Thesis for the Degree of Doctor of Philosophy

Investigation of the Influences of Human Error Factor in Maritime Transportation

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Abstract

Marine transport has a vital role in people and cargo transport across the world, where, more than 90% of the world's cargo transports by merchant ships. Marine transport industry is considered one of the huge and high-risk industries. This clarify why safety is one of the imperatives of the maritime industry and which highly affect the success and efficient exist of this industry. Therefore, reducing the associate risks and improving maritime safety are of the essential requirements for main marine transport industry.

There are many parameters contributing into improving maritime safety and reducing the associate risks of accidents. Efforts are presented and attention is given by shipping industry toward that. This is mainly by focusing in safety regulations, improving ship's structural design and construction methodologies and techniques and by improving ship's systems operation and reliability. Accordingly, improvements in ship's hull design, building processes and methodologies; utilization of advanced technologies and equipment and improving ships legislation and regulations have been clearly noticed. Instead of that, the maritime casualty rate and accidents are still high. This is because ship structure and system reliability are a relatively small part of the safety equation. Where, ship safety is highly affected by human actions as the majority of maritime accidents are consequences of human error. Meanwhile, human factors have the largest share in marine accidents, where, more than 80% of marine accidents have been caused by human error. Therefore, human error is one of the most important issues

concerning global maritime communities and it is one of the important factors in the assessment of maritime accidents.

Several studies are conducted to assess the contribution of human factors in maritime accidents in order to reduce the overall number of marine accidents. The study of human behavior in the field of marine activities is challenging task due to the difficulties, expenses, and time-consuming factors. Moreover, there is lack of information on the role of human in marine accidents.

This study aiming at presenting the effect of human errors in the overall maritime safety. This is through analyzing 98 of ships accidents happened during 2014-2017 to investigate the main parameters contributing in these accidents, identify human error related causes and estimate the overall contribution of the human error causes to the occurrence of these accidents. The results of the analysis indicated that 75% of the causes of the registered accidents were due to human error.

In order to provide details about the contribution of the human error to the overall ship accidents causes, analysis to the reported accidents by European Marine Casualty Information Platform from 2011-2017 for cargo ships, fishing vessels, passenger ships and service ships. The results of survey indicated high contribution of human error to the causes of ships accidents, where it represents:

- 62.2% of the total of 156 accidental events analyzed of service ships
- 60.8% of the total of 781 accidental events analyzed of cargo ships
- 54.4% of the total of 338 accidental events analyzed of fishing vessels
- 51.4% of the total of 319 accidental events analyzed of passenger ships

Moreover, a detailed analysis of a collision case study between Kuwaiti oil tanker “Kaifan” and cargo ship “Unison Star” collided at Chittagong - Bangladesh anchorage area (2017). The analysis of the collision case study conducted using step-by-step events evaluation technique and a systematic process for accident investigation based on comprehensive and multi linear description of events sequences using STEP methodology to investigate rout causes of the collision and identify the contribution of human error causes. The results of investigation clearly prove the contribution of human error as a main factor led to collision.

In addition, this thesis investigates collision avoidance procedures, which use a dedicated negotiation and communication system to optimize locally found trajectories according to a global performance measure. This is by introducing, discussing and analyzing of three ship collisions avoidance algorithms based on multiple-ship situations, which are the Distributed Local Search Algorithm (DLSA), the Distributed Tabu Search Algorithm (DTSA) and the Distributed Stochastic Search Algorithm (DSSA) Furthermore, in experimental results, compared to DLSA and DTSA, DSSA produced good results, such as decreasing the number of messages. Therefore, DSSA enables ships to exchange significantly fewer messages than DLSA and DTSA then I developed a mathematical algorithm for the risk assessment and collision avoidance and calculating collision risk index and present a criteria to be applied and present the MATLAB code which used to calculate collision risk index.

Finally, the thesis ended by detailed conclusions, remarks and recommendations to improve maritime safety and improving human factor by eliminating the concerned associated errors.

Nomenclature

$	Dollar Sign
%	Percent
!	Examination Mark
t_{start}	Start Time
t_{end}	End Time
m	Meter
^{o}	Degree
j	Neighboring Ship
crs	Candidate Course
self	Home Ship
α	Weight Factor
θ	Relative Degree
△	Largest Improvement
V	Course Giving the Largest Improvement
T	Estimated Position in a Specific Time
DoR	Distance to Recognized Neighboring Ships
D	Distance must be Maintained
ID	Identification given at an Initial State
x_o, y_o	The Geographic Coordinates of the Ship
$\emptyset_o$	Direction of Ship
v_R	Relative Speed
R	Relative Distance
U_{DCPA}	The Functional Function of DCPA
K	Speed Factor
d_1	The Minimum Safe Pass Distance
d_2	The Safe Encounter

Abbreviations

UK:	United Kingdom
P&I:	Protection and Indemnity
KOTC:	Kuwait Oil Tanker Company
AGCS:	Allianz Global Corporate and Specialty
IMO:	International Maritime Organization
FTA:	Fault Tree Analysis
STEP:	Sequential Timed Events Plotting
ETA:	Event Tree Analysis
PRA:	Probabilistic Risk Analysis
MMD:	Man-Made Disasters Theory
SOP:	Standard Operating Procedure
STAMP:	Systems-Theoretic Accident Modelling and Processes Model
DNV:	Dot Norsk Virits
KPC:	Kuwait Petroleum Corporation
OE:	Operator Error
N:	Negligence
PPE:	Personal Protected Equipment Related
STF:	Slips, Trips, Falls
TPF:	Third Party Fault
PF:	Procedure Failure
BW:	Bad Weather
E/MF:	Equipment/Material Failure
TSB:	Transportation Safety Board
EMCIP:	European Marine Casualty Information Platform
CR:	Collision Risk
TCPA:	Time to Closest Point of Approach
DLSA:	Distributed Local Search Algorithm
DTSA:	Distributed Tabu Search Algorithm
DSSA:	Distributed Stochastic Search Algorithm

QLM: Quasi-Local Minimum

ARPA: Automatic Radar Plotting Aid

AIS: Automatic Identification System

VCD: Variation of Compass Degree

TCPA: Time to the Closest Point of Approach

DCPA: Distance to the Closest Point of Approach

GA: General Algorithm

LSA: Local Search Algorithm

SDA: Ship Safe Distance of approach

CRI: Collision-Risk Index

DLA: Distance for Latest Actions

Chapter 1 Introduction

1.1 Research Motivation and Problem Identification

Marine transport has a vital role in people and cargo transport across the world as the ship is a watercraft to transport passenger or cargo from one to another, she has long been used throughout the world. Marine transport industry is considered one of the huge and high-risk industries. There are many kinds of ships depending on the purpose, such as bulk carrier, tanker, container, LNG (liquefied natural gas), and submarine. As vital transportation carriers in trade, ships have the advantage of stability, economy, and bulk capacity over airplanes, trucks, and trains so more than 90% of the world's cargo transports by merchant ships. Even so, their loss and cost due to accidents exceed those of any other mode of transportation. The size and speed of ships is rapidly increasing in order to boost economic efficiency. However, navigation technology has been developing year after year. This clarify why safety is one of the imperatives of the maritime industry and which highly affect the success and efficient exist of this industry. Therefore, reducing the associate risks and improving maritime safety are of the essential requirements for main marine transport industry [1].

The issue of marine safety should be regarded as the key priority concerning the planning and practice of maritime transport procedures, in a worldwide scale. Since the vast majority of world trade is being conducted through sea-borne ways, maritime safety should be viewed as a factor that needs extreme caution, detailed planning, self-commitment and obligatory enforcement. The term marine safety has a multi-fold content, with a serious impact on numerous aspects of the maritime transport chain; more specifically, it involves the aversion of human losses and injuries, the preservation of marine and coastal environment and the protection of vessels and their cargoes. Hence, safety topics are not to be simply pinpointed and addressed in the aftermath of a significant, or a mass media-adduced, naval accident. On the contrary, these matters should be dealt proactively, in order to provide for an efficient, profit making and environment-friendly maritime transport network.

There are several causes that can rupture the aforementioned transport chain, with undesired consequences. This can be resulted from unsolved mechanical or electrical problems, hazardous external conditions (such as severe weather), poor human factor behavior or performance (e.g. inadequate bridge resource management), accidental events (like an unpredictable hull problem) etc.

Meanwhile, human factors have the largest share in marine accidents, where, more than 80% of marine accidents have been caused by human error. However, it is a fact that human element is the basic and by far the most frequent reason that leads towards marine accidents [2]. Each involved player (e.g. crew, shore management, classification societies etc.) has been recorded as the responsible component for numerous verified mishaps, which could have been averted under different circumstances. An individual can follow the procedure precisely and still perform a human error, because the individual does not perform as desired (i.e., there is a gap between actual and desired performance). In this situation, the procedure specifies the incorrect method for performing the task. Thus, the correct way to respond to casualties and exploit its knowledge potential is to analyze the "mistakes" (mainly human errors) that caused them and assay to prevent them from appearing ever again. This thesis aims at presenting the effect of human errors in the overall maritime safety, presenting the contribution percentage of human errors in marine accidents, analyzing a ship accident case study to know the effect of human error factor and finally make a comparative analysis between ship collision avoidance algorithms.

1.2 Ship Accident Types

A shipping accident could be defined as "a usually sudden event or change, occurring without intent or volition through carelessness, unawareness, ignorance, or combination of causes and producing an unfortunate result". Any shipping accident, whatever in nature, is an unfortunate event. Should it occur in a confined area, like a channel or a strait where the traffic is heavy, several as well as serious risks are likely to be faced.

On the other hand, ships accident is a term generally used for any accident results in financial loss, either in life and/or property or both [3]. There are many classification methods for ships accidents. In general, ships accidents are classified based on the type of accidents to:

[1] Collision or Contact.

Collision is a casualty caused by ships striking or being struck by another ship, regardless of whether the ships are underway, anchored or moored. This type of casualty event does not include ships striking underwater wrecks. The collision can be with other ship or with multiple ships or ship not underway.

Contact *i*s a casualty caused by ships striking or being struck by an external object. The objects can be:

- Floating object such as cargo, ice, other or unknown.
- Fixed object, but not the sea bottom; or Flying object.

[2] Capsize. Capsizing or keeling over occurs when a ship is turned on its side or it is upside down in the water. The act of reversing a capsized vessel is called righting.

[3] Foundering. Foundering is considered when the vessel has sunk. Foundering should only be regarded as the first casualty event if the details of the flooding, which caused the vessel to founder are not known.

[4] Grounding and Stranding occur when a moving navigating ship, either under command, under power, or not under command, drifting, striking the sea bottom, shore or underwater wrecks. Grounding may result in certain disadvantages such as damages to ships and environmental damages and even sinking.

[5] Fire or Explosion is due to an uncontrolled ignition of flammable chemicals and other materials on board of a ship.

1.3 Human Error Definition

Despite great breakthroughs in marine industry technology and safety regulations, the marine industry experienced serious accidents and still suffering from accidents and increasing number of causalities. This is mainly because the focus of shipping industry in improving maritime safety has been mainly focused in improving ship's structural design and construction and the reliability of ship's operating systems with less attention to the main factor of safety, which is the human element [4]. Thus, the fact that International Maritime Organization (IMO) is responding accordingly with effective design practices, standards and associated management systems, the maritime safety remains a concern. As indicated in Figure (1-1), "The maritime system is a people system and human errors figure prominently in casualty situations"

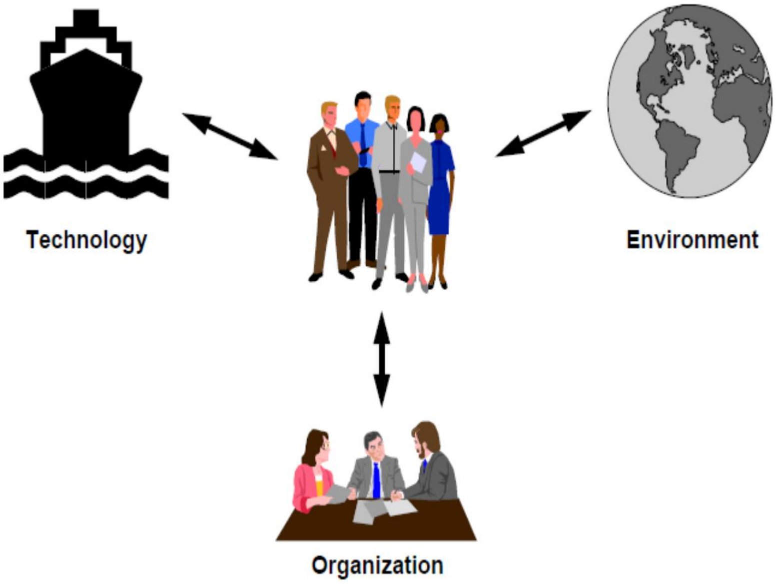


Figure 1-1: The Maritime System "Is a People System"

The terms human error defined as referring to the cause of an accident, which happened because of people, an individual or organization, as opposed to because of a technical fault [4].

Human error is a general term which covers a variety of unsafe acts, omissions, behaviors and unsafe conditions or a combination of these in which the individual should have had acted in a different manner [4].

1.4 Research Questions

The main research question of this thesis could be phrased as:

1. What are the causes of marine accidents, which have resulted in damages?
In order to attain a significant and reliable answer, this thesis is supported by a database containing all reported incidents that have taken place during 2014-2017 to 30 different ships types owned to Kuwait Oil Tanker Company "KOTC" and providing a detailed analysis to operational registered maritime accidents from 2011-2016 reported by the European Marine Casualty Information Platform (EMCIP) as discussed in Chapter 3.

Once the information has been filtered to match the thesis requirements, it can be used to answer the secondary research questions, which are the following:

2. What are the main contributors to the occurrence of ship accidents?

3. To what proportion are human error factors cause marine accident?
As mentioned before, these research questions will be investigated by analyzing the existing database as presented in Chapter 3.

4. How could engineer investigate the marine accident causes and describe the accident by a comprehensive analysis method?
In order to attain a significant and reliable answer, this thesis is supported by a collision accident case study between Oil Tanker "Kiafan" and Bulk Carrier "Unison Star" in Chittagong – Bangladesh so I analyze the accident and investigate the causes in Chapter 4.

5. What are the possible algorithms that could be used to predict collision accident?

In order to attain a significant and reliable answer, this thesis is supported by multiple scenarios for ship collision conditions by using distributed ships collision avoidance algorithms to reduce the ship collision risk and developed a mathematical algorithm for the risk assessment and collision avoidance as discussed in Chapter 5.

1.5 Aim and Objectives

The aim of this research is to investigate detailed analysis and information about the influences of human error factor in overall marine transportation safety. This aim was achieved through the following set objectives:

- Detailed analysis and investigation of Human Error Factor influences in Maritime Transportation Safety.
- Analysis and detailed evaluate of ships accidents surveys as an overall case study to show the main contributors to the occurrence of ship accidents.
- Evaluation the overall contribution of human error to the ship accidents which selected to be a case study for research.
- Step-by-Step detailed analysis methodology for ship accident case study to present the effect of human error as a main cause of marine accidents.
- Propose a systematic process for accident investigation based on multi linear events sequences and a process view of the accident phenomena.
- Simulation and evaluation of multiple scenarios for ship collision conditions by using ships collision avoidance algorithms to reduce the ship collision risk and make comparative analysis between them.
- Develop a mathematical algorithm for the risk assessment and collision avoidance and calculating collision risk index.

1.6 Contribution

This research has made the following contribution to knowledge:

1) Investigation factors affecting human error, causations of human errors and presents different models used to analysis and investigate human error contribution to marine accidents.

2) Detailed statistical analysis and investigation of 98 ship accidents happened during 2014-2017 of 30 ships owned to Kuwait Oil Tanker Company "KOTC" to show the overall contribution of human error as a main cause of marine accidents.

3) Using step-by-step detailed analysis methodology to highlight the influences of human error factor in marine accidents.

4) Propose a systematic process for accident investigation based on comprehensive and multi linear description of events sequences.

5) Suggestion three types of ships collision avoidance distributed algorithms, such as Distributed Local Search Algorithm (DLSA), Distributed Tabu Search Algorithm (DTSA) and Distributed Stochastic Search Algorithm (DSSA), explaining variables and procedures for the proposed algorithm and enhance the idea by simulation results.

6) Comparative analysis between ships collision avoidance algorithms.

7) Development of the Distributed Algorithms and also suggest a new cost function that considers both safety and efficiency to find a safe course.

8) Develop a mathematical algorithm for the risk assessment and collision avoidance and calculating collision risk index and present a criteria to be applied.

9) Simulate the mathematical algorithm by using MATLAB code in Appendix (A) to calculate the collision risk index.

1.7 Thesis Structure

This thesis consists of six (6) chapters beginning with a general introduction and a conclusion. Each chapter begins with a background information or brief introduction. It is structured in such a way that every chapter build upon the previous one. Apart from the first and last chapter, concluding remarks were presented at the end of the chapters. Chapters 3 – 5 contain the contributions by the author.

Chapter 1 presents the motivation of this thesis; the answers of research questions; the aim and objective of the study and finally the perceived contribution to knowledge.

Chapter 2 presents the review of necessary literature upon which the study revolves around and the identification of the gap in knowledge which this study attempts to fill. The main areas of review are on studies which performed to investigate human error contribution to the overall maritime safety. Also, detailed analysis to the factors affecting human errors and control methodologies are included. Other areas reviewed in this chapter are several examples than can depict the significance of human factor in relation to safe maritime management, even from a high level point-of-view. Finally, an overview of the methods of investigation and analysis of accidents.

Chapter 3 presents detailed statistical analysis and investigation of 98 ship accidents happened during 2014-2017 of 30 ships owned to Kuwait Oil Tanker Company "KOTC". This is to identify the different causes led to ships accidents, identify human error causes and investigate the overall contribution of human error to the case study ships accidents. Moreover, this chapter presenting a systematic developed analysis of general ship registered accidents during 2010–2017 by European Maritime Safety Agency, in order to present the trend in ship collisions and the concerned effect and contribution of human error.

Chapter 4 presents Step-by-Step detailed analysis methodology for ship accident case study to identify the main causes of accident and the contribution of human error to that and propose a systematic process for accident investigation based on comprehensive and multi linear description of events sequences.

