 23	0.00328

Source: Created by the author using the center of gravity approach utilizing defuzzing method formulas

3.4.1.2.8. Computing MCSs and Total Failure Probability of TE

The group of significance indicator, which is computed to determine the likelihood of TE, is one of the most essential FTA outcomes. We may use the important measures to show how much each MCS increases the likelihood of TE. There are two approaches for determining significance. These procedures are outlined below: The Fussell-Vesely Importance Measure (F-VIM) is a measure of MCS contribution to the likelihood of TE. For each MCS, the F-VI measure may be determined, allowing us to select the MCSs based on their influence on TE likelihood. F-VI is determined by adding all of the TE MCSs containing the specific occurrences (Lavasani et al., 2011). This function is assigned to MCSs in order to determine their significance.

The relevance of each MCS on the fault tree was determined using **Equation (1)-(3)**. For the top event, there were a total of 90 MCSs in this thesis. In addition, the fault tree has only 23 basic events and 90 minimal cut sets. It indicates that there are more pathways for top events to occur and fewer control channels, demonstrating that this system is relatively risky. The more basic cut sets there are, the more risky the system becomes. As a result, increasing the fundamental events of the minimal cut sets will assist to improve system security and reduce the likelihood of a contingency occurring. The FTA discovered 90 different combinations that related to the incidence of accidents. Table 18 shows the hazard scenarios and their probability.

Table 18: Minimum Cut Sets (accident combinations) Causing Self-heaitng/ignition Accidents

MCS$_{1}$	BE$_{1}$*BE$_{19}$	4,871E-06	MCS$_{31}$	BE$_{7}$*BE$_{19}$	5,189E-04	MCS$_{61}$	BE$_{13}$*BE$_{19}$	4,567E-04
MCS$_{2}$	BE$_{1}$*BE$_{20}$	8,061E-06	MCS$_{32}$	BE$_{7}$*BE$_{20}$	8,588E-04	MCS$_{62}$	BE$_{13}$*BE$_{20}$	7,559E-04
MCS$_{3}$	BE$_{1}$*BE$_{21}$	5,846E-06	MCS$_{33}$	BE$_{7}$*BE$_{21}$	6,228E-04	MCS$_{63}$	BE$_{13}$*BE$_{21}$	5,482E-04
MCS$_{4}$	BE$_{1}$*BE$_{22}$	1,945E-06	MCS$_{34}$	BE$_{7}$*BE$_{22}$	2,072E-04	MCS$_{64}$	BE$_{13}$*BE$_{22}$	1,824E-04
MCS$_{5}$	BE$_{1}$*BE$_{23}$	5,576E-07	MCS$_{35}$	BE$_{7}$*BE$_{23}$	5,940E-05	MCS$_{65}$	BE$_{13}$*BE$_{23}$	5,228E-05
MCS$_{6}$	BE$_{2}$*BE$_{19}$	7,644E-04	MCS$_{36}$	BE$_{8}$*BE$_{19}$	1,481E-04	MCS$_{66}$	BE$_{14}$*BE$_{19}$	4,309E-04
MCS$_{7}$	BE$_{2}$*BE$_{20}$	1,265E-03	MCS$_{37}$	BE$_{8}$*BE$_{20}$	2,452E-04	MCS$_{67}$	BE$_{14}$*BE$_{20}$	7,132E-04
MCS$_{8}$	BE$_{2}$*BE$_{21}$	9,175E-04	MCS$_{38}$	BE$_{8}$*BE$_{21}$	1,778E-04	MCS$_{68}$	BE$_{14}$*BE$_{21}$	5,172E-04
MCS$_{9}$	BE$_{2}$*BE$_{22}$	3,052E-04	MCS$_{39}$	BE$_{8}$*BE$_{22}$	5,914E-05	MCS$_{69}$	BE$_{14}$*BE$_{22}$	1,721E-04
MCS$_{10}$	BE$_{2}$*BE$_{23}$	8,751E-05	MCS$_{40}$	BE$_{8}$*BE$_{23}$	1,696E-05	MCS$_{70}$	BE$_{14}$*BE$_{23}$	4,933E-05
MCS$_{11}$	BE$_{3}$*BE$_{19}$	4,530E-04	MCS$_{41}$	BE$_{9}$*BE$_{19}$	1,040E-04	MCS$_{71}$	BE$_{15}$*BE$_{19}$	1,920E-05
MCS$_{12}$	BE$_{3}$*BE$_{20}$	7,497E-04	MCS$_{42}$	BE$_{9}$*BE$_{20}$	1,721E-04	MCS$_{72}$	BE$_{15}$*BE$_{20}$	3,177E-05
MCS$_{13}$	BE$_{3}$*BE$_{21}$	5,437E-04	MCS$_{43}$	BE$_{9}$*BE$_{21}$	1,248E-04	MCS$_{73}$	BE$_{15}$*BE$_{21}$	2,304E-05
MCS$_{14}$	BE$_{3}$*BE$_{22}$	1,809E-04	MCS$_{44}$	BE$_{9}$*BE$_{22}$	4,153E-05	MCS$_{74}$	BE$_{15}$*BE$_{22}$	7,665E-06
MCS$_{15}$	BE$_{3}$*BE$_{23}$	5,186E-05	MCS$_{45}$	BE$_{9}$*BE$_{23}$	1,191E-05	MCS$_{75}$	BE$_{15}$*BE$_{23}$	2,198E-06
MCS$_{16}$	BE$_{4}$*BE$_{19}$	1,003E-04	MCS$_{46}$	BE$_{10}$*BE$_{19}$	3,736E-04	MCS$_{76}$	BE$_{16}$*BE$_{19}$	2,836E-04
MCS$_{17}$	BE$_{4}$*BE$_{20}$	1,660E-04	MCS$_{47}$	BE$_{10}$*BE$_{20}$	6,184E-04	MCS$_{77}$	BE$_{16}$*BE$_{20}$	4,695E-04
MCS$_{18}$	BE$_{4}$*BE$_{21}$	1,204E-04	MCS$_{48}$	BE$_{10}$*BE$_{21}$	4,484E-04	MCS$_{78}$	BE$_{16}$*BE$_{21}$	3,405E-04
MCS$_{19}$	BE$_{4}$*BE$_{22}$	4,004E-05	MCS$_{49}$	BE$_{10}$*BE$_{22}$	1,492E-04	MCS$_{79}$	BE$_{16}$*BE$_{22}$	1,133E-04
MCS$_{20}$	BE$_{4}$*BE$_{23}$	1,148E-05	MCS$_{50}$	BE$_{10}$*BE$_{23}$	4,277E-05	MCS$_{80}$	BE$_{16}$*BE$_{23}$	3,247E-05
MCS$_{21}$	BE$_{5}$*BE$_{19}$	2,785E-04	MCS$_{51}$	BE$_{11}$*BE$_{19}$	3,825E-04	MCS$_{81}$	BE$_{17}$*BE$_{19}$	9,876E-04
MCS$_{22}$	BE$_{5}$*BE$_{20}$	4,609E-04	MCS$_{52}$	BE$_{11}$*BE$_{20}$	6,331E-04	MCS$_{82}$	BE$_{17}$*BE$_{20}$	1,635E-03
MCS$_{23}$	BE$_{5}$*BE$_{21}$	3,343E-04	MCS$_{53}$	BE$_{11}$*BE$_{21}$	4,591E-04	MCS$_{83}$	BE$_{17}$*BE$_{21}$	1,185E-03
MCS$_{24}$	BE$_{5}$*BE$_{22}$	1,112E-04	MCS$_{54}$	BE$_{11}$*BE$_{22}$	1,527E-04	MCS$_{84}$	BE$_{17}$*BE$_{22}$	3,943E-04
MCS$_{25}$	BE$_{5}$*BE$_{23}$	3,188E-05	MCS$_{55}$	BE$_{11}$*BE$_{23}$	4,379E-05	MCS$_{85}$	BE$_{17}$*BE$_{23}$	1,131E-04
MCS$_{26}$	BE$_{6}$*BE$_{19}$	2,768E-04	MCS$_{56}$	BE$_{12}$*BE$_{19}$	5,100E-05	MCS$_{86}$	BE$_{18}$*BE$_{19}$	4,676E-04