Chapter 5 aims at helping ships to find routes that will best enable them to avoid a collision. This is by presenting three of the developed ships collision avoidance algorithms, which were developed based on many-to-many ships situation. In this chapter, I explain the background of my work. Furthermore, I show how the Algorithms is applied to ship collision avoidance, show the reason of selection, explaining variables, procedures for the proposed algorithm, show simulation results and make Comparative analysis between the algorithms and develop a mathematical algorithm to calculate collision risk index.

Chapter 6 is the final chapter. It presents conclusions drawn from findings and results obtained in the entire thesis. Recommendations for further work are highlighted

Appendix (A) develop a mathematical algorithm to calculate collision risk index and present the application of mathematical simulation for collision avoidance which simulate five ships with different variables and calculate the collision risk index.

Chapter 2 Literature Review

2.1 Introduction

Maritime Accidents take place every day all over the world, and they often make the first page news when lives have been lost or environmental catastrophes are a result of the accident. Two clear examples of this have been the Titanic and the Exxon Valdez, and more recently the oil spill in the Gulf of Mexico due to the explosion of a drilling rig.

It is known that once such a regrettable event happens, many institutions are involved in the investigations. These investigations may start close to home, been carried out by the branch of a company or the company itself, or international institutions.

The main objective of investigating an accident is to determine its circumstances and the causes. This is done in order to improve the safety of life at sea and to avoid accidents to happen in the future.

Maritime Accidents may have other consequences besides the two previously mentioned. They can also result in injuries, asset damages, and if lucky, in near misses.

Although all of them are important, this chapter will focus on the accidents and analyzing the main causes of accidents and the contribution of human error.

The chapter opens with a set of research studies, outlining the causes of different types of ship accidents. It continues by quoting different sources that, outlining the contribution of human error to maritime accidents. Finally, an overview of the methods of investigation and analysis of accidents.

2.2 Investigation the Causes of Marine Accident

Several research studies conducted to investigate the causes of different types of ship accidents. Macrae (2009) [5]evaluated 30 maritime accident reported by the

Australian Transport Safety Bureau (ATSB) and concluded that human and organization related errors were the main causes tended to collisions and groundings. The study revealed that, in general, groundings were caused by passage plan errors, failure of position-fixing, or lack of communication among the bridge team, whereas collisions were caused by errors in determining the speed, or even presence, of another ship and errors in collision prevention plans.

Eliopoulou and Papanikolau (2007) have examined in detail the raw accident data which are at very severe accident level, as occurred in oil tankers over 80.000 deadweight tonnage (dwt), in the period between 1978 and 2003, and they have evaluated the accidents using statistical methods. Furthermore, the accidents causing oil pollution have been positioned throughout the world map, with the dimension of the pollution, a map of oil pollution caused by large oil tankers being formed [6].

Pillay et al. (2005) have examined marine accidents of fishing boats in the period between 1992 and 1999, putting forth the common factors causing accidents and the relation of accidents with the boat length [7].

Similar studies presented by Butt *et al.* [8] for the period 1997-2011 and by Allianz Global Corporate and Specialty (AGCS) for the period 2002-2013. The annual frequencies of total losses by these studies are presented in Figure (2-1).

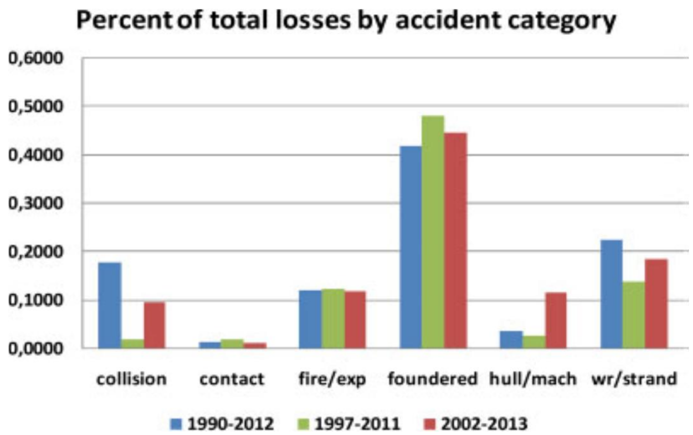


Figure 2-1: Total Losses by Accident Category for Different Periods

EMCIP addresses the accidental events and contributing factors having led to casualties and incidents for the 2011-2017 period. Figure (2-2) shows the distribution of accidental events, where, from a total of 1645 accidental events analyzed during the investigations, 57.8% were attributed to a Human Erroneous Action [9].

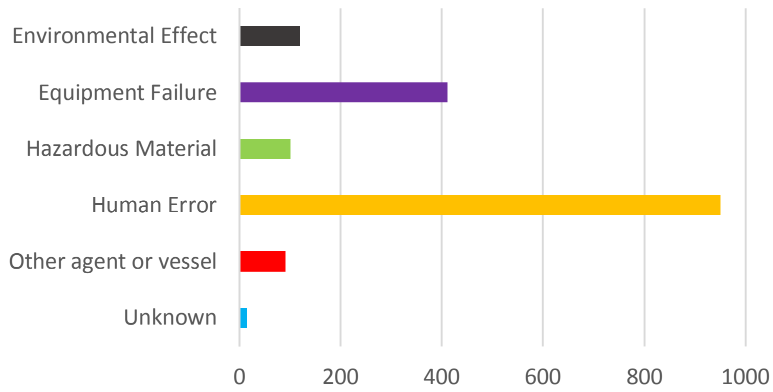


Figure 2-2: Distribution of Accidental Events for 2011-2017

Antoa and Soares (2006) [10]used formal safety assessment methodology of the International Maritime Organization (IMO) to determine the causes for collisions and groundings involving Ro-Pax ships. Their study concluded that failing to use navigational aids effectively, failures in maneuvering and system errors were common factors behind collisions. Mullai and Paulson (2011) [7]conducted a study in the registered accidents database of the Swedish Maritime Administration to investigate the main factors led to ships accidents. Their study concluded that the factors that cause ship accidents are categorized under eight main categories and 94 headings, including human error, technical, operational, managerial, organizational, and external factors. They also concluded that, 54% of the accidents that took place in the Baltic Sea were collisions and groundings, mainly caused by bad weather conditions and navigational hazards in regions with intense shipping.

As mentioned before, and in this particular case, maritime accidents may lead to injuries, property damages and, in the worst case, death. Throughout the years studies and statistics derived from reporting systems have identified the many factors that can cause accidents.

Mankabady (1987) [11], in his time, classified the possible causes into seven categories:

- Defects in the design, structure of the ship or failure of the machinery
- Nature of the cargo, fires, explosion and/or method of stowage
- Perils of the sea
- Sub-standard ships
- Working methods
- Human error
- War, sabotage and maritime fraud

The classification society Det Norske Verita´s (DNV), opted for codifying the causes into more detailed ones, where each division could be sub-divided into 10 or more causes. The main divisions are:

- Circumstances not related to the ship (11 sub-causes)
- Construction of the ship and location of equipment on board (9 sub-causes)
- Technical conditions concerning equipment on board (10 sub-causes)
- Conditions concerning use and design of equipment (5 sub-causes)
- Cargo, safeguarding and treatment of cargo and bunkers (7 sub-causes)
- Communication, organization, procedures and routines (19 sub-causes)
- Individual on board, situation judgment, reactions (16 sub-causes)

Psaraftis et al. [12] Concludes in its paper, that a broad sub-division like the one offered by the code list of DNV, does not guarantee an easy identification of the cause of the accident. Going into too much detailed resulted in having different codes describing the same accident and/or that it was needed more than one of the codes to properly describe the cause of the accident.

More recently and based on a legal background, The Online Lawyer Source (2010) [13] stated that the causes of maritime accidents could be categorized mainly as:

- Equipment malfunctions
- Extreme weather conditions
- Human error (negligence, recklessness, inexperience of crew or passengers)
- Intoxication of a vessels operator

2.2.1 Gained Points from Literature Review

The conclusion from the previous studies have shown that following are the main causes for maritime accidents:

- Human failure (lack of training, operational error, negligence)
- Mechanical failure (Lack of maintenance)
- Lack of communication
- Equipment failure
- Fault of design
- Unfavorable and external cause
- Lack of procedures or incomplete procedure implementation
- Operation in hostile waters
- Management failure

2.2.2 Human Errors Contribution on Maritime Accidents

The corresponding literature contains several examples that can depict the significance of human factor in relation to safe maritime industry, even from a high level point-of-view.

The case of the collision between the passenger vessel (*Noordam)* and the loaded bulk carrier (*Mount Ymitos)* could be considered as a typical example of documenting the involvement of human element in marine accidents [14]. This accident happened near the Southeast Pass in the Gulf of Mexico, and both vessels were moderately damaged. The human errors that were pinpointed by the corresponding investigation were, the failure of officers on the (*Noordam)* to maintain a vigilant watch, the preoccupation of (*Noordam)* bridge crew with arrival activities and a certain lack of communication betwixt the two ships.

Another similar example is the collision between the supply vessel (*Galveston)* and the Panamanian bulk carrier (*Atticos)* in the Lower Mississippi River near Venice, Louisiana [14]. This accident resulted into the rapid sinking of (*Galveston)* and the loss of three of its crewmembers. The detected human errors were the failure of the (*Galveston)* crew to maintain a proper lookout (either visually or by radar), the insufficient time to adapt to the darkness and the failure to establish a proper passing agreement.

Tzannatos (2010) [15] examined the maritime accidents of Greek ships during the pre-ISM (International Safety Management Code) and post-ISM periods. The study concluded that collisions and groundings involving Greek ships were closely associated with the shipmaster.

Papanikolaou et al. (2007) have carried out accident analysis in marine accidents in Aframax tankers (over 80.000 dwt) between 1978 and 2003, which caused environmental pollution and economical loss. The data related to the accidents have been obtained from Lloyd's Marine Information Services Ltd (LMIS) database. Such data have been obtained by International Association of Independent Tanker Owners (INTERTANKO). The data in the study have been evaluated by the expert team, a new data base, which is easier to evaluate in systematic sense, being constituted and the accidents have been graded. The fault tree and event tree programs being used, the occurrence of accidents resulting in economic loss and environmental pollution has been summarized and it has been observed that the accidents are highly related to human error. The study covers ships over 80.000 dwt [16]**.**

Martins and Maturana (2010), taking into account IMO's FSA (formal safety assessment) recommendations, have with numerical values analyzed the human error contribution to collision and grounding accidents in tankers at Brazilian coasts. This analysis was carried out in three stages: identification of the hazard, risk analysis, and risk control. A fault tree has been made up by utilizing the data on initial events that cause accidents, and occurrence of accidents has been summarized with numerical data, the necessary safety precautions being determined [17].

As per the Dutch study conducted on 1987 of 100 marine casualties [18].human error was found to contribute to **96** of the **100** accidents, where every human error that was made was determined to be a necessary condition for the accident. This clarify that accidents results as a consequences of human error and chain of accident events can be broken by eliminating the occurrence of human errors. Therefore, marine safety can be significantly improved by finding out methods to prevent or at least reduce the probability of human errors to be happened, where such errors will be noticed and corrected.

Antao and Soares (2006) have researched the possible hazards related to accidents which may arise from Ro-Ro and passenger ships (RoPax) and the role of human error in accidents. The study has focused on the relations of basic events which may result in accident. As a first step in accident analysis, FSA has been executed and the relation between accident-causing events as well as the relation of human error with the accident has been determined by means of the fault tree modelling. In this study, accident data regarding RoPax ships could not be reached, therefore, the accident data on passenger ships have been utilized and the continuous error rate in initial events has been assumed to be 0.0004 for human error and 0.0001 for mechanical error, and a fault tree being formed. At the end of the study, it has been found that as significant a rate as 90% can be attributed to human error in grounding and collision accidents [10].

Köse, Dinçer, and Durukanoğlu (1998) have explained systematic analyses of fishing boat accidents. Statistical data have been examined, the fault tree method being used in the determination of the importance of each factor. In this study, sinking of the ship has been selected as the main event and separated into sub-branches such as human error, structural error and shipping of fish on deck. As a result of the analysis, it has been manifested that human error is the main factor in accidents in fishing boats [19].

Baker and McCafferty [20] in their research also stated that from 1991 to 2000, 80% to 85% accidents involved human error and 50% out of it were initiated by human error whereas another 30% was because of human error where the human error from the other party initiated the accident sequence and the failure in performance led to the failure of avoiding the accident.

2.2.3 Gained Points from Literature Review of Human Error Contribution

Human error has a contribution in large number of maritime accidents and incidents. As in the aviation and other transportation modes, human error is at the root of most preventable casualties in the maritime field and around 70 to 95% of transportation crashes are, directly or indirectly, the result of human error. Studies have shown that human error contributes to:

- **84-88%** of tanker accidents.
- **79%** of towing vessel grounding.
- **89-96%** of collisions.
- **75%** of allisions.
- **75%** of fires and explosions.

As discussed above, human is the main root of marine incidents. Human error is a complicated terms where it involves many parameters. The effects of human error in marine incidents can be divided into two main categories, which are:

1) Human error, which have operational, legal, and knowledge□based errors
2) Human element, which consists of personal, group, and organizational factors

Human factors deal with the followings parameters [21]: Manpower, Organization management, Allocation of responsibility, Automation, Communication, Skills, Training, Health, Safety, Prevention of errors or accidents and design and layout of equipment and workplaces. The main parameters of human factors are safety, efficiency and comfort.

On the other hand, human error is defined as a result of observable behavior originated from psychological processes on different levels such as, perception, attention, memory, thinking, problem solving, decision making, evaluated against some performance standards, initiated by an event in a situation where it was possible to act in another way considered to be right in order not to cause an accident [22]. Also, human error is described as being one of the following:

- An incorrect decision
- An improperly performed action
- An improper lack of action (inaction).

2.3 Marine Accident Investigation Methods

2.3.1 Events and Causal Factors Charting (ECFC)

Events and causal factors charting is a graphical display of the accident's chronology and is used primarily for compiling and organizing evidence to portray the sequence of the accident's events. The events and causal factor chart is easy to develop and provides a clear depiction of the data. Keeping the chart up-to-date helps insure that the investigation proceeds smoothly, that gaps in information are identified, and that the investigators have a clear representation of accident chronology for use in evidence collection and witness interviewing. Events and causal factors charting is useful in identifying multiple causes and graphically depicting the triggering conditions and events necessary and sufficient for an accident to occur. Events and causal factors analysis is the application of analysis to determine causal factors by identifying significant events and conditions that led to the accident. As the results from other analytical techniques are completed, they are incorporated into the events and causal factors chart. Assumed events and conditions may also be incorporated in the chart.

DOE (1999) [23] pinpoints some benefits of the event and causal factors charting:

1) Illustrating and validating the sequence of events leading to the accident and the conditions affecting these events
2) Showing the relationship of immediately relevant events and conditions to those that are associated but less apparent – portraying the relationships of organizations and individuals involved in the accident
3) Directing the progression of additional data collection and analysis by identifying information gaps
4) Linking facts and causal factors to organizational issues and management systems
5) Validating the results of other analytic techniques
6) Providing a structured method for collecting, organizing, and integrating collected evidence
7) Conveying the possibility of multiple causes
8) Providing an ongoing method for organizing and presenting data to facilitate communication among the investigators
9) Clearly presenting information regarding the accident that can be used to guide report writing
10) Providing an effective visual aid that summarizes key information regarding the accident and its causes in the investigation report.

Figure (2-3) gives an overview over symbols used in an event and causal factor chart and some guidelines for preparing such a chart. Figure (2-4) shows an event and causal factors chart in general.

Symbols	Events Accidents Conditions Presumptive events Presumptive conditions or assumptions Connector Transfer between lines LTA Less than adequate (judgment)
Events	- Are active (e.g. "crane strikes building") - Should be stated using one noun and one active verb - Should be quantified as much as possible and where applicable - Should indicate the date and time, when they are known - Should be derived from the event or events and conditons immediately preceding it
Conditions	- Are passive (e.g. "fog in the area") - Describe states or circumstances rather than occurrences or events - As practical, should be quantified - Should indicate date and time if practical/applicable - Are associated with the corresponding event
Primary event sequence	Encompasses the main events of the accident and those that form the main events line of the chart
Secondary event sequence	Encompasses the events that are secondary or contributing events and those that form the secondary line of the chart

Figure 2-3: Guidelines and Symbols for Preparing an Events and Causal Factors

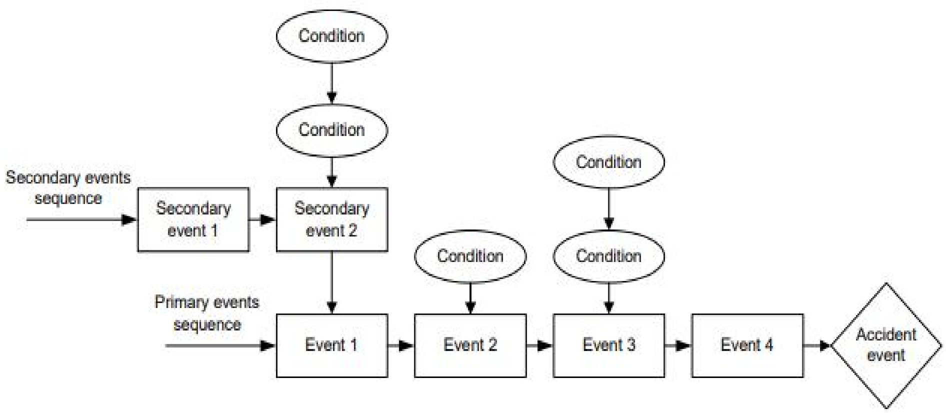


Figure 2-4: Simplified Events and Causal Factors Chart

2.3.2 STEP (Sequential Timed Events Plotting)

The STEP-method was developed by Hendrick and Benner (1987) [24]. They propose a systematic process for accident investigation based on multi linear events sequences and a process view of the accident phenomena.

STEP builds on four concepts:

1) Neither the accident nor its investigation is a single linear chain or sequence of events. Rather, several activities take place at the same time.
2) The event Building Block format for data is used to develop the accident description in a worksheet. A building block describes one event, i.e. one actor performing one action.
3) Events flow logically during a process. Arrows in the STEP worksheet illustrate the flow.
4) Both productive and accident processes are similar and can be understood using similar investigation procedures. They both involve actors and actions, and both are capable of being repeated once they are understood.

With the process concept, a specific accident begins with the action that started the transformation from the described process to an accident process, and ends with the last connected harmful event of that accident process.

The STEP-worksheet provides a systematic way to organize the building blocks into a comprehensive, multi-linear description of the accident process. The STEP-worksheet is simply a matrix, with rows and columns. There is one row in the worksheet for each actor. The columns are labelled differently, with marks or numbers along a time line across the top of the worksheet, as shown in Figure (2-5). The time scale does not need to be drawn on a linear scale, the main point of the time line is to keep events in order, i.e., how they relate to each other in terms of time.

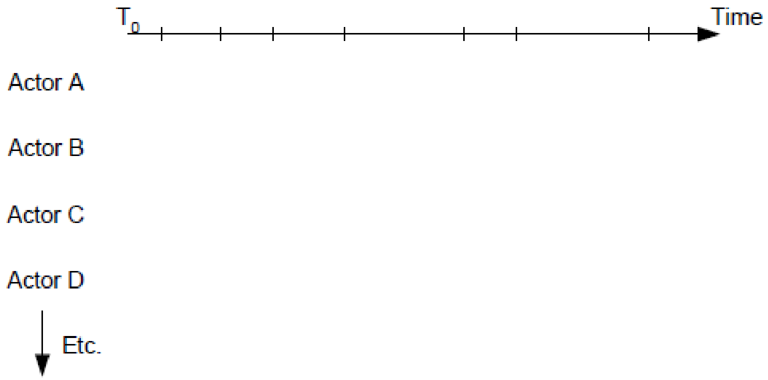


Figure 2-5: STEP-Worksheet

2.3.3 Fault Tree Analysis (FTA)

Fault tree analysis is a method for determining the causes of an accident (or top event). The fault tree is a graphic model that displays the various combinations of normal events, equipment failures, human errors, and environmental factors that can result in an accident. An example of a fault tree is shown in Figure (2-6) [25].

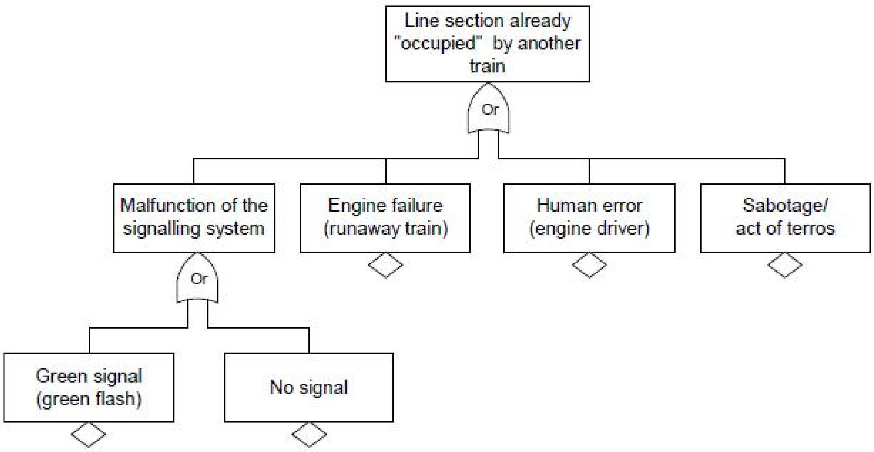


Figure 2-6: Illustration of a Fault Tree (example from the Åsta-Accident)

The Fault Tree is a technique that can be used both for a qualitative and a quantitative analysis. Qualitatively it is used to identify the individual scenarios (so called paths or cut sets) that lead to the top (fault) event, while quantitatively it is used to estimate the probability (frequency) of that event. A component of a Fault Tree has one of two binary states, either in the correct state or in a fault state. A Fault Tree is basically the graphical representation of the Boolean (logical) equation which links the individual component states to the whole system state. By using the property of the Boolean algebra it is possible to establish the combinations of basic (components) failures which can lead to the top (undesirable) event when occurring simultaneously. These combinations are so called “minimal cut sets” and can be derived from the logical equation represented by the Fault Tree [26]. As a Fault Tree represents a logical formula it is possible to calculate the probability of the top event by ascribing probabilities to each basic event and by applying the probability calculation rules and the Boolean algebra properties [27].When the events are independent and the probabilities are low, it is possible to roughly estimate the probability of the output event if an OR gate is the sum of the probabilities of the events of the input. On the same condition, the probability of the output event of a gate can be calculated as the product of the probabilities of the events of the input. On the other hand, the estimation of the top event probability is less accurate, more and more conservative, when the probabilities increase, even if the events are independent. This kind of qualitative analysis is very powerful and interesting, but, unfortunately, for large and/or complex Fault Trees, it is rather difficult to extract these minimal cut sets. However, a large number of existing computer programs have been developed for finding the minimal cut sets in a more or less efficient way, resulting in exact results being able to handle very large Fault Trees and find minimal cut sets or prime implicates.

2.3.4 Event Tree Analysis

An event tree is used to analyze event sequences following after an initiating event. The event sequence is influenced by either success or failure of numerous barriers or safety functions/systems. The event sequence leads to a set of possible consequences. The consequences may be considered as acceptable or unacceptable. The event sequence is illustrated graphically where each safety system is modelled for two states, operation and failure.

Figure 2-7 illustrates an event tree of the situation on Rørosbanen just before the Åsta-accident. This event tree reveals the lack of reliable safety barriers in order to prevent train collision at Rørosbanen at that time [28].

An event tree analysis is primarily a proactive risk analysis method used to identify possible event sequences. The event tree may be used to identify and illustrate event sequences and also to obtain a qualitative and quantitative representation and assessment. In an accident investigation we may illustrate the accident path as one of the possible event sequences. This is illustrated with the thick line in Figure (2-7).

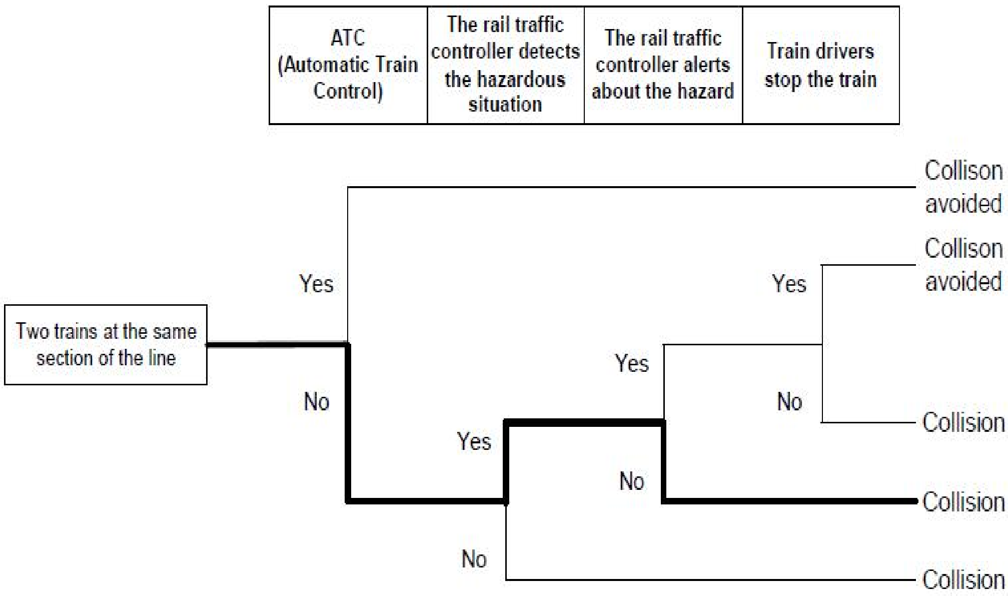


Figure 2-7: Simplified event tree analysis of the risk case

2.3.5 Root Cause Analysis

Root cause analysis is any analysis that identifies underlying deficiencies in a safety management system that, if corrected, would prevent the same and similar accidents from occurring. Root cause analysis is a systematic process that uses the facts and results from the core analytic techniques to determine the most important reasons for the accident. While the core analytic techniques should provide answers to questions regarding what, when, where, who, and how, root cause analysis should resolve the question why. Root cause analysis requires a certain amount of judgment. A rather exhaustive list of causal factors must be developed prior to the application of root cause analysis to ensure that final root causes are accurate and comprehensive.
One method for root cause analysis described by DOE is TIER diagramming. TIER-diagramming is used to identify both the root causes of an accident and the level of line management that has the responsibility and authority to correct the accident's causal factors. The investigators use TIER-diagrams to hierarchically categories the causal factors derived from the events and causal factors analysis. Linkages among causal factors are then identified and possible root causes are developed. A different diagram is developed for each organization responsible for the work activities associated with the accident.

The causal factors identified in the events and causal factors chart are input to the TIER-diagrams. Assess where each causal factor belong in the TIER-diagram. After arranging all the causal factors, examine the causal factors to determine whether there is linkage between two or more of them. Evaluate each of the causal factors statements if they are root causes of the accident. There may be more than one root cause of a particular accident as shown Figure (2-8).

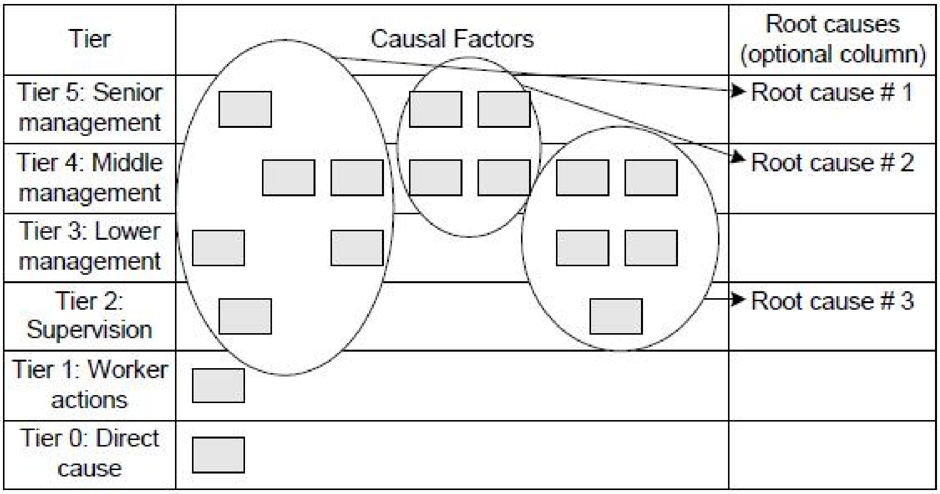


Figure 2-8: Identifying the Linkages to the Root Causes from a TIER-Diagram

Kingery (2005) in her presentation describes the root cause analysis process in a more systematic manner [29]. Figure (2-9) illustrates it.

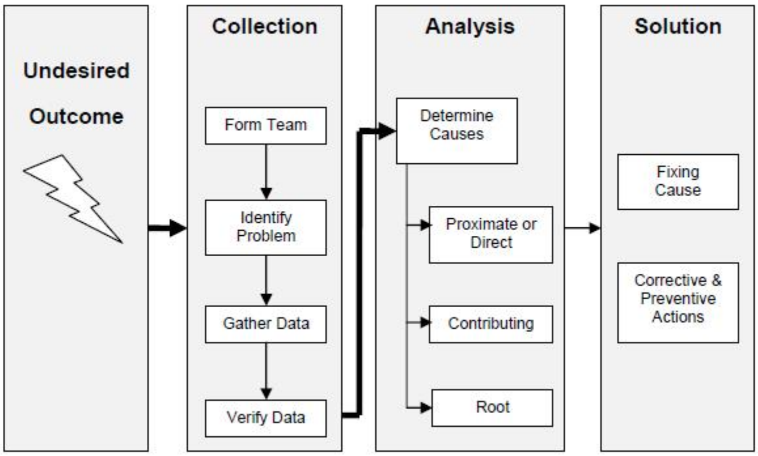


Figure 2-9: Root Cause Analysis Process

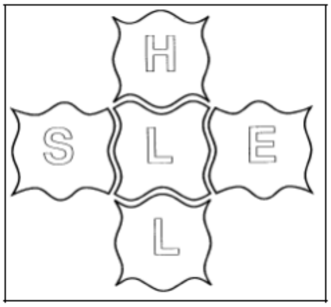
The undesired outcome is the answer to the question "What happened?" For example: the vessel collided, the crane malfunctioned, a fire took place or the propeller got jammed. It should be short, simple, and concise and focus on one problem.

2.3.6 SHELL Analysis Method

The SHEL Model, which was originally developed by Edwards (1972) and modified by Hawkins (1984, 1987), provides a simple means of breaking down the various elements related to human factors.

The SHEL Model consists of four components:

- Software - S
- Hardware - H
- Environment - E
- Liveware – L



The model is commonly depicted as seen in the diagram. It highlights not only the elements themselves but also the relationship between the key human component (Central Liveware) and the other components. The diagram attempts to highlight that the matches or mismatches of the interfaces are just as important as the components themselves, and are therefore just as important to investigate as the elements themselves [30].

1. **Liveware (central component)**

The most valuable and flexible component in the system is the human element, the Liveware, placed at the Centre of the model. Each person has his or her own capabilities and limitations, be they physical, physiological, psychological, or psychosocial. This component can be envisaged as any person involved with the operation or in support of the operation under investigation. This person will interact directly with each one of the four other elements. The person and each interaction, or interface, represents potential areas of human performance investigation

2. **Liveware (peripheral component)**

The peripheral Liveware refers to the human-human interactions of the system being investigated, including such factors as management, supervision, crew interactions, safety culture and communications.

Consider the interaction between the person at the Centre of the investigation and the other people he/she was working with or otherwise who had influence over his/her work.

3. **Hardware**

Hardware refers to the equipment involved in the accident. It includes the design and condition of workstations, displays, controls, seats, and all other physical parts of a ship or system.

Consider the interaction between the person (the central component) and the equipment he/she was using at the time, including its design and condition. Look for any incompatibility or mismatch

4. **Software**

Software is the non-physical part of the system including organizational policies, procedures, manuals, checklist layout, charts, maps, advisories, computer programs and the safety management system.

Consider the procedures, rules, regulations, documents and computer programs that may have influenced the actions of the human at the Centre of the investigation.

5. **Environment**

Environment includes the internal and external climate, temperature, visibility, vibration, noise and other factors which constitute the conditions within which people are working. The broad political and economic constraints under which the marine system operates, and the safety culture of the ship and the organization, can be included in this element. The regulatory climate is also a part of this environment in as much as its climate affects communications, decision making, control and coordination.

Consider how the internal, external, regulatory or safety environment may have affected the decision making of the person(s) at the Centre of the investigation.

The investigator should use the acronym SHEL as a constant reminder throughout the investigation to prompt him to ensure all areas of enquiry should be pursued and the relevant evidence collected.

2.3.7 Step-By-Step Approach

A step-by-step approach is a way to describe events before an accident or incident. This method is graphical and involves preparation of a diagram [31]. The development of this approach is conducting as follows:

- **The first step** is to plot the horizontal line representing the time and continues from t-start to t-end. The level of the diagram below this line is divided into several lines, where each line represents an actor or an object in which has been involved in that event which can be a particular person or any object such as radar, lever, push switch, screen, crane hook, container, etc.
- **The second step** is the definition of the event's final status at the point of trend.

The mechanism of this method bases on going back from the point t-end to the t-start point and investigate about the status, performance and position of each actor.

Step method used to provide an overview of the circumstances in which an incident or event has occurred, which can help to understand exactly what has happened and investigate evidences from multiple sources or witnesses [31].

Chapter 3 Analysis and Investigation of Human Error Influences on Maritime Transportation

3.1 Introduction

Marine transport is one of the vital means in transporting people and cargo across the world. The steady growth in seaborne trade has meant an increase in global shipping movements and tonnage. At the same time, vessels are under pressure to meet deadlines imposed by shipping companies and to comply with a raft of legislation pertaining to safety, security and the protection of the marine environment.

Maritime safety is increasingly significant in a growing. Despite that, shipping accidents still occur globally on a regular basis. Therefore, maritime safety is remaining as a big concern due to the continuous suffering from accidents and increasing number of causalities. There is a big concern toward identifying the main parameters affecting maritime safety and finding the best methodologies to reduce the associate risks. In the same context, there are efforts presented toward identifying the causes of these accidents and to share information with the industry to learn from the experiences and recommendations made as a result.

This chapter is contributing to such efforts by:

- Providing a detailed analysis to operational registered accidents occurred during 2014-2017 to 30 different ships types owned to Kuwait Oil Tanker Company “KOTC”.
- Presenting a systematic developed analysis of general ship registered accidents during 2011– 2016 by European Maritime Safety Agency [32].
- Human error contribution to the overall ship accidents reported from 2011-2018 by European Maritime Safety Agency.

The objectives of this chapter are to show the main parameters which were contributed in the occurrence of ship accidents and the effect of human error among these parameters.

3.2 Analysis of KOTC's Ships Accidents

3.2.1 Statistical Survey of KOTC's Ships Accidents

KOTC is a subsidiary of Kuwait Petroleum Corporation "KPC" responsible for the transportation of Kuwait's oil and gas products. Today, KOTC Operates a fleet of 28 modern crude, product and gas carries to carry much of Kuwait's exports to world markets.

Thirty different types' of ships owned to KOTC involved are considered in the survey. Table (3-1), illustrates the details of the registered operational accidents for each KOTC ship indicating the type of the ship and the number of accidents registered for each year from 2014-2017.