MCS_{27}	BE_6*BE_{20}	4,581E-04	MCS_{57}	BE_{12}*BE_{20}	8,441E-05	MCS_{87}	BE_{18}*BE_{20}	7,739E-04
MCS_{28}	BE_6*BE_{21}	3,322E-04	MCS_{58}	BE_{12}*BE_{21}	6,121E-05	MCS_{88}	BE_{18}*BE_{21}	5,612E-04
MCS_{29}	BE_6*BE_{22}	1,105E-04	MCS_{59}	BE_{12}*BE_{22}	2,036E-05	MCS_{89}	BE_{18}*BE_{22}	1,867E-04
MCS_{30}	BE_6*BE_{23}	3,168E-05	MCS_{60}	BE_{12}*BE_{23}	5,838E-06	MCS_{90}	BE_{18}*BE_{23}	5,353E-05

Source: Created by the author

3.4.1.2.9. Ranking The MCS

The relevance of each MCS to the frequency of the TE is represented by the MCS rating. The Vesely-Fussell Importance Measure (V-FIM) approach can be used to rate the MCSs using **Eq. (1)**. To put it another way, the sensitivity of TE's probability is calculated by ranking MCSs according to their contribution to TE probability and their relevance level. V-FIM is employed to analyze the sensitivity in this investigation (Ünver et al., 2019).

The MCS of the FTA have been ranked using **Eq. (2).** The MCSs are ranked in Table 16 depending on their determined significance ratings.