Table 3-1: KOTC's Ships Involved in the Study

#	Ship Name	Ship Type	No. of Accidents/ year				Total Accidents No
			2014	2015	2016	2017	
1	UMM ALAISH	VLCC	3	1	4	2	10
2	KAZIMAH III		2	1	1	3	7
3	DAR SALWA		-	-	1	1	2
4	AL YARMOUK		-	1	-	1	2
5	AL SHEGAYA		-	4	1	-	5
6	AL SALHEIA		-	2	-	1	3
7	AL SALMI		-	1	-	1	2
8	AL RIQQA		1	2	4	1	8
9	AL DERWAZAH		2	2	-	2	6
10	AL JABRIYAH II		-	2	-	-	2
11	AL KOUT		-	1	-	1	2
12	AL FUNTAS		-	2	-	-	2
13	GAS AL MUTLAA	LPG Carriers	-	4	1	2	7
14	GAS AL NEGEH		1	-	1	1	3
15	GAS AL KUWAIT II		1	-	1	-	2
16	GAS AL GURAIN		1	1	1	-	3
17	WAFRAH	Products Carriers	-	2	3	1	6
18	HADIYAH		-	1	-	-	1
19	KAIFAN		-	-	3	1	4
20	BURGAN		3	2	-	1	6
21	BUBYAN		-	1	-	1	2
22	BNEIDER		1	-	1	1	3
23	ARABIYAH		-	1	-	-	1
24	BAHRA		-	-	-	1	1
25	AL DASMA		-	-	-	2	2
26	ALSOOR II		-	1	1	-	2
27	AL SALAM II		-	-	-	1	1
28	AL WATANIYAH IV	Bunkers	1	-	-	-	1
29	SEDRA 11		-	-	-	1	1
30	AL SABRIYAH	Tug / Supply	-	-	-	1	1

Figure (3-1), shown the total number of accidents registered for each of the survey years.

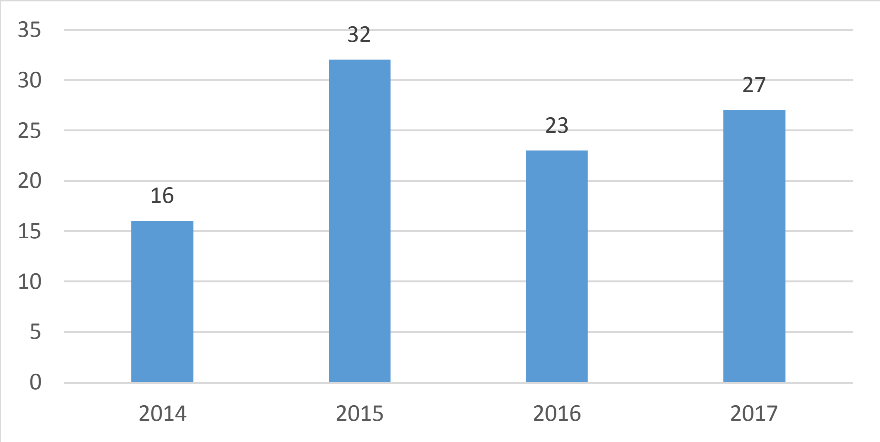


Figure 3-1: Total Number of KOTC's Ships Accidents per each of Survey Years (2014-2017)

As per the registered KOTC's ships accidents, 98 accidents occurred from 2014-2017. KOTC reporting system classifies ships accidents into the following main groups:

[1] Operator Error (OE)
[2] Negligence (N)
[3] Personal Protected Equipment (PPE) Related
[4] Slips, Trips, Falls (STF)
[5] Third Party Fault (TPF)
[6] Procedure Failure (PF)
[7] Bad Weather (BW)
[8] Equipment/Material Failure (E/MF)

Table (3-2), shows the 98 accidents as per KOTC's accidents classification method for each ship.

Table 3-2: Causes of KOTC's Ships Accidents 2014-2017

#	Ship Name	No of Acc.	Classification of Accidents based on Causes							
			OE	N	PPE	STF	TPF	PF	BW	E/MF
1	Umm Alaish	10	3	2	-	-	-	-	1	4
2	Kazimah III	7	1	-	2	1	1	-	-	2
3	Dar Salwa	2	-	1	-	-	-	-	-	1
4	Al Yarmouk	2	-	1	-	1	-	-	-	-
5	Al Shegaya	5	1	-	-	-	-	1	-	3
6	Al Salheia	3	1	1	-	1	-	-	-	-
7	Al Salmi	2	1	-	-	1	-	-	-	-
8	Al Riqqa	8	2	3	-	2	-	1	-	-
9	Al Derwazah	6	1	3	-	-	-	2	-	-
10	Al Jabriyah II	2	-	-	-	-	-	1	1	-
11	Al Kout	2	-	1	-	1	-	-	-	-
12	Al Funtas	2	1	-	-	-	-	-	-	1
13	Gas Al Mutlaa	7	1	-	1	1	1	1	-	2
14	Gas Al Negeh	3	-	3	-	-	-	-	-	-
15	Gas Al Kuwait II	2	1	1	-	-	-	-	-	-
16	Gas Al Gurain	3	1	1	-	1	-	-	-	-
17	Wafrah	6	-	2	1	1	-	-	-	2
18	Hadiyah	1	1	-	-	-	-	-	-	-
19	Kaifan	4	1	-	-	-	-	-	-	3
20	Burgan	6	1	2	2	1	-	-	-	-
21	Bubyan	2	-	1	-	-	-	-	1	-
22	Bneider	3	2	-	-	1	-	-	-	-
23	Arabiyah	1	-	-	-	-	-	-	-	1
24	Bahra	1	-	-	-	1	-	-	-	-
25	Al Dasma	2	-	1	1	-	-	-	-	-
26	Alsoor II	2	1	-	-	-	-	-	-	1
27	Al Salam II	1	-	-	-	1	-	-	-	-
28	Al Wataniyah IV	1	-	-	-	-	-	-	-	1
29	SEDRA II	1	1	-	-	-	-	-	-	-
30	Al Sabriyah	1	-	-	-	-	-	1	-	-

Figure (3-2) shows the number of accidents for each KOTC's accident classification category.

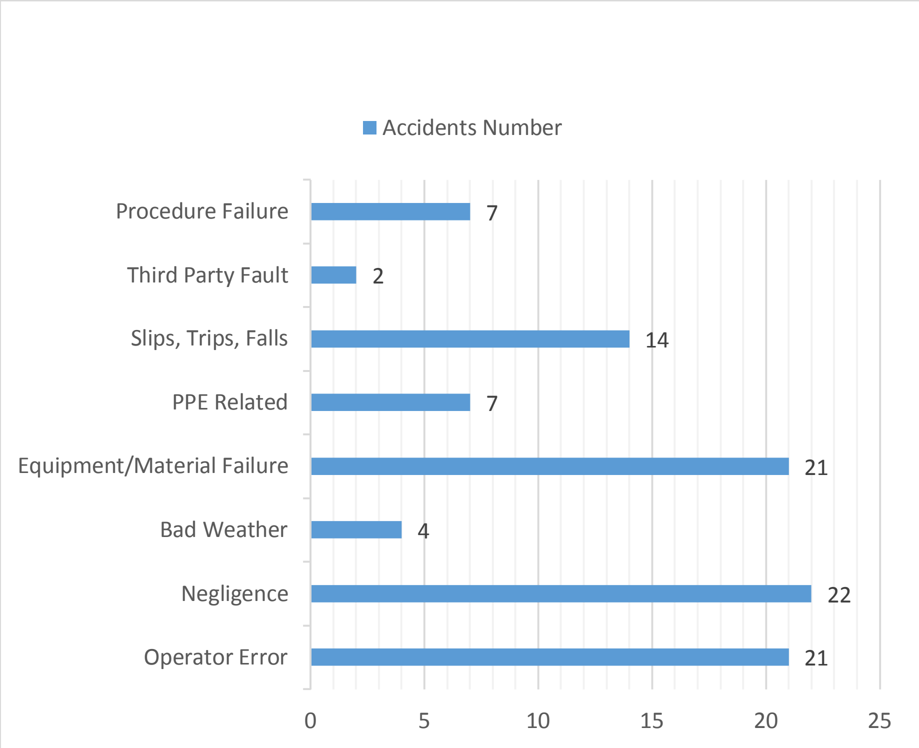


Figure 3-2: Number of Accidents per each Identified Accident Cause

As per the overall ship accidents causes, ship accidents are classified according to their causes into [33]:

- Accidents due to natural conditions and poor weather
- Accidents due to ship-related factors
- Accidents due to technical failures
- Accidents due to cargo-related factors
- Accidents due to human errors

In this context, the causes of KOTC's ships accidents can be categorized accordingly into the followings categories:

- **Accidents due to natural conditions and poor weather**

These will cover the accidents happened due to bad weather which are "**4 accidents**" as indicated in Figure (3-2).

- **Accidents due to technical failures**

These will cover the accidents happened due to Equipment / Material Failure which are "**21 accidents**" as indicated in Figure (3-2).

- **Accidents due to human errors,** which include the intentional and non-intentional human errors causes, These will cover the accidents happened due to:
  - Operator Error: **21 accidents**
  - Negligence: **22 accidents**
  - PPE related: **7 accidents**
  - Slips, Trips, Falls: **14 accidents**
  - Third Party Fault: **2 accidents**
  - Procedure Failure: **7 accidents**

Total accidents due to human errors are 73 accidents from 98 total registered accidents

Figure (3-3), shows the classification of the KOTC's ships accidents (2014-17) as per main ship accident causes.

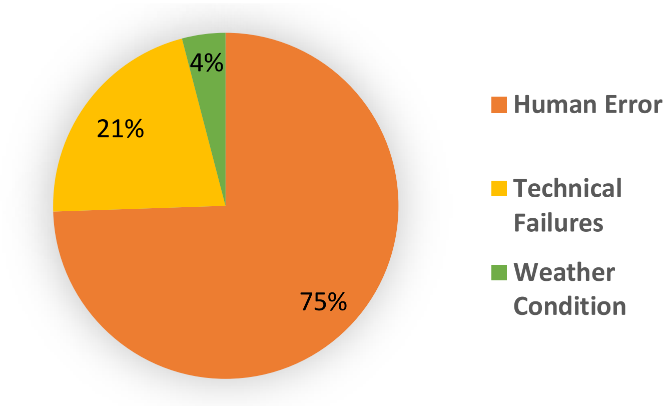


Figure 3-3: Main Categories of KOTC's Ships Accidents Causes (2014-2017)

3.2.2 Human Error Types on Ship Accidents

The analysis of ship accidents causes indicated in Figure (3-3) shows that accidents due to human error causes are presenting the majority of the accidents occurred to KOTC's ships accidents (~75%) .

Figure (3-4) shows the analysis of the accidents due to human error as per type of error occurred.

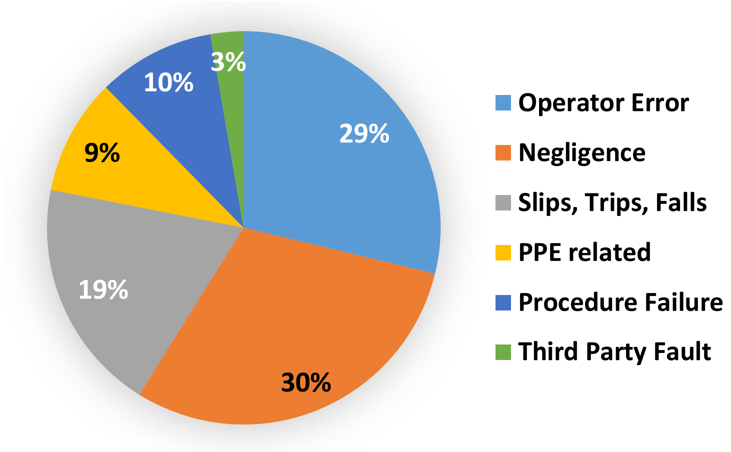


Figure 3-4: Effect (weight) of the Human Error Causes of KOTC's Ships Accidents

As indicated by the analysis of the KOTC 30 ship accidents during the period of 2014-2017, human error contributes to the vast majority of the registered accidents. It contributes approximately to (~75%) of the occurred accidents.

The analysis of human error causes indicated in Figure (3-4), reflects the followings:

1. **High weight of accidents due to Negligence**.
   As indicated in Figure (3-4), accidents due to negligence presents 30% of the total of human error causes categories. Such percentage/weight reflects the behavior of employees and the repetition of such cause reflects the poor or ineffective management control system implemented by the shipping company. These give a trigger to the shipping company to take correction actions toward improving the

working environment, placing and activating effective monitoring and supervisory system and improving the communication and reporting systems with employees. Implementation of such corrective actions will highly contribute in reducing this type of error and improve ship image and safety.

2. **High weight of accidents due to Operator Error**

As indicated in Figure (3-4), accidents due to negligence presents 29% of the total of human error causes categories. It has the second larger contribution of the accidents due to human error causes. Such high percentage gives indications to the awareness and familiarity of employees to their assigned tasks and jobs. Moreover, it indirectly reflects the training and development programs quality provided by the shipping company.

Elimination of accidents due to operator error can be achieved through:

1) Providing clear job detailed distribution documents and making these documents available and easy to be accessed.
2) Providing in-job training programs.
3) Providing awareness and information training and sessions to new employees as well to all employees once using new facility/equipment
4) Conducting job discussion meetings prior starting the shift in order to well assign tasks explain the expected deliverables and identify the needed support.
5) Scheduling and providing training and career development programs with clear tracking system.
6) Developing job supervision and accountability procedures to be linked with acknowledgment and rewarding system.
7) Providing programs concerned with improving the communication skills and networking of employees.

3. **Accidents due to Slip, Trip or Falls**

A slip, trip or fall at work can lead to injuries and even death in some cases. The analysis of the accidents survey indicates 19% of total human error accidents occurred due to slip, trip or fall. This is a high percentage as the result of this cause is mainly injury or death. Such result will highly affect the work onboard ship due to the limited staff numbers and difficulties in replacement mainly when the ship is sailing in deep seas and away from land. These sobering statistics are a stark reminder that workers need to know how to prevent slips, trips and falls and stay safe. To help preventing such causes, the followings are recommended:

1) Clean up spills immediately and place "wet floor" warning signs for workers.
2) Keeps walkways and hallways free of debris, clutter and obstacles.
3) Keep filing cabinets and desk drawers shut when not in use.
4) Cover cables or cords in walkways.
5) Replace burnt-out light bulbs promptly.
6) Consider installing abrasive floor mats or replacing worn flooring.
7) Encourage workers to wear comfortable, properly fitted shoes.
8) Conducting safety awareness and information training and sessions.

4. **Accidents due to Procedure Failure**

This accident category occurred due to not following up the assigned operation, maintenance and / or emergency procedure. To eliminate such accidents, procedures need to be clearly understood, visible, accessible and available. Moreover, task structure should be combined with the associate procedure to eliminate any error. Shipping company should strength the monitoring, supervision and following up roles and improve the communication and work assignment procedures.

5. **Accidents due to Wrong Attach or Wearing Personnel, Protective Equipment**

Personal Protective Equipment (PPE) is equipment that will protect workers against health or safety risks on the job. The purpose is to reduce employee exposure to hazards when engineering and administrative controls are not feasible or effective to reduce these risks to acceptable. Wrong attach of PPE or not wearing PPE may expose the employee to high risks. To eliminate such risk, company should ensure providing the wright PPE to all employees. On the other hand, employee should ensure that his PPE are fit and maintain in good condition. Therefore, awareness and information session should be conducted to indicate how to use the wright PPE, monitoring and supervisory action should be taken when PPE are not used or used in improper way and instructions and workplace requirements should be published and clearly placed at working place.

6. **Accidents due to Third Party Fault**

Accidents due to third party fault has a low weight in the human error accidents as indicated in Figure (3-4). However, such accidents can highly eliminated and reduced by clear supervision and monitoring to any third party work onboard ships. Therefore, clear third party job instructions should be placed, explained and discussed before any associate work involvement.

Prevention of human error is a paramount importance to reduce the number of marine accidents and its severity. There are many factors affecting the occurrence of human errors, which tend to occur because of technologies, working environments, non-familiarity or working procedures, lack of training and experiences, and management systems. Therefore, human errors could be reduced significantly by taking more concern about improving quality of crew training and capabilities development programs, improving working environment, providing clear job related procedures and implementing regulations to control human error.

3.3 Analysis of Ship Accidents Types and Causes Reported By EMCIP

The recent update of the maritime accidents from 2011-2016 reported by the European Marine Casualty Information Platform (EMCIP) reported the followings [49]:

- 18655 Ships involved in accidents
- 16539 casualties and incidents
- 253 ships lost
- 5607 persons injured
- 600 fatalities
- 869 investigations

The register of marine accidents indicates that since 2014, the number of reported accidents seems to have stabilized at around 3200 occurrences per year. While the number of very serious and serious marine casualties and incidents remained at levels similar to previous years, a limited but continuing increase of less serious accidents reported was noted.

Over the period 2011-2016, half of the casualties were of a navigational nature, such as contacts, grounding/stranding or collision. Amongst occupational accidents, 40% were attributed to slipping, stumbling and falling of persons. Human erroneous action represented 60% of accidental events and 71% of accidental events were linked to shipboard operations as a contributing factor.

From 2011 to 2016, 2.4% of casualties with a ship were very serious, 20.7% serious, 57.6% less serious and 19.3% marine incidents. The distribution of casualty events with ships is indicated in Figure (3-5). As indicated in the figure, the combination of contact (18%), collision (16%) and grounding/stranding (15.6%) shows that navigational casualties represent 50% of all casualties with ships. Where, 10687 casualties with a ship have a unique casualty event and 429 casualties with a ship have more than one casualty event.

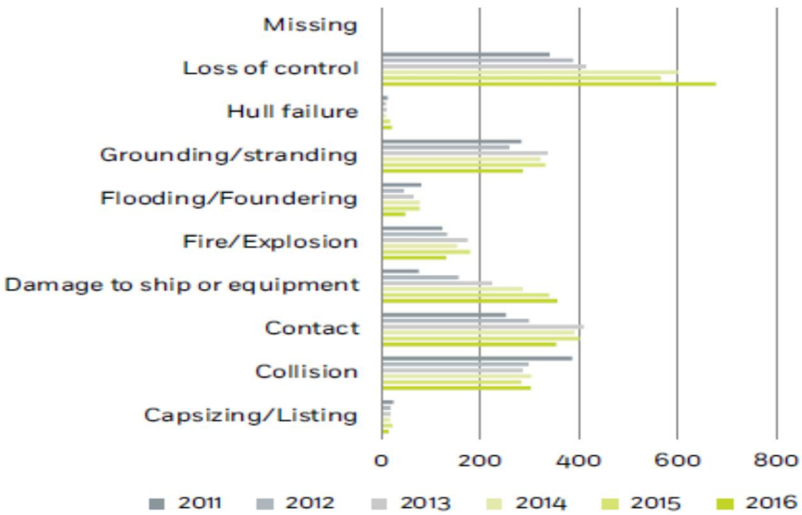


Figure 3-5: Distribution of Casualty Events with Ships (2011-2016)

The results of investigators search for the root causes of the casualty or incident are indicated in Figure (3-6). From 1170 accidental events analyzed during the investigations, 60.5% were attributed to a Human Erroneous Action.

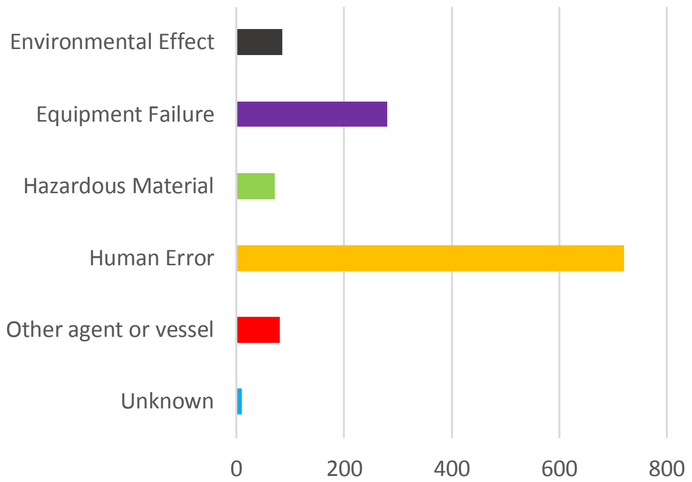


Figure 3-6: Distribution of Accidental Events (2011-2016)

Figure (3-7) shows the classification of accidental events parameters, where contributing factors are separated into two categories: shore management and shipboard management. As indicated, shipboard operations represented the main contributing factor at 71% of the total.

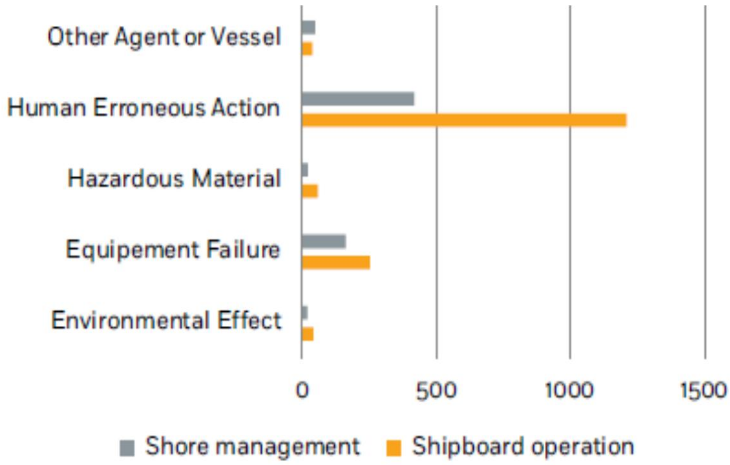


Figure 3-7: Relationship between Accidental Events and the Main Contributing (2011-2016)

3.4 Human Error Contribution to the Overall Ships Accidents (2011 – 2017)

In the following sections, the human error contribution to the overall causes of ships accidents will be presented and discussed categorized by ship type accidents.

Human Error Contribution to the Overall Cargo Ships Accidents (2011 – 2017)

Figure (3-8) shows the distribution of cargo ships accidents reported by European Marine Casualty Information Platform (2011-2017). The analysis of the reported accidents indicates that general cargo ships accidents represented 32.3%, followed by container ships by 17.6% and bulk carriers by 15.5%.

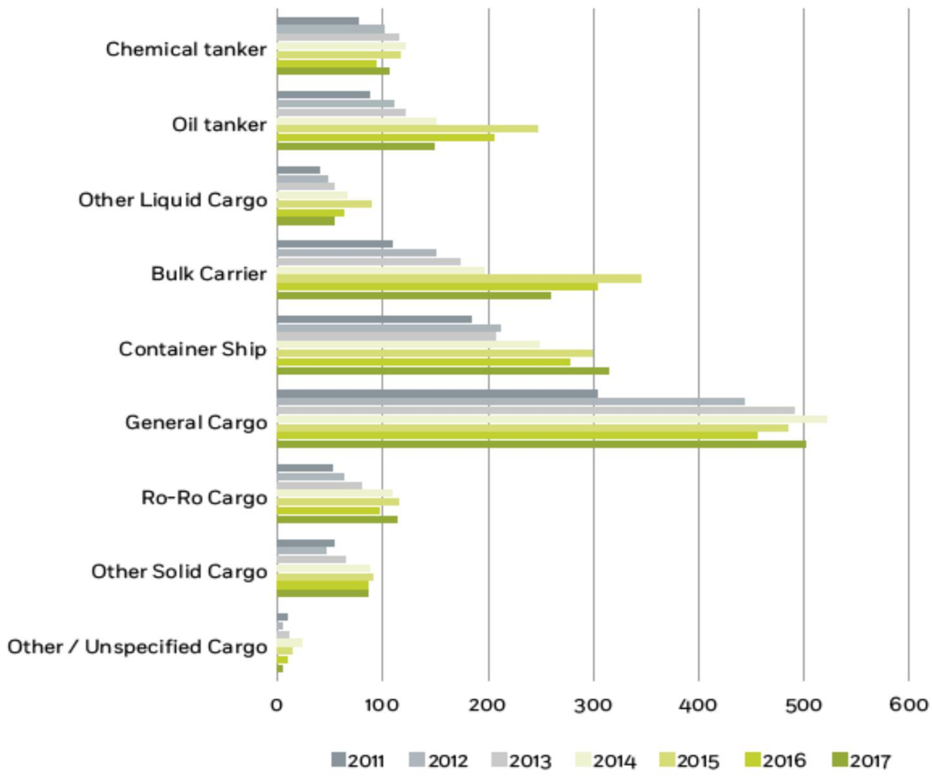


Figure 3-8: Distribution of Cargo Ships Accidents (2011-2017)

Figure (3-9) shows the analysis of the main causes to the registered cargo ships accidents. As indicated in the figure, loss of control represents 24.4% of the events involving cargo ships, followed by collision of 20.4% and contacts of 19.2%.

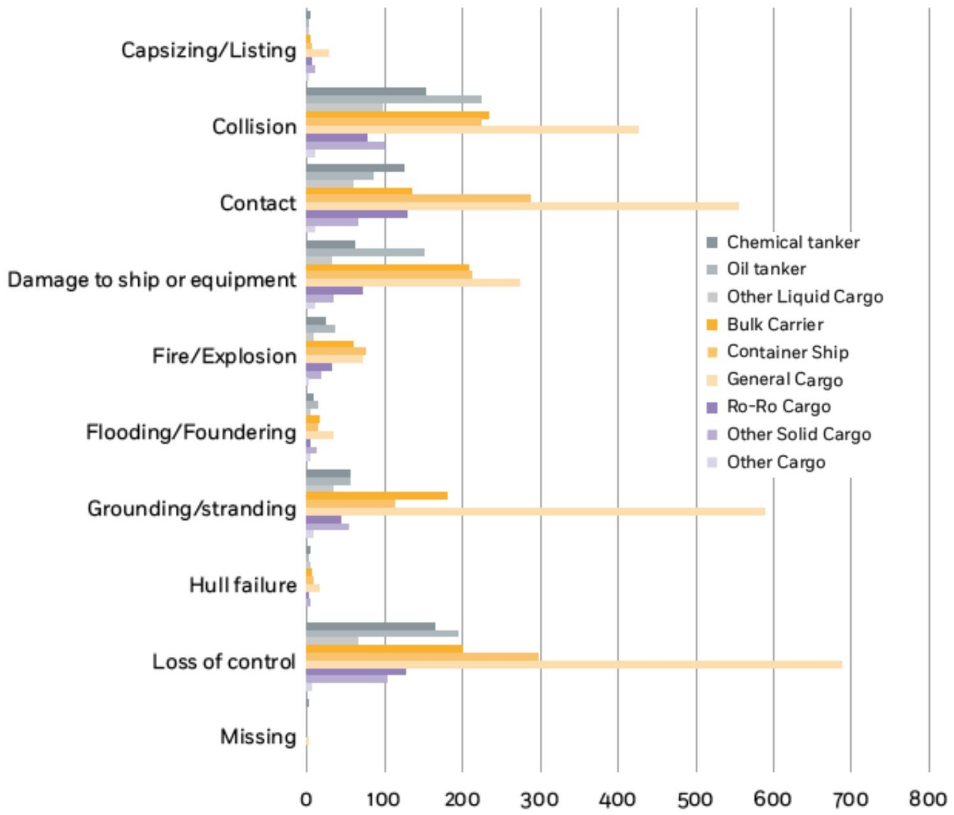


Figure 3-9: Distribution of Casualty Events per Cargo Ship Type for 2011-2017

Figure (3-10) shows the distribution of accidental events for the registered cargo ships accidents (2011-2017). Among the 781 accidental events related to cargo ships, human erroneous actions were quoted most often 60.8%, followed by equipment failure 20.1%.

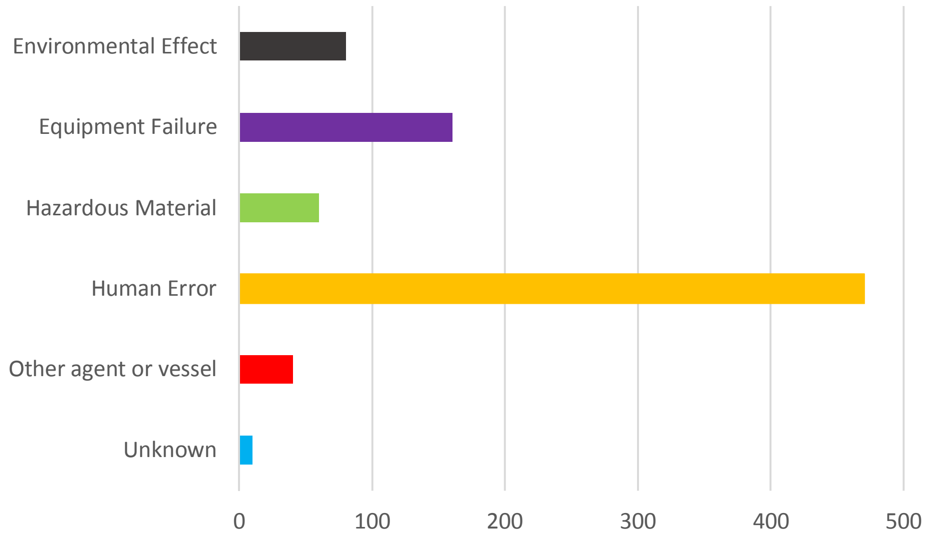


Figure 3-10: Distribution of Accidental Events for Cargo Ships (2011-2017)

Human Error Contribution to the Overall Fishing Vessels Accidents (2011 – 2017)

Figure (3-11) shows the distribution of fishing vessels accidents reported by European Marine Casualty Information Platform (2011-2017). The analysis of the reported accidents indicates that among fishing vessels involved, the most specified subcategory was trawlers represented by 59.5%.

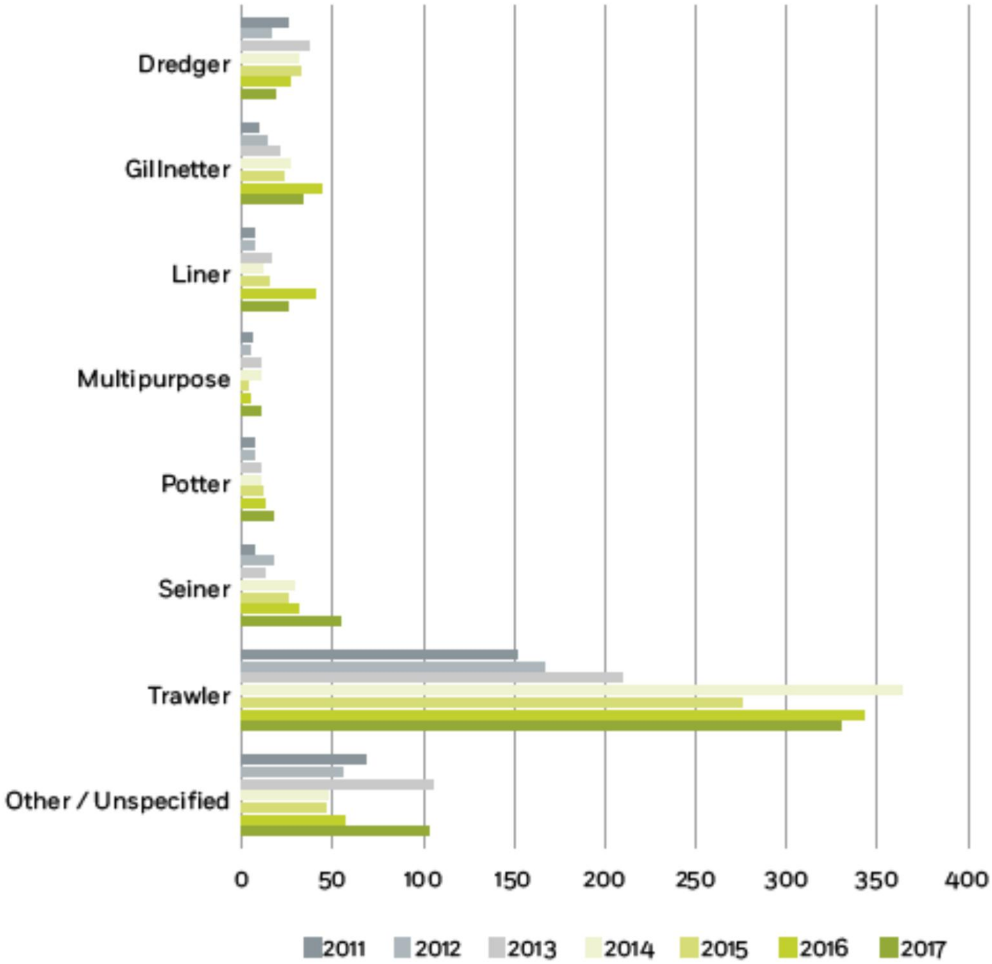


Figure 3-11: Distribution of Fishing Vessels Accidents (2011-2017)

Figure (3-12) shows the analysis of the main causes to the registered fishing vessels accidents. As indicated in the figure, the two most quoted categories of casualty events were collision and loss of control of propulsion power.

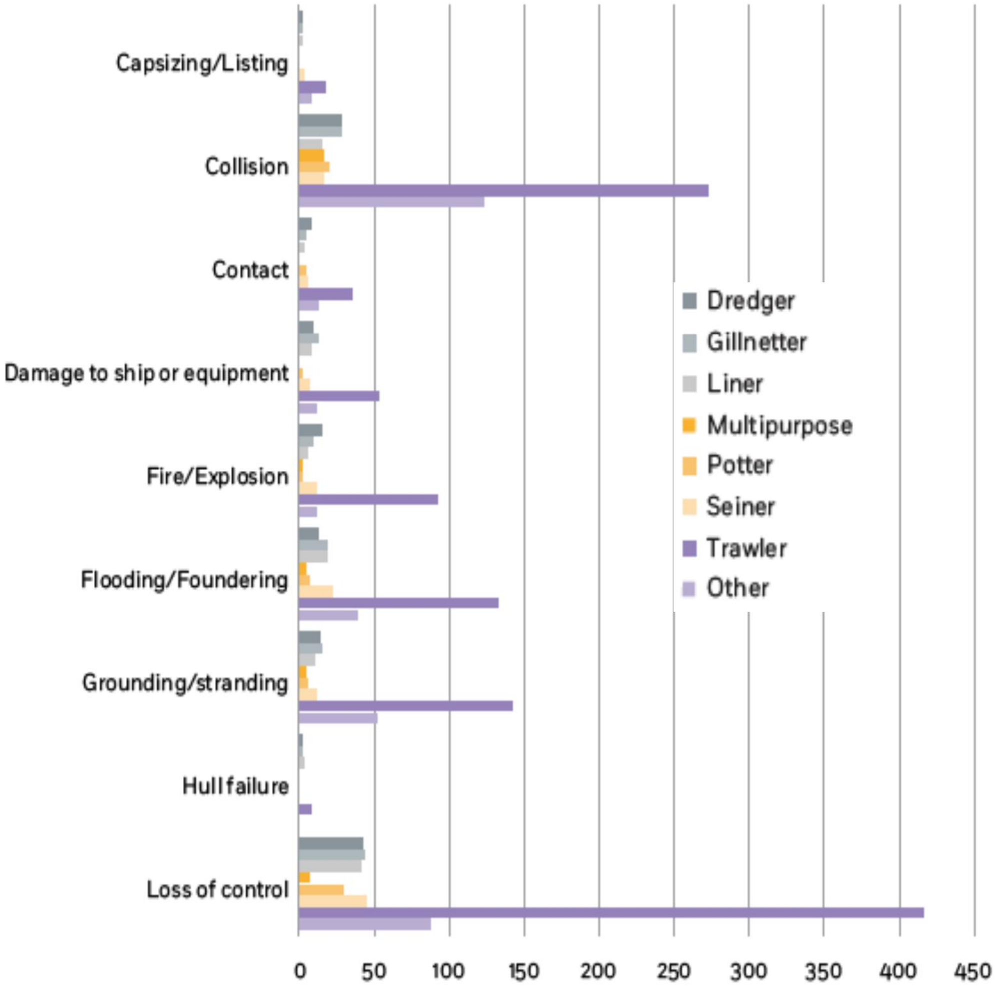


Figure 3-12: Distribution of Casualty Events per Fishing Vessels Type for 2011-2017

Figure (3-13) shows the distribution of accidental events for the registered fishing vessels accidents (2011-2017). From a total of 338 accidental events analyzed during the investigations, 54.4% were attributed to a Human Erroneous Action.