The MCSs rated the top ten significant contributions to the Self-Heating/Ignition likelihood, as shown in Table 17, and the MCSs of BE17*BE20, BE2*BE20, and BE17*BE21 are correspondingly significant failures impacting the probability of occurrence of the TE. This specifies that these MCSs are the main links of the self-heating/ignition of the Coal Carriers. The path MCS BE17*BE20 (‘Improper Ventilation’ and ‘Air Gap between Particles’ occur simultaneously) has the highest likelihood of event for this Self-Heating/Ignition accident, which correlates to the official inquiry conclusions. Table 19 illustrates 10 cut sets with the highest-ranking values.

Table 19: Top Ten MCS List

Top Ten Minimal Cut Set Combinations			
	Minimal Cut Set Combination	Basic Events	Probability Values
1	MCS_{82}	$BE_{17}*BE_{20}$	0.00163457
2	MCS_{7}	$BE_{2}*BE_{20}$	0.00126517
3	MCS_{83}	$BE_{17}*BE_{21}$	0.00118542
4	MCS_{81}	$BE_{17}*BE_{19}$	0.00098757
5	MCS_{8}	$BE_{2}*BE_{21}$	0.00091753
6	MCS_{32}	$BE_{7}*BE_{20}$	0.00085878
7	MCS_{87}	$BE_{18}*BE_{20}$	0.00077389
8	MCS_{6}	$BE_{2}*BE_{19}$	0.00076438
9	MCS_{62}	$BE_{13}*BE_{20}$	0.00075587
10	MCS_{12}	$BE_{3}*BE_{20}$	0.00074971

Source: Created by the author

Moreover, based on their FV-I values, it can be shown that the top five BEs make up the majority of these highest MCSs. BE3 (Inaccurate Declaration), BE21 (Coal in Stockpile), BE17 (Improper Ventilation), BE20 (Air Gap Between Particles) and BE10 (Lack of Experience) are among the BEs whose significant relevance is revealed by the ranking findings. These findings can aid decision-makers in implementing targeted preventative actions, such as tighter management regulation, security checks, and maintenance, to eradicate or diminish the discovered safety flaws, and thereby avoid or minimize the occurrence of self-heating/ignition incidents.

To fulfill the required risk assessment for self heating/ignition in coal shipment, consequences testing is conducted after computing the occurrence probability of TE and MSCs. The ET graph is generated with the help of maritime experts to accomplish this.

3.4.2. Event Tree Analysis

Based from the findings of the next IE, the branches that were left behind will proceed to split into two. This procedure is used until all of the system's occurrences have been examined. The event tree's subsequent branches will lead to distinct findings for the analyzer. The chance of each conclusion on the right side of the event tree will be equal to the sum of the likelihood of all branches leading to it.

In this paper, ETA is being used to anticipate the results of a potential change and to estimate the likelihood of various results arising as a result of alternative change implementation situations. Each branch of the change event tree is considered a situation.

3.4.2.1. Applying Qualitative ETA

The ET diagram is created by determining the failure's initial event. It is necessary to establish the safety functions that will deal with the beginning and effect of the system's safety. Failure event chains are specified in this stage. Other crucial events that may occur after the starting event are referred to as relevant occurrences (TE). The first event is in the diagram's left corner, followed by related segment events on the right side. Then, from the starting event to the first event, a lateral line may be written. The lateral line's TE denotes success, while the system's lower end denotes failure. Similarly, the procedure is repeated until the event is completed.

In order to achieve the study's third goal, an event diagram for the probable effects of the prospective modification must be constructed in this stage. The implications of a prospective change are projected depend on the maritime expert's skill and experience, and several change scenarios (CSs) (i.e. event tree routes) are generated. When the results of the change event are obtained, which are frequently the influence of change on schedule, expense, and quality targets, the event tree assessment is almost over. The event tree's newly established structure aids in understanding the repercussions of change implementation and how it might contribute to delays, cost overruns, and quality deterioration. In the initial circumstance of failures resulting in self-heating/ignition, the ET graphic illustrates four intermediary events. (Table 20).

Table 20: Barriers for ETA

E1	Failure of Gas Detector	Fixed gas detection system sensors on dry bulk carriers must be inside the tolerances established by the manufacturer approved by class and must pass subsequent calibration checks. Thus, the Co2 flooding system is the most often utilized technology for combating fires in cargo compartments of conventional cargo ships. A monitoring system (smoke, flame, and heat detectors) and a security system, as well as Co2 cylinders, make up the Co2 system.
E2	Failure of Awareness	Situational awareness entails the following: having an excellent sense of your environment at all times, grasping what's going on around you, and correctly projecting how this will impact your vessel Situational awareness refers to being aware of what is going on around you and what is probable to occur.
E3	Failure of Cooling	Cooling system against self-heating and/or fire due to Cargo based in dry bulk carrier consists of cooling like sea water or fresh water and chokedamp gases. For example A continuous installation used to evacuate oxygen from the defined area and put out flames in engine rooms, boiler rooms, pump rooms, and cargo compartments. Generally, the unit composed of a succession of huge CO2 cylinders.
E4	Failure of Extinguished	When a fire occurs on board a ship, there is no fire department on hand to help put it out; it is entirely depended on to the crew to do it themselves. The results may be disastrous, and everyone who has worked aboard a ship knows how difficult it is to control a fire and how critical it is to prevent one. Furthermore, any accidents or events involving coal cargo arising from ships may generate in significant costs for the shipping company and P&I clubs of the vessels, as well as total loss.