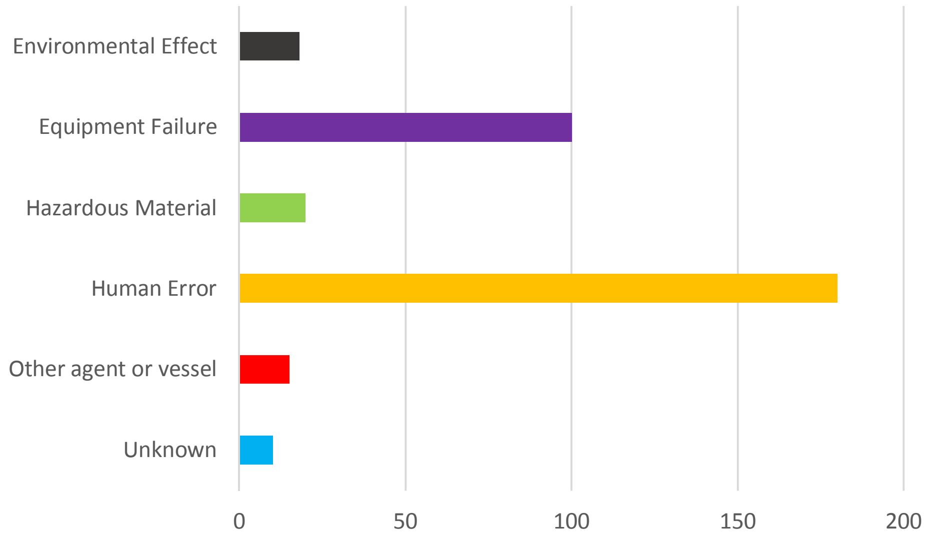


Figure 3-13: Distribution of Accidental Events for Fishing Vessels (2011-2017)

Human Error Contribution to the Overall Passenger Ships Accidents (2011 – 2017)

Figure (3-14) shows the distribution of passenger ships accidents reported by European Marine Casualty Information Platform (2011-2017). The analysis of the reported accidents indicates that among passenger ships involved, the most quoted subcategory was 'passenger and Ro-Ro cargo' ships (also known as 'Ferries') during domestic voyages (49.3%) followed by ships carrying only passengers on international voyage (16.5%).

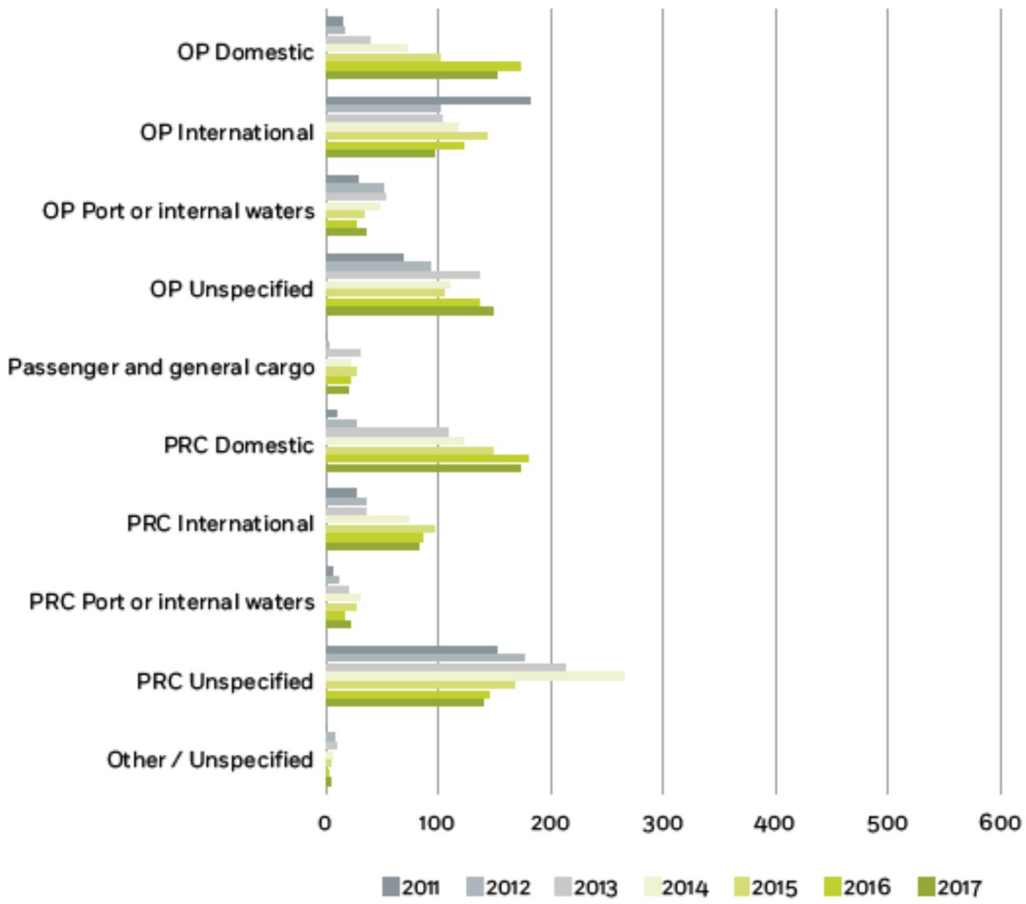


Figure 3-14: Distribution of Passenger Ships Accidents (2011-2017)

Figure (3-15) shows the analysis of the main causes to the registered passenger ships accidents. As indicated in the figure, navigational accidents (collision, contact and grounding) represented 46.5% of events that affected passenger vessels.

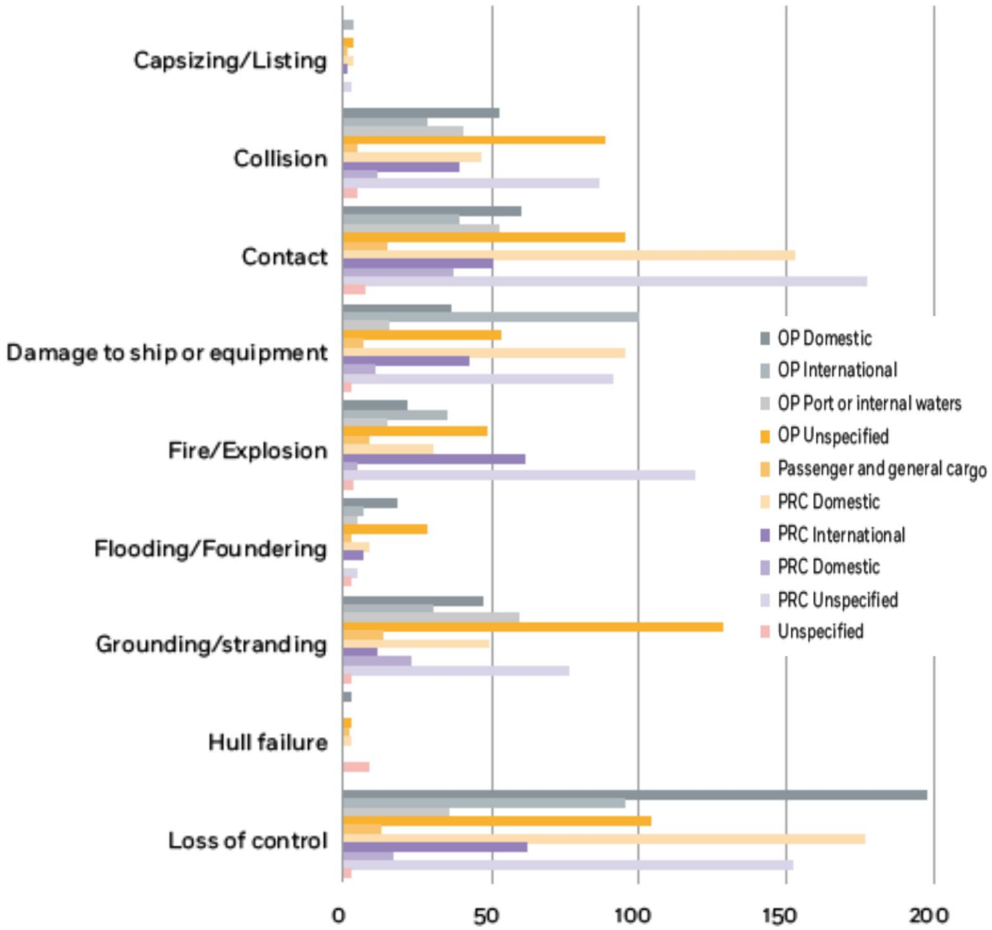


Figure 3-15: Distribution of Casualty Events per Passenger Ships Type for 2011-2017

Figure (3-16) shows the distribution of accidental events for the registered passenger ships accidents (2011-2017). From a total of 319 accidental events analyzed during the investigations 51.4% were attributed to a human erroneous action.

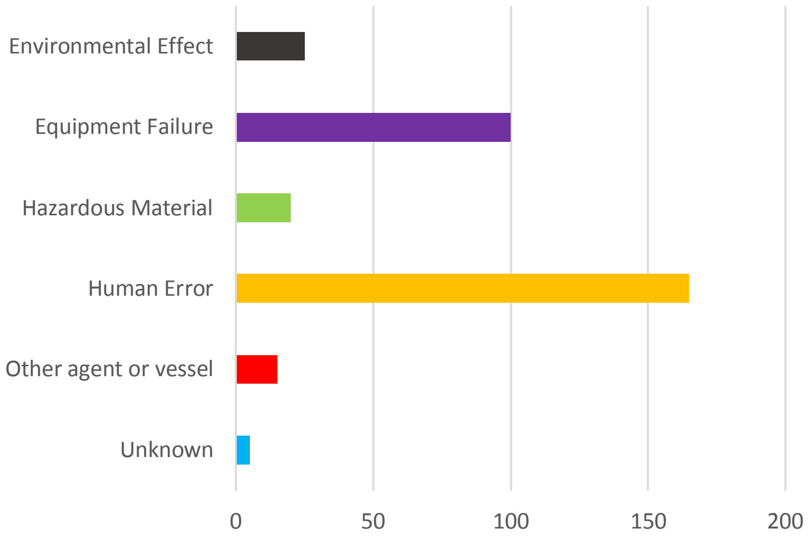


Figure 3-16: Distribution of Accidental Events for Passenger Ships (2011-2017)

<u>Human Error Contribution to the Overall Service Ships Accidents (2011 – 2017)</u>

Figure (3-17) shows the distribution of passenger ships accidents reported by European Marine Casualty Information Platform (2011-2017). The analysis of the reported accidents indicates that among service ships involved, the main subcategory was tugs by 24.1%, followed by dredgers by 15.2% and offshore supply ships by 13.2%. The number of service ships involved in 2017 was equal to the one in 2016 (405 ships).

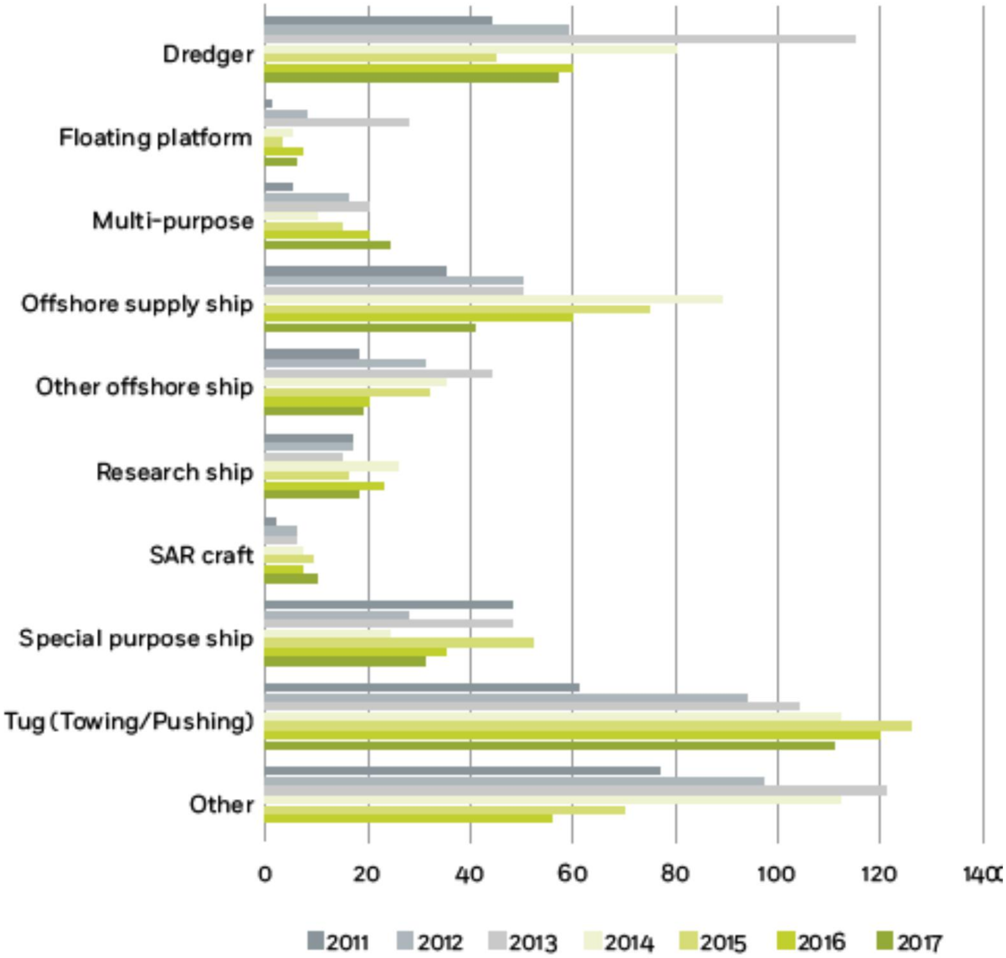


Figure 3-17: Distribution of Service Ships Accidents (2011-2017)

Figure (3-18) shows the analysis of the main causes to the registered service ships accidents. As indicated in the figure, navigational accidents (collision, contact and grounding) are the main casualty events (57%) across all the service ship types.

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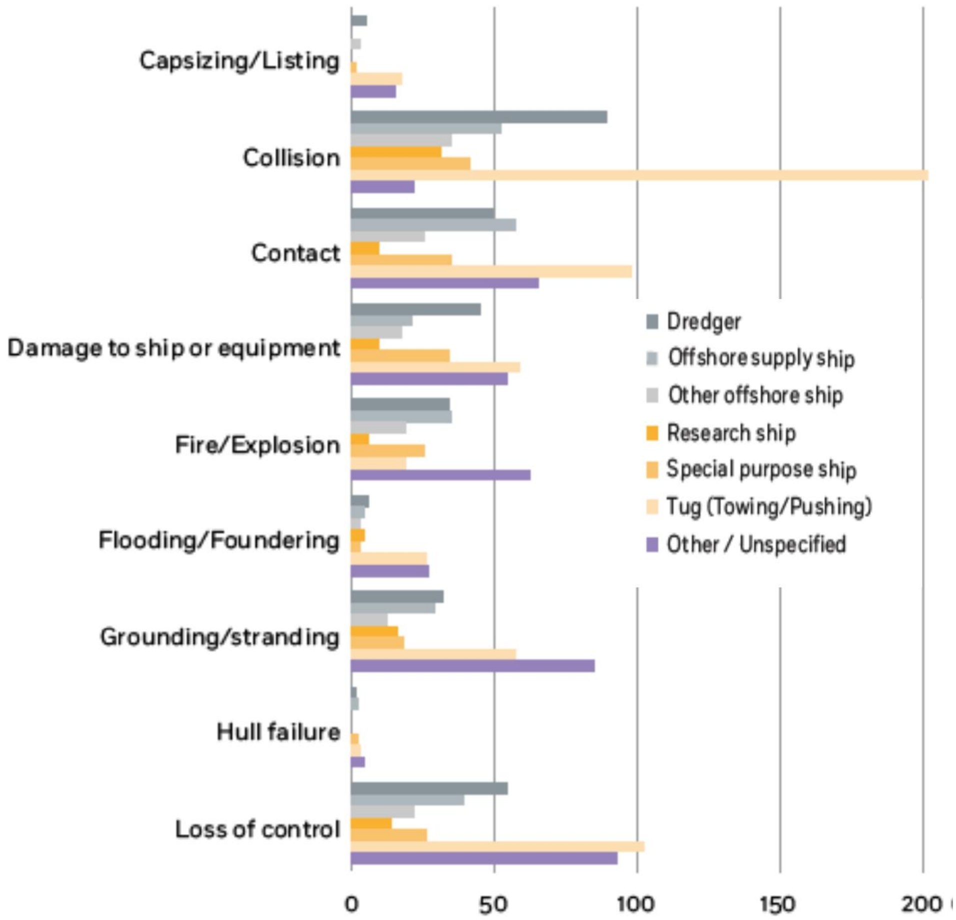

Figure 3-18: Distribution of Casualty Events per Service Ships Type for 2011-2017

Figure (3-19) shows the distribution of accidental events for the registered service ships accidents (2011-2017). From a total of 156 accidental events analyzed during the investigations 62.2% were attributed to a human erroneous action.

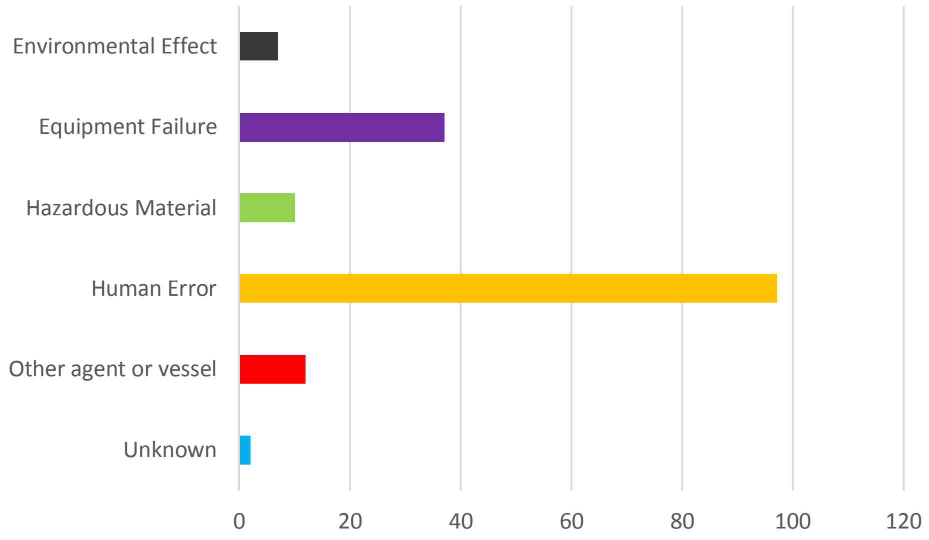

Figure 3-19: Distribution of Accidental Events for Service Ships (2011-2017)

The results of the analysis of the reported accidents by European Marine Casualty Information Platform from 2011to 2017 for cargo ships, fishing vessels, passenger ships and service ships indicated high contribution of human error to the causes of ships accidents, where it represents:

- 62.2% of the total of 156 accidental events analyzed of service ships
- 60.8% of the total of 781 accidental events analyzed of cargo ships
- 54.4% of the total of 338 accidental events analyzed of fishing vessels
- 51.4% of the total of 319 accidental events analyzed of passenger ships

Chapter 4 Detailed Analysis Methodology of KOTC Ship Accident Case Study

4.1 Introduction

The maritime shipping industry is considered as one of the huge and high-risk industries, where, there is a big concern toward reducing the associate risk of this industry and improving the maritime safety. As indicated in the literature, ship safety is highly affected by human actions and the majority of maritime accidents are consequences of human error. It is obviously clear from the occurrence of marine accidents and increase of casualty's number instead of vast improvement in the ship's design, using of advanced technological equipment and implementation of strict maritime safety regulations and legislation.