Source: Created by the author

In this thesis, within seven outcomes, the methods employed in battling following self-heating/ignition on board are investigated. The ETA system, on the other hand, aids in tracking the effects of change and how they might lead to unintended consequences. To accomplish this, the ETA's ramifications are decided by a consensus of maritime experts. (Table 21)

Table 21: Shows the Outcomes of ETA

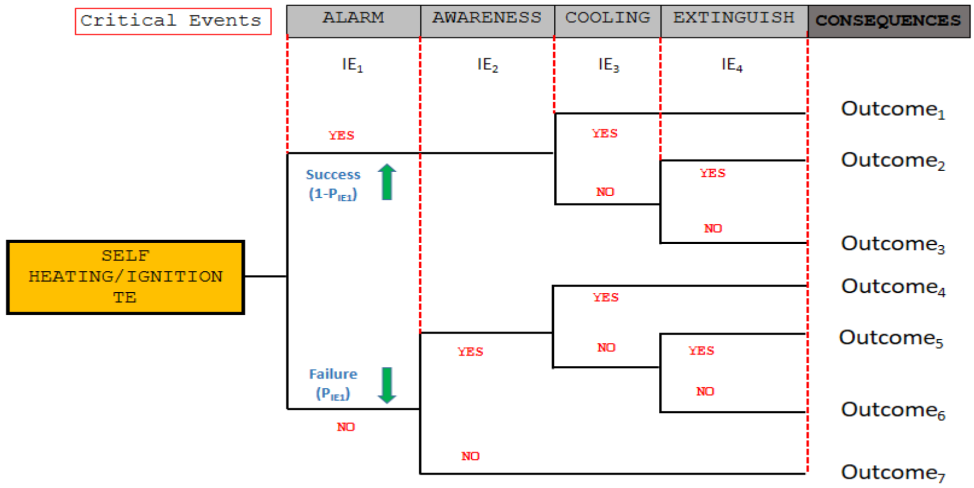
Event	Outcomes
O1	NEAR MISS & INCIDENT
O2	CARGO & LIMITED DAMAGED
O3	DAMAGED TO HULL & LOSS OF LIFE
O4	NEAR MISS & INCIDENT
O5	INCIDENT & FINANCIAL DAMAGE
O6	DAMAGED TO HULL & LOSS OF LIFE
O7	POLLUTION & TOTAL LOSS

Source: Created by the author

3.4.2.1.1. Constructing Event Tree Diagram

First, the IE was determined. The IE was considered as self heating/ignition accidents occurring loading, discharging and during carriage of Coal Cargo as bulk in Bulk Carriers. Thereafter, appropriate decreasion barriers to handle self heating/ignition accidents in dry bulk carrier with the least damage were selected and an ET diagram was built under the guidance of six maritime experts, with the beginning event being self-heating/ignition during the shipment of coal cargoes.

Figure 17: ET Diagram for Self-heating/Ignition with Probabilities and Relevant Outcomes



Source: Created by author

3.4.2.2. Applying Quantitative Fuzzy ETA

In this thesis, a detailed risk analysis was carried out to determine the functionality of the designated barriers to fight self heating/ignition that may occur in the bulk carriers of 500 GRT and above.

The probability of a path is evaluated using quantitative method of an event tree by combining the likelihood of occurrence of all the PEs situated in that path (Hong et al. 2009). The probability of occurrence of the initial event (PE0) is essential to measure an event tree. The likelihood of PE0 may be calculated by combining the ETA with the FTA approach. Furthermore, The Experts' language evaluations were used to compute the likelihood of each result.

In addition, Maritime experts' linguistic assessments of each barrier's priority show in Table 22. On the Event Tree, Table 22 indicates the language assessment of each result.

Table 22: Linguistic Evaluations of The Maritime Experts for Priorities of Each Barrier

	M.Exp 1	M.Exp 2	M.Exp 3	M.Exp 4	M.Exp 5	M.Exp 6
E 1	VL	ML	L	L	VL	L
E 2	ML	M	L	ML	M	M
E 3	MH	MH	M	ML	M	ML
E 4	VH	H	MH	MH	H	MH
L: Low, VL: Very low, ML: Medium low						

Source: Created by the author

Defuzzy possibilities for each barriers were defined Table 23.