In this chapter, a detailed step-by-step events evaluation technique of a collision case study is used to investigate human error factors participated as main causes of the accident. Then made a detailed comprehensive description of the events prior to collision are given in timely and action performed by each vessel crew. This is through analyzing the collision happened between Oil Tanker "Kiafan" and Bulk Carrier "Unison Star" in Chittagong - Bangladesh (24 July 2017), while Kaifan was in the Chittagong - Bangladesh anchorage area. The collision caused hull damage for both ships with no injuries and pollution. The detailed collision events, consequences, actions and recommendations are presented in this chapter.

4.2 Description of Chittagong – Bangladesh Port

The Port of Chittagong is the principal Port of the People's Republic of Bangladesh. It is situated on the right bank of the river Karnafuli at a distance of about nine nautical miles from the shore line of the Bay of Bengal. River Karnafuli rising in the Lushai Hill falls in the Bay of Bengal after taking a winding course of 120 nautical miles through the districts of Chittagong Hill Tracts and Chittagong. Figure (4-1), illustrates a descriptive map of Chittagong – Bangladesh Port [34].

Figure 4-1: Chittagong – Bangladesh Port Map

Chittagong – Bangladesh Port has the followings general polices for ships to enter the port [34]:

1) The maximum permissible draft for entering &leaving Chittagong Port is 9.5 m.
2) The maximum permissible length for entering Chittagong Port is 190 m.
3) The maximum permissible entry length for night navigation is 170 m.
4) The maximum permissible draft for Main Jetty areas are:
   - Jetty No.2 to Jetty No.4: up to 7.5 m
   - Jetty No. 5 to Jetty No. 13: 8.55 m

Chittagong anchorage zone is very active and densely populated. Therefore, the anchorage presents many navigational challenges as vessels wait to berth or undertake cargo operations with lightering vessels.

Most collisions in the Chittagong anchorage result from maneuvering vessels failing to take account of the variability and strength of the tide and currents, leading to contact between anchored and embarking vessels. Therefore, ships masters should be cognizant of these conditions when entering and leaving the port [4]. Moreover, special concern should be taken to the weather and sea conditions (tides, currents and wind directions).

Anchoring at Chittagong port need well skilled and knowledgeable crews familiar with port operating polices.

Operational Guidelines and Policies for Chittagong Outer Anchorage

The risk of collision at anchorages outside the port of Chittagong, Bangladesh, has recently increased mainly due to strong spring/flood/monsoon tides and silted shallows. Anchorage in outside the Chittagong port is ship captain responsibility, therefore, Chittagong port authority issued the following recommendations for master anchoring at Chittagong anchorage & entering harbor [35]**:**

1. Anchor at a safe distance from other vessels at anchor.

2. If the under keel clearance is less than two meters there is a possibility to the anchor to be dragged. This is more prominent during spring tides and during monsoons. The tide can be as strong as 6 to 7 knots. The chance of dragging anchor increased if the ship is lightering with other vessels alongside.

3. As a precaution use more chains, keep your engine standby all the times and keep the nos. of lighter vessel alongside to minimum.

4. Keep a good anti-theft lookout and employ watchmen onboard.

5. Ship Master must note that strong tidal condition prevail at outer anchorage and utmost care must be taken while maneuvering anchoring or heaving up anchors.

6. Crossing of bow at close range shall never be attempted.

7. All vessels within Port Limit shall strictly comply with existing Port Rules.

8. Ship Masters approaching Chittagong Road are advised not to attempt to cross the bow of vessels at anchor/underway to avoid drifting on them resulting probable collision in view of the prevailing strong current at outer anchorage. However, if it is inevitable to cross, Ship Master may do so with caution by giving wider berth to the vessels at anchor/underway considering the minimum velocity of the current being 6 Knots and other marine factors.

9. Deep draught vessels lightering at Alpha anchorage shall shift to Bravo or Charlie when they attain required draughts to make room for safe anchoring of newly arrived deep draft vessels.

10. Vessel must have at least 16 rope for safe berthing. Tanker vessel having wire rope must have at least four polypropylene rope.

11. To facilitate smooth operation, at berth master of mother vessel must allow lighter tanker/fresh water barge to stay alongside as required by Harbor Master office.

12. Vessel should have at least 0.20 m by stern trim for channel navigation to get good steering effect.

13. While at anchor never keep any loose mooring Rope/gear on deck.

14. Ship Master must not anchor their vessels near the river entrance "*Prohibited Anchorage*".

15. Ship Master must maneuver with great care while embarking or disembarking Pilots.

4.3 Description of Vessels

4.3.1 Kaifan Oil Tanker

KAIFAN is a Chemical/**Oil tanker** built in 2014 by Hyundai Mipo Dockyard Co. LTD. - Ulsan, South Korea. Sailing under the flag of Kuwait. The detailed data sheet of the oil tanker is given in Table (4-1) and Kiafan's photo is illustrated in Figure (4-2) [36].

Figure 4-2: Kiafan Oil Tanker

Table 4-1: Kiafan Oil Tanker Data Sheet

Vessel Description	
Ship's Name	Kaifan (9656046)
IMO number	9656046
Ship's Type	Oil tanker
Date delivered	Jul 24, 2014
Builder	Hyundai Mipo Dockyard
Flag / Port of Registry	Kuwait / Kuwait
Type of hull	Double Hull
Dimensions	
Length overall (LOA)	185.99 m
Length between perpendiculars (LBP)	176.96 m
Extreme breadth (Beam)	32.23 m
Moulded depth	18.5 m
Tonnage	
Net Tonnage	12436
Gross Tonnage	31445
Deadweight	46327 t
Length Overall x Breadth Extreme	185.99m × 32.2m

Kiafan oil tanker crew management consists of the followings:

- **Crew data:**
  - Total number of crew: 32
  - Nationalities of Crew: 8 Nationalities, include: Kuwaiti, Indian, Egyptian, Bulgarian, Lebanese, Polish, Yemenite and Filipino
  - Language used on board the tanker is English

- **Kiafan's Captain:**
  - Age / Nationality: 39-year-old / Indian

- Captain since 2015 with overall 44 months experience as captain. He assigned as Kiafan's Captain in 22 June 2017, which is approximately one month before the accident.

- **Kiafan's Third Officer:**
  - Age / Nationality:24-year-old / Kuwaiti
  - Joined KOTC since 2009
  - Joined Kiafan since April 2017 (two and a half months) and it was his first trip as navigation watch keeping officer

- **Kiafan's Bridge Sailor:**
  - Age / Nationality: 45 year-old / Filipino
  - Joined KOTC since April 2016
  - Joined Kiafan since April 2017

4.3.2 Unison Star Bulk Carrier

Unison Star is a Bulk carrier built in 2011 by STX OFFSHORE & SHIPBUILDING CO. LTD. - Jinhae, South Korea. Currently sailing under the flag of Hong Kong. Formerly also known as Uniso H, Umz\8 Bgxy0e1, Unison Star. The details of Unison Star are given in Table (4-2) and Unison Star's photo is illustrated in Figure (4-3) [37].

Figure 4-3: Unison Star Cargo Ship

Table 4-2: Unison Star's Ship Data Sheet

Vessel Description	
Ship's Name	M/V UNISON STAR
IMO number	9579391
Ship's Type	Bulk carrier
Date delivered	2011
Builder	STX Offshore & Shipbuilder CO., LTD. KOREA
Flag / Port of Registry	Hong Kong SAR
Type of hull	Single
Dimensions	
Length overall (LOA)	189 m
Length between perpendiculars (LBP)	180 m
Extreme breadth (Beam)	30 m
Moulded depth	15 m
Tonnage	
Net Tonnage	12,342
Gross Tonnage	24,735
Deadweight	38,190.2 KT
Length Overall x Breadth Extreme	189m × 30.36m

4.4 Collision Case Study

4.4.1 Course of Events

In the following section, a detailed illustration of the events prior to collision are given in timely and action performed by each vessel crew.

- **23 July 2017 (10:00 am):** KOTC'S Kiafan oil tanker arrived at Kotopia's - Bangladesh anchorage area to unload a shipment consists of gasoline oil and aviation fuel oil. Unloading operation scheduled to be in three stages, where Kiafan oil tanker will unload part of the shipment to small ship in each stage.

- **23 July 2017 (01:00 pm):** KOTC'S Kiafan oil tanker anchored at Alfa birth - Chittagong – Bangladesh. As per the regulation of Chittagong – Bangladesh, the anchorage position is decided by the ship captain.

- **23 July 2017 (12:00 pm):** successfully completed the first unloading operation of the shipment to small port tanker.

- **24 July 2017 (04:48 am):** successfully completed the second unloading operation of the shipment to small port tanker.

- **24 July 2017:**
    - **08:00 am:** Kiafan's third officer started his shift accompanied by a qualified sailor who was on duty at the bridge. At this time, a bulk carrier ship "Blue Lotus" anchored with a distance of 4.6 Nautical Mile from Kiafan. At 09:00 am Kiafan's captain went to the bridge for daily office work and check. This is comply with the recommendation of the Chittagong Port Authority "CPA" to keep monitoring the ship all the time once it is in the anchorage area and registering any observation.

    - **10:49 am:** Kiafan's bridge sailor observed that a ship "Unison Star bulk carrier" entered to the anchorage area for anchoring with a speed of 4.9

knots. Unison Star was approaching the Blue Lotus in a precarious situation. Therefore, Kiafan's bridge sailor informed the captain and the third officer that the two ships Unison Star and Blue Lotus had been very close in a precarious situation, which had witnessed the rapprochement situation. Accordingly, Kiafan's third officer called Blue Lotus ship to raise their attention regarding to the situation. Kiafan's captain thought that it is not a dangerous situation as Unison Star has full control on the ship engine and are aware of the area and regulations, so there is no risk on Kiafan. Therefore, the action taken only to observe the rout of the Unison Star on the radar.

- **11:04 am:** Kiafan's bridge sailor and third officer observed that Unison Star began to retreat away from the Blue Lotus mainly due to water current effect (4.1 knots) and began to swing sharply towards the starboard direction, where it highly affected by the current in the horizontal direction. The Unison Star was on a 322^{o} course and was running at 5.5 knots and Kaifan direction was 166.3^{o} and the sea current was 4.1 knots as indicated in Figure (4-4) [38].

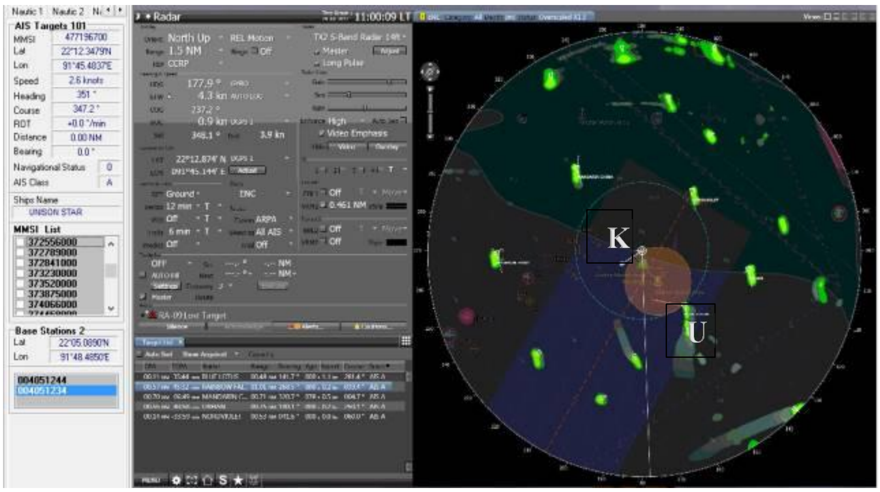

Figure 4-4: Radar Location of Kiafan's "K" and Unison Star "U"

- **11:06 am:** Unison Star begun to drift towards the Kiafan. Accordingly, Kiafan third officer called Unison Star via radio call but no answer. The third officer informed the captain who informed the crew about the approaching of Unison Star carrier and tried to make call Unison Star using the maritime radio but no response received. Therefore, the captain called the port authority to inform them and report the situation.

- **11:08 am:** Kiafan's Captain contacted the Unison Star ship using maritime radio and requested them to operate their engine at full speed in the forward direction to avoid approaching collision situation. Unison Star responded by using their half speed (medium speed), which caused Unison Star to move quickly towards the Kiafan. At this situation, Kiafan third officer recommended to move back to avoid direct collision and accordingly Kiafan captain ordered to move back slowly, then increased the speed of the main engine to move half its power towards the rear after 30 seconds.

- **11:09 am:** the Unison Star was approximately 1.0 nautical miles from the front of Kiafan tanker. Kiafan's captain realized that the collision was imminent, therefore he triggered the alarm and announced the possibility of collision. The collision happened at the left rear of the Unison and up to midway with the front of the Kiafan.

In the following section, a detailed illustration of the events of Post collision are given in timely and action performed by each vessel crew.

- **11:11 am:** Unison Star continued to swing in the direction of the starboard. The Unison Star was at 138° and 1.5 knots, while the Kaifan was at 148° and 1.7 knots in the rear direction and continued to move back with full engine power.

- **11:12 am:** Unison Star stopped to swing to the starboard direction. At the same time, Kaifan's engine stopped working.

- **11:14 am:** Unison Star was unable to separate from Kaifan and was not moving as Kaifan's anchor chain turned around Unison Star propeller.

- **11:21 am:** Kaifan started to move backwards using half engine speed.

- **11:23 am:** Kaifan stopped its engine as the rear of Unison Star was stuck on the port side of Kaifan.

- **11:26 am:** the Kaifan engine turned on its engine again to operate half the engine power towards the rear. Kaifan's captain tried to contact the Unison Star using the maritime radio but with no respond. Kiafan's captain was trying to move away from Unison Star to avoid any impact from the uncontrolled swing of Unison Star, which may increase the damage and affect the ship stability.

- **11:47 am:** Kiafan's moved forward with maximum capacity and keeping its steering wheel towards the far right. This caused Unison Star to come close to Kiafan from front port side and suspend to Kiafan. Then, it separated due to the forward movement of Kiafan and became far from Kiafan by a distance. Therefore, Kiafan reduced it speed to half of the full ahead speed. Unison Star confirmed no control on ship engine as they lost the propeller and they are no longer using the main engine. Therefore, Kiafan moved to another safe location (12:47).

Figure (4-5), shows a sketch diagram to the main collision time. The Figure illustrate the first possible collision between Unison Star and Blue Lotus, which not happened, and the collision events between Unison Star and Kiafan.

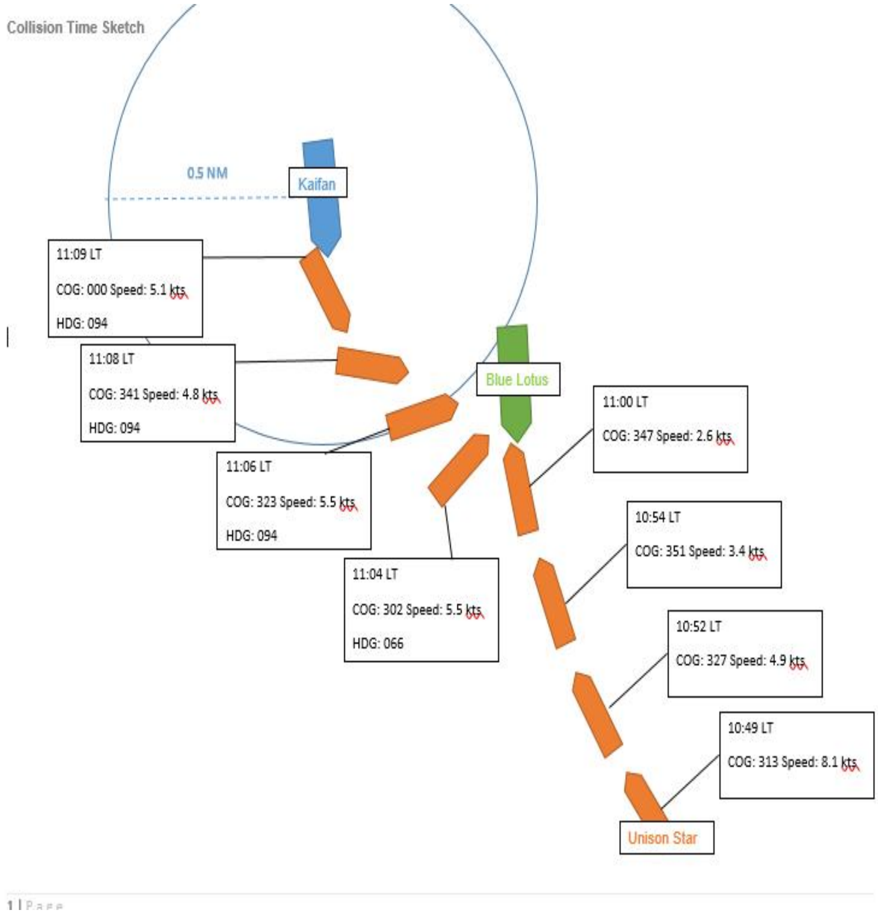

Figure 4-5: Illustration Sketch for Unison Star Collision Scenarios

4.4.2 Comprehensive and multi-linear description of the accident process

In the following section, a detailed comprehensive description of the events prior to collision are given in timely and action performed by each vessel crew. I propose a systematic process for accident investigation based on multi-linear events sequences and a process view of the accident phenomena. This comprehensive description is done be using **STEP** (Sequential timed events plotting**).**

The STEP diagram provides a systematic way to organize the events into a comprehensive, multi-linear description of the accident process. Also shows the use of arrows to link tested relationships among events in the accident chain. Figure (4-6), (4-7) shows the collision case study, Union Star ship is called (A), Blue lotus ship is called (B) and Kiafan ship is called (C).