Table 23: Aggregated Expert Judgments and Defuzzified Failure Possibilities for Each Barrier

Barriers	Aggregated Expert judgements on failures				Defuzzified possibility
B1	0.079	0.143	0.193	0.293	0.179
B2	0.288	0.388	0.423	0.523	0.405
B3	0.366	0.466	0.531	0.631	0.498
B4	0.618	0.718	0.783	0.867	0.746

Source: Created by the author

Table 24: Aggregated Expert Judgments and Defuzzified Failure Probabilities for Es.

Barrier	Failure probabilities	Barrier	Failure probabilities
E 1	0.000149527	E 3	0.004934467
E 2	0.00243127	E 4	0.024686087

Source: Created by the author using the center of gravity approach utilizing defuzzing method formulas Sugeno (1999)

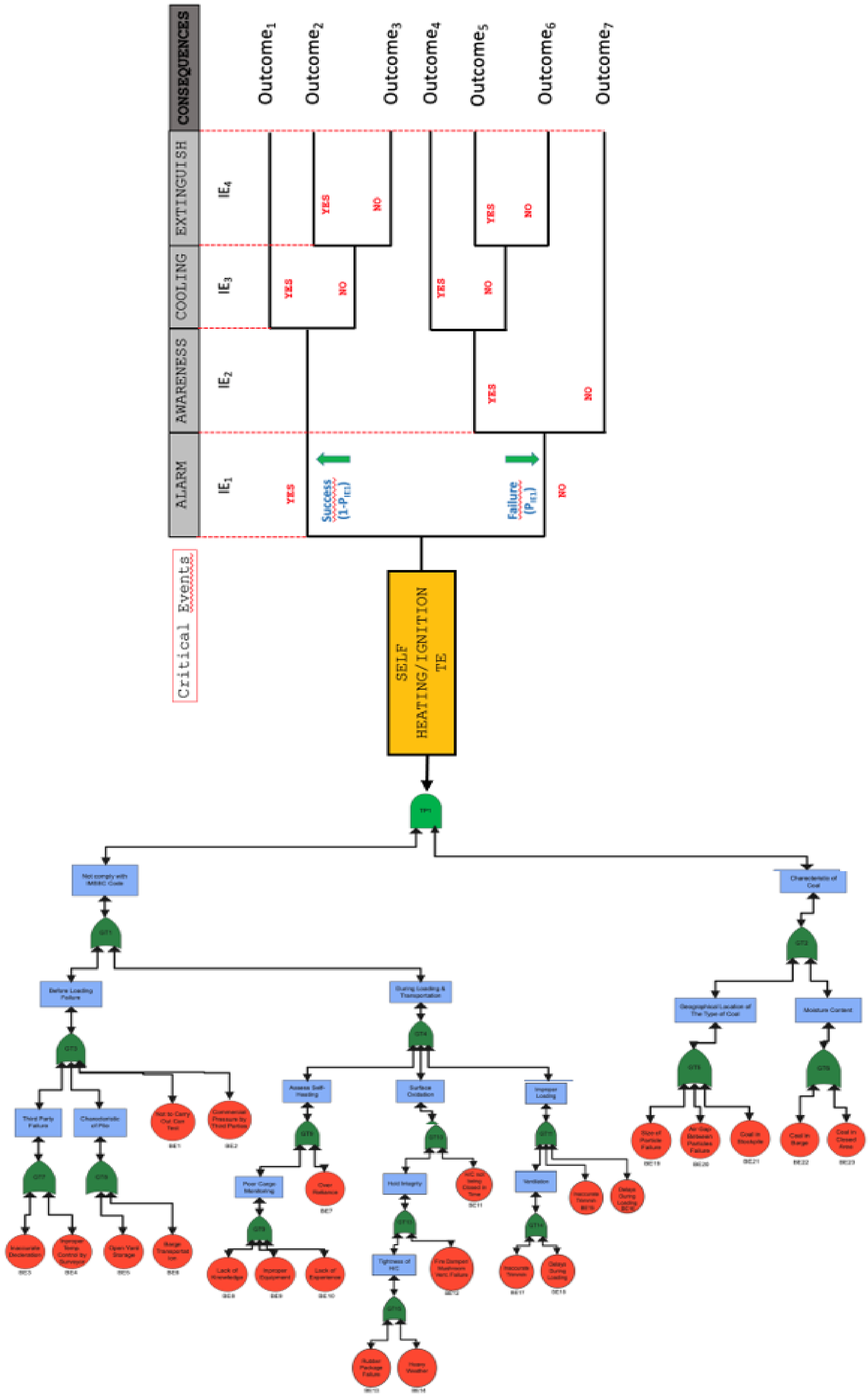
Table 25: Failure Probabilities for Each Barriers and Outcomes

Barriers	Probabilities obtained from possibilities	Outcomes	Calculated probabilities for each outcomes
B_1	0.00015	O1	2,302E-02
B_2	0.002431	O2	1,136E-04
B_3	0.004934	O3	2,818E-06
B_4	0.024686	O4	3,435E-06
		O5	4,205E-10
		O6	4,205E-10
		O7	8,412E-09

Source: Created by the author

The bow-tie diagrams, as well as the likelihood of each result, are shown in Figure 18.

Figure 88: Bow-tie diagram



Source: Created by author

CONCLUSIONS

The chance of self-heating/ignition (TE of the problem) during the loading, unloading, and transportation of coal cargoes was calculated to be 2.31E-02 as a consequence of the examination of the fuzzy fault tree. The results indicate that a self-heating/ignition accident in a coal shipment offers a significant danger. BEs with the highest failure chance can be deleted to lessen the risk. Expert opinions show that BE3, BE21, BE17, BE20, and BE10 have the most impact on the TE.

The probability of the top event occurring (self-heating/ignition) is assessed as 2,31E-02 (0,02314) based on detailed risk study on self-heating/ignition during loading, unloading, and transportation of coal cargo in dry bulk carriers. It indicates that in 2 out of 100 scenarios (Coal Cargo Shipments), self-heating/ignition failure may cause an accident. The TE's probability verifies that there is a significant danger of self-heating/ignition in dry bulk cargo loading, unloading, and transportation.

The study begins with basic circumstances that might also trigger TE to develop for the purpose of undertaking a complete examination. According to the data, the BE3 (Inaccurate Decleration)has a significant impact on the TE. BE21 (Coal in Stockpile), BE17 (Improper Ventilation), BE20 (Air Gap Between Particles Failure) and BE10 (Lack of Experience) respectively. MCSs are therefore important points that influence the TE's likelihood of failure.

The BE3 (Occurrence probability of 8,19E-01), The most crucial event/failure initiating self-heating/ignition in dry bulk cargo carriers seems to be inaccurate coal cargo declaration prior to loading. Shippers and coal exporting countries are anxious to sell more coal, get more currency input, and enhance revenues, which leads to inaccurate coal cargo declarations. They are, however, completely unconscious of the risk of self-heating and igniting that their flawed thinking has produced. The IMSBC Code and SOLAS 74, Chp. VI require that the Shipper Declaration for coal cargoes be declared and presented to the Master of the vessel prior to loading. In order to prevent cargo failure due to incorrect declaration, not only should the master be familiar with Group A and B coal kinds and should ensure that accurate cargo records are received before shipment, but the harbour master should also provide and submit a mandatory certificate referencing coal cargo parameters of coal cargoes, as well as the criteria for transporting self-heating group B coal shipments.

The IMSBC Code additionally requires the shipper to ensure the Master with information on the coal cargo, as well as proposed safe loading and transport methods. This papers should at the very least comprise the cargo's contract moisture, sulphur, and size criteria. It is necessary to consider the cargo declaration, bearing in mind that it may be erroneous. All coal cargo shipments should be regarded as potentially harmful until otherwise verified (in particular, as being prone to self-heating).

In this situation, inspecting or evaluating the cargo's qualities in accordance with the Shipper Declaration is exceedingly difficult for the ship's Master. To avoid an inaccurate cargo declaration, the shipowner should nominate an independent surveyor or P&I club for the coal cargo before the loading procedure (when the cargo is at the port or in the barge). Samples of loaded coal ought to be getting from various areas on the cargo pile, such as the bottom, corner, surface, and so on, at the port or on the barge, before the procedure begins. It's also worth mentioning that no over than 7 days before loading, tests should be obtained.

The second most serious failure that may lead to self-heating/ignition is the BE21 (Occurrence probability 7,00E-01), Stockpiled coal in the light of moisture content of the coal's characteristic. The coal shipments from the stockpile are prone to spontaneous heating. Because Coal is a prone to oxidation material. As a result, at stockpile temperature, the stored coal interacts with the oxygen in the air, and the oxygen is physically bonded to the coal. Oxidation is an exothermic process. As a result, the temperature of the coal pile rises in full agreement with the oxidation process. If the heat that has collected at various spots in the pie cannot be transmitted to the atmosphere, the temperature rises and the coal burns.

Self-heating and igniting of stacked coal is a long-standing thermal dynamic hazard that is probable to happen during transport, processing, and storage under favorable conditions. Furthermore, coal will be more hazardous during transportation and after loading into the ship since it is prone to self-heating and igniting. In most cases, the shipper is responsible for loading the coal cargo to the vessel in good and safe condition.

As a conclusion, the actions that should be taken by master or nominated surveyor to minimize or at least reduce this risk are described follow. The stockpile's coal particle sizes should be as close together as possible. The degree of oxidation is one of the security precautions that must be considered. The coal absorbs oxygen from the air and its reductivity reduces if the deposited layer is left for a long time before a fresh layer is set on top of it.

The BE17 (Occurrence probability 6,79E-01), Improper Ventilation: According to the IMSBC Code, the gas monitor used to carry coal must be connected to at least oxygen (O2), flammable gas (LEL) (with an alarm set to a %age of the lower explosive limit of methane), and carbon monoxide (CO) sensors.

The fundamental guideline for coal cargo ventilation management is that if there is a self-heating/ignition hazard, the cargo ought not to be vented (to reduce oxygen availability), but it should be ventilated if there is an explosion threat (to block the accumulation of methane). If there is no signs of self-heating or methane emission, or unless specified explicitly in the IMSBC Code, for the first 24 hours after leaving the loading port, the holds must be surface circulated. Throughout this period, the gas in the cargo compartment headspace should be evaluated once per test point per cargo compartment, which will need turning off the circulation for a period of time.

Even if methane (CH_4) concentrations are above a manageable level, coal shipments ought not to be vented further after the previous 24-hour period unless absolutely essential. By delivering oxygen, unnecessary ventilation can either commence or enhance a self-heating process. Ventilation should be stopped and monitoring should continue if the CH_4 level is less than 20 % of the Lower Explosion Limit (LEL). Continuous circulation should only be cappraised if the CH_4 concentrations have not reduced to an acceptable level, and only for as long as it takes to remove the stored methane.

In addition, when each cargo hold has been loaded, the hatches should be secured as quickly as possible. With enough sealing tape, the hatch coverings might also be sealed. Surface air circulation should be confined to the shortest time possible to eliminate any methane that has been generated. The use of proper ventilation is not recommended. Air should not be directed into the coal's body under any circumstances, since this may promote self-heating. The master must ensure that any emissions created by the materials do not collect in closed enclosed spaces as much as possible. Enclosed working places, such as store rooms, carpenter's shops, passage ways, and tunnels, must also be examined for methane, oxygen, and carbon monoxide on a regular basis by the Chief Officer and/or Master. This space needs to be adequately ventilated.

Only considering ventilation if the LEL levels begin to climb, and only for as long as it takes to eliminate any collected methane. According to the IMSBC Code, if LEL levels reach 20 % or more, ventilation shall be maintained at all times (except for the purpose of gas monitoring). Expert assistance should be sought promptly if the LEL level keeps increasing after 24 hours of continuous ventilation or if CO levels begin to rise.

If excessive levels of CH_4 are discovered in unventilated cargo spaces, for example, the IMSBC Code's Special Precautions for coals generating methane must be implemented. If the CH_4 level reaches 20 % of the LEL or above after 24 hour period of considerable freshening the Cargo compartments, ventilation should be continued. Wherever feasible, avoid introducing air into the coal's body, as this might boost self-heating.

The master must use all reasonable efforts to avoid any gases generated by the coal transport from gathering in nearby restricted spaces. Carbon monoxide (CO) levels more than 50 ppm (or increasing over three days) indicate that the cargo is self-heating, and the hold ventilation system ought to be switched off and the vent ports closed. Before entering any areas near cargo compartments, the atmosphere must be examined. Special measures for self-heating coals indicated in the IMSBC Code should be observed. When self-heating is discovered, this provides a list of details that should be notified to the shipper and the authorized Parties' shore based office. Finally, Section 5 of the IMSBC Code's Special Precautions for Self-Heating Coals outlines the minimum information that must be provided.

The BE10 (Occurrence probability 5,97E-01), Lack of Experience: The crew must consider the characteristics and special characteristics of the material being delivered. "On board, suitable equipment must be available to measure important influencing elements such as cargo and ambient temperature, relative humidity and dew point within and outside the hold, and sea temperature," Vandenborn emphasizes. "These readings should be performed on a frequent basis during the journey to estimate how they will affect the environment inside the cargo holds." All readings, events, and measures relating to the cargo and its condition should be kept in order to give a continuous record in the event that any concerns arise after the ship arrives at its destination."

The master and officers must be aware of the coal cargo's moisture limit as well as the cargo's moisture content, and the master should have no reservations about the cargo's TML. The temperature and gas levels of the coal cargo in all holds, including oxygen, sulphur, and methane, must also be monitored on a regular basis by the seafarer's on board. In addition, the Master of the Ship assures that the vessel's master has appropriate coal cargo shipment expertise and experience in all eventualities on board.

The first three MCSs with the greatest V-FIM values were identified using V-FIM analysis. For the MCS composing of $BE_{17}*BE_{20}$, the maximum V-FIM value was found to be (0,00163457). This means that the MCS consisting of $BE_{17}*BE_{20}$ improves the probability of the TE occurring by about 0.17 %. Secondly, for the MCS consisting of $BE_{2}*BE_{20}$, this value was obtained to be (0,00126517). This figure suggests that this MCS contributes about 0.12 % of the time to the occurrence of the TE. The MCS comprised of $BE_{17}*BE_{21}$ had the third highest V-FIM value (0,00118542). This implies that the impact of this MCS on the occurrence of the TE is around 0.12 %. In addition, the MCS comprised of $BE_{17}*BE_{19}$ had fourth highest V-FIM value (0,00098757) and mentiones that the impact of this MCS on the occurence of the TE is 0,09 % and lastly $BE_{2}*BE_{21}$ had fifth highest V-FIM value (0,00091753), respectively.

The failure of the extinguished system (P(B4): 0,024686) was found to have the highest likelihood of failure after the risk evaluation of the barriers developed in this study was completed. In this regard, technical investigations into the factors that may generate the outage of the falilure of extinguished, with the highest probability of failure, should be conducted in order to better combat potential self-heating/ignition in coal carriers. It is well understood that smoke and heat sensors should run in lockstep, and that fire detection and alarm systems should be operational to prevent self-heating/ignition.

The Failure of Cooling (P(B3): 0,004934) was determined to be the barrier with the second highest likelihood of failure. When the other barriers are taken into account, the likelihood of failure for Failure of Awareness (P(B2):1.63E-04) and Failure of Gas Detector (P(B1): 0,00015) accordingly ranges from highest to lowest. When all impediments are evaluated, the probability of failure is significantly small. However, given that self-heating/ignition in coal carriers is critical for ships and that self-heating/ignition accidents have a high potential to occur spontaneously, conducting appropriate technical inspections to further decrease the probability of failure of the barriers investigated in this study is obviously of the greatest priority.

As a outcomes, the near miss and incident (2,302E- 02) has the greatest likelihood in the case of a Gas Detector Failure that causes ships to fire and spontaneously combust due to self-heating/ignition, as shown in Table 23 (Failure probabilities for each barrier and outcome), which indicates the possible dangers of self-heating/ignition and occurrence probabilities. The second most likely scenario is a Coal Cargo ship Cargo & Limited Damaged (1,136E-04) due to self-heating/ignition, since the gas detector may cause the ship's cargo holds to burn and explode, but not to pollute or cause total loss.

Limitations: There isn't enough current academically published study on self-heating/ignition incidents or challenges in coal shipment by vessels or port operations. Because of commercial pressure, P&I insurance, and shipping company reputations, not much literature and accident statistics published in a risky section of the risk evaluation of coal cargo shipment in maritime transportation connected to self-heating/ignition could not be obtained, which is a significant drawback.

Due to a shortage of enough literature and data, expert views were employed during the data collection stage. Despite the fact that considerable concern was spent in obtaining and interviewing experts, human error may slip in during the examination of the possibilities. Regardless of the fact that the ship masters whose judgments were sought as experts have engaged in bulk cargo shipments in numerous locations throughout the world with ships of varied tonnages, the study's second limitation is that all of the experts were Turkish ship masters. Because experts were picked from a variety of cultures, it may have been possible to explore the factors in multiple dimensions at this point.

During the risk evaluation, the bow-tie construction is examined on a ship carrying bulk coal with the collaboration of the crew of the ship, and the outcomes are obtained after the operation. This could allow for the detection and correction of network structural issues. However, such an implementation could not be conducted out because there was no vessel capable of transporting coal cargo shipments at the time the research was produced.

Future Research: It's critical to check the structure's accuracy by installing the bow-tie construction on coal-carrying bulk carriers or a vessel that will perform loading and unloading operations and evaluating the outcomes. Furthermore, by creating and executing an online version of this network structure using a broad-band internet connection, which is widely utilized in shipping companies and ships, and emerging technologies, evaluations can be conducted dynamically to prevent potential self-heating/ignition in coal cargo shipments.

Bow-tie assessment on a data set might be undertaken in the future if enough accident files or coal shipment data become available, and the results of these two studies compared. As a result, any human errors that may arise as a result of the expert opinion used in this study's data collection approach are eliminated. Furthermore, the findings of the current study can be evaluated to the findings of the current study by re-evaluating the findings with a larger sample size in the future, which includes not only Turkish but also international ship masters as experts. The findings could be conducted by seafarers, shipping companies, superintendents and safety inspectors, and other maritime experts to prevent similar disasters and maintain safe coal cargo operations.

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APPENDIX

APPENDIX 1: Semi-Structured Interwiev Form

SEMI-STRUCTURED INTERWIEV FORM

Profile Attanded Survey:

Name – Surname	
Age	
Competency	
University / School	
Years Maritime Experienced	
Years Maritime Experienced as a Master on Bulk Carriers	
Shore-based Service Time	
What is the name of the Shipping company are you working ?	
What is your position in your shipping company ?	
How many years have you worked for this position ?	

INTERWIEV QUESTIONS for FTA

1. Please indicate the threats that you think are the most dangerous operation and events during coal transportation and coal activities on bulk carriers?
2. What are the possible reasons of self-heating/ignition on bulk carriers during coal operations?
3. What are the causes of hold ventilation in bulk carrier self-heating/ignition accidents during coal operations?
4. What are the possible causes of self-heating/ignition incidents that occur in coal operations on bulk carriers involving ship crew?
5. What are the possible causes of self-heating/ignition incidents that occur in coal operations on bulk carriers as a result of the coal's geography and structure?
6. What are the causes of the ship's constructual features in self-heating/ignition accidents on bulk carriers carrying coal**?**