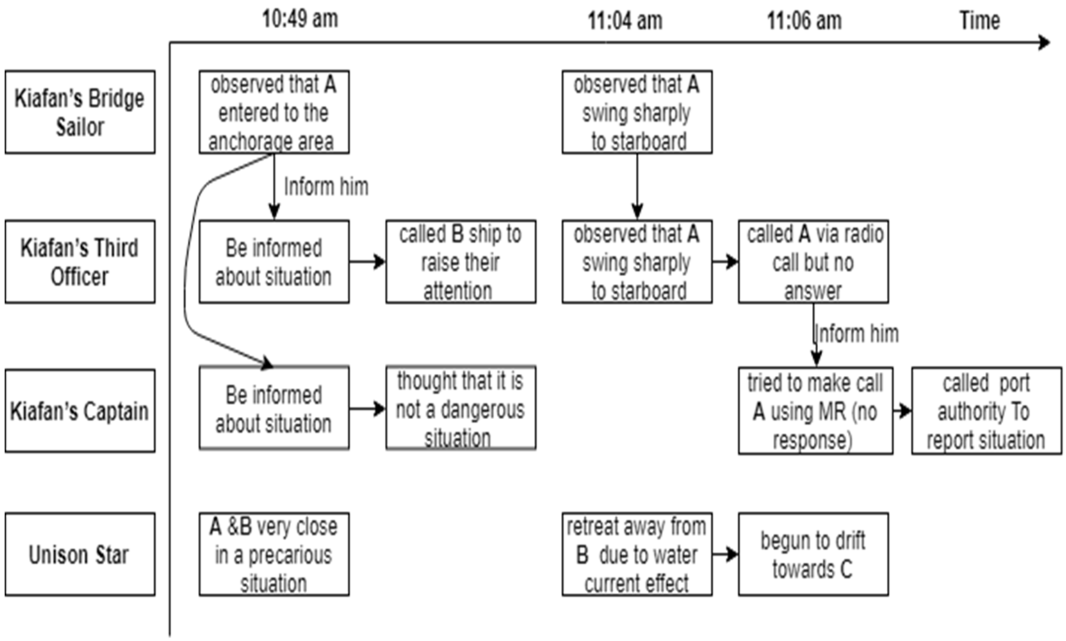

Figure 4-6: STEP- Diagram for Collision Process (a)

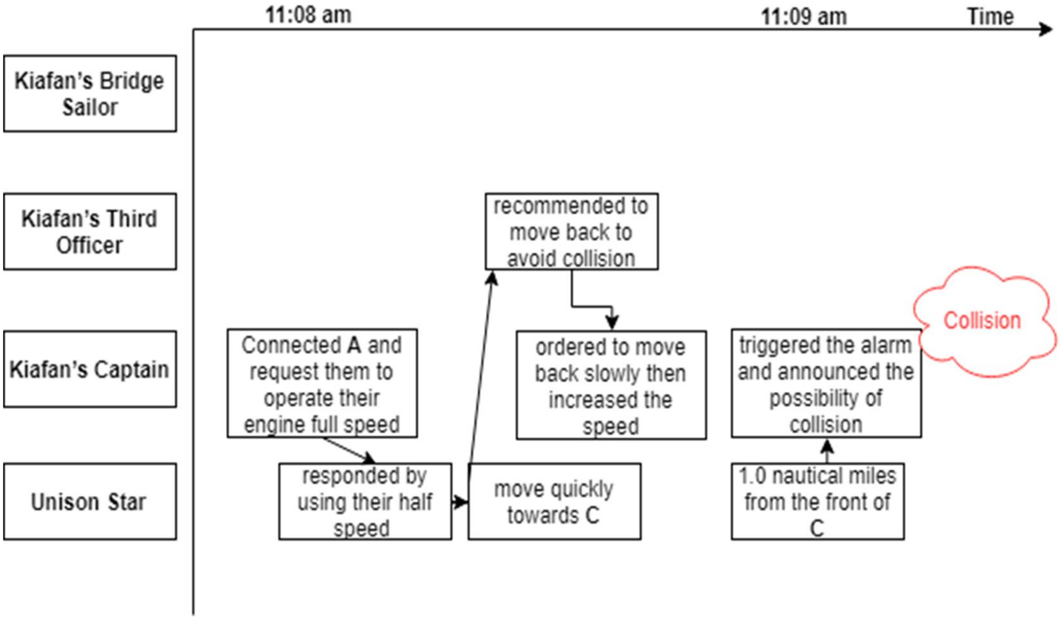

Figure 4-7: STEP Diagram for Collision Process (b)

In the following Figure (4-8), (4-9), a comprehensive description of the events of Post collision are given in timely and action performed by each vessel crew.

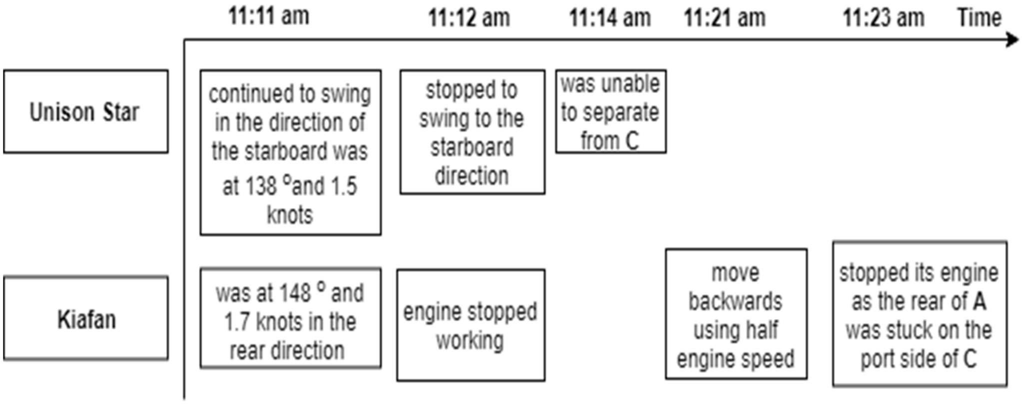

Figure 4-8: STEP Diagram for Post Collision Process (a)

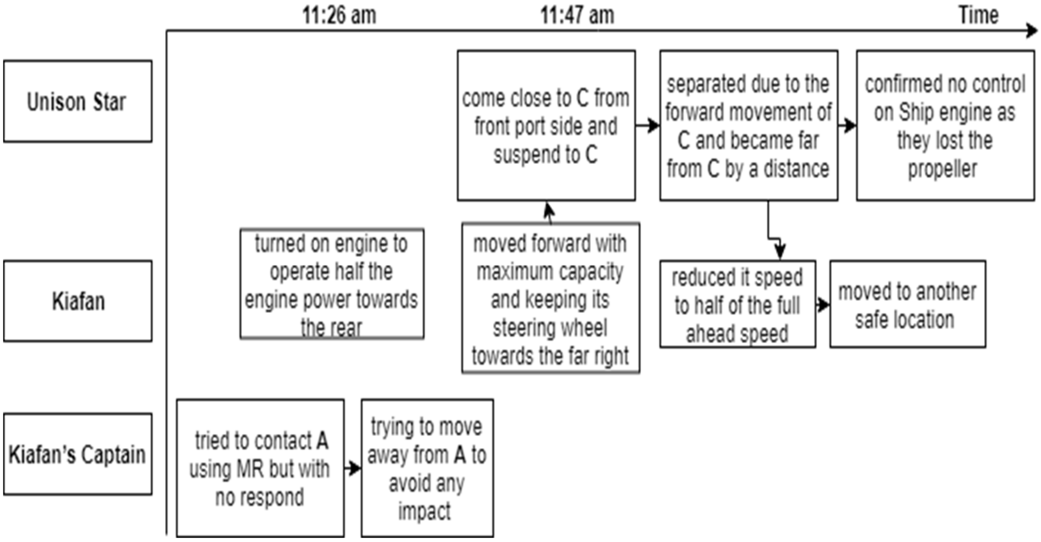

Figure 4-9: STEP Diagram for Post Collision Process (b)

4.4.3 Collision Consequences

The collision caused hull damage for both ships with no injuries and pollution. Beside the hull damage, Unison Star lost the main propeller and extensive maintenance needed to the main propulsion system. The detailed report of the damages caused by the collision to Kiafan oil tanker indicates the followings:

1) 12 shackles of port anchor chain lost to sea.

2) Structural Damages include:

- Shell plates damage and members deformed at forward starboard side.
- Shell plates damage and members deformed at bulbous bow.
- Three tie guard rails deformed and broken, emergency embarkation light post damaged, windless compressor damaged at fore castle deck and forward at starboard side.
- Shell plates damage at wing tank starboard side.
- Shell plates damage at wing tank port side.
- Shell plates damage at wing tank port side.

- Ship side shell plates damage at pot quarter Webs, side longitudinal and transverse frame deformed at steering gear room at port side.
- Aft bulkhead, web frames and scupper pipe deformed at engine room internals of port side shell plate.

The location of collision damages to Kiafan at forward port and starboard sides are illustrated in Figure (4-10) [39].

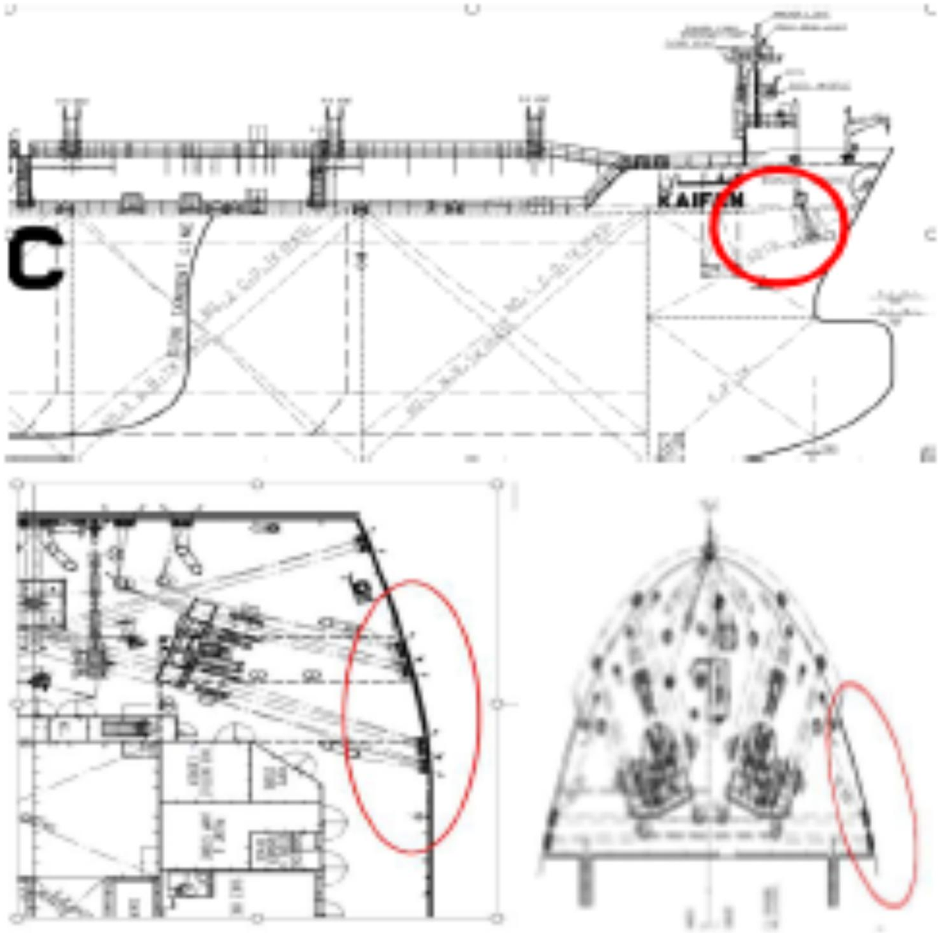

Figure 4-10: Locations of Kiafan's Hull Damages due to Collision

4.4.4 Results and Discussion

Casual factors of the Accident

The followings highlight the main causes contributed to the occurrence of the collision, which are directly associated with human factor:

- **Unison Star ship** entered the anchorage area with relatively high speed, which is against CPA polices that instruct all vessels to enter in low speed and anchorage at safe distance from other vessels.

- **Kiafan's Captain** limited the risk of the situation when Unison Star entered the anchorage area with high speed to normal or low risk. He built his judgment on general conclusions that all ships working in this region are familiar and aware of the regulations and have the experience in entering such areas.

- **Unison Star** did not consider /estimate the high effect of water current in this area, which led at the end to lose the control on the ship.

- **Unison Star** did not response to Kiafan's captain calls and warnings in order to clarify its situation and to be at safe distance from Kiafan.

- **Unison Star** responded to Kiafan radio directions once they are at critical situation. This clarify that they were able to receive the calls but they did not answer. Moreover, they did not response to the requested action by Kiafan to avoid the collision.

- **Kiafan Tanker.** The low estimation of the risk and unexperienced crew with the region and collision situation are highly contributed in bad evaluation of the situation and delay in taking correction actions toward moving the tanker in full speed to the rear direction.

- **Unison Star.** Loss of ship control due to lack of experience and violation of port authority polices, where it is clearly indicated that crossing of bow at close range shall never be attempted, increased the risks that led to collision.

- **Actions taken** by both ships to be apart clearly show the lack of experience of both crews in dealing with emergencies.

As per the illustrated events of the accident and the investigation report, the main cause of the accident was the completely loss of control on Unison Star to avoid colliding with a Blue Lotus ship, which caused drifting of Unison Star towards Kiafan oil tanker. However, the tracking of the accidents events and detailed analysis of the actions taken by both ships clearly show that human error is the main cause of this collision.

The analysis of the collision events clearly showed that both ships indicated lack of experiences and knowledge in managing such situation, which highly affected by the short time window of the accident. Moreover, the dispersion and absence of control of the Chittagong port authority contributed as main factor for this accident.

The analysis of human error causes of the collision case study as per the main human error categories shows the followings:

1. **Unintended Actions** attended to collision. These errors represented by no situational awareness and dispersion in dealing with the situation from both ships.

2. **Intended Actions** Mistakes attended to collision. These mistakes are represented by neglecting the use ship positioning identification system by Kiafan. Ship positioning identification system interferes with the electronic mapping system, which provides early assessment of the position where collision can be avoidance. Kiafan's third officer focused in using radar system to track the change of Unison Star position when it was about two nautical miles away, which was too late to avoid collision. No significant attempt to avoid collisions was taken by Kaifan's Captain when Unison Star was in close

proximity to Blue Lotus. However, the action taken to move Kiafan backward was too late.

3. **Intended Actions** Violations attended to collision. These errors represented by Non-compliance of Unison Star with CPA polices for approaching and entering anchorage area. Violation of Union Star of CPA polices for crossing ships of bow at close range. No response of Union Star to Kiafan radio calls.

4.5 Recommendation

As lesson learned from the collision and in order to eliminate the repetition of such situation, KOTC issued the followings corrective actions:

- Reviewed the emergency response procedures for anchor operation and clarified all the possible emergency situation to crew.

- Reviewed and updated the company senior officers' assessment and upgrading system to have more focus in leadership and control competencies.

- Considered registering Kiafan captain in an effective leadership and management courses.

- Considered offering courses for crew management at emergency situations to ensure efficient utilization of manpower onboard ship.

- Considered contracting with third party to unload KOTC charge from oil at Cotubidia port instead of anchorage area of Chittagong, which will reduce the risk during the unloading process, especially during seasonable wind times where the maximum impact of the current occurs.

Moreover, the followings are recommendations from the collision case study:

- Shipping companies should seriously consider the experience of the captain and crew when working is high-risk areas. Captain should accompanied with expert crew when assigned to work in such area for the first time. This will reduce the risk of bad judgment.

- Working in high-risk navigation areas require regular review of the emergency response and procedures of these areas. This is to ensure the awareness and knowledge of all the concerned crew. Training courses and well-established emergency operational guidelines for high-risk areas will highly assist in reducing human errors.

- To reduce risk of collision specifically due to human error in anchorage areas, the followings are recommended:
    1. Bridge watch should be continuously maintained, and a vessel's position accurately monitored.
    2. Close monitoring of the position of the surrounding vessels
    3. Main engines should always be on standby
    4. Windlasses should be kept ready with available power to raise the anchor quickly at short notice.
    5. Anchor chains should not be over-extended, to avoid the swinging of the vessel over a greater-than-normal arc, increasing the risk of collision.
    6. Contact should be maintained with the Port Authority to view the latest advisories and updates regarding tide, current and wind conditions.
    7. In a crossing situation, continue to keep a proper lookout in order to judge the risk of collision properly.
    8. If the other vessel does not take action to avoid a collision, immediately give a warning signal.

Chapter 5 Ships Collision Avoidance Algorithm

5.1 Introduction

The navigation technology has been developing year after year, ship collision still accounts for a large percentage of maritime accidents. Ship collision is a physical impact between ships or a ship and a floating or fixed objects. If ships collide, the damage and cost can be astronomical. There are huge impacts on our life, economy and environments. It is very difficult for officers to ascertain routes that will avoid collisions, especially when multiple ships proceed the same waters. To prevent ship collisions many ways have been suggested, e.g., lookouts, radar, and VHF radio. The 1972 COLREGs which is the regulation for preventing collision between ships. It specifies navigation rules to be followed by all ships at sea to prevent collisions. However, it would be very hard to describe all possible conditions in the form of rules due to the complexity of the actual marine environment. On top of that, it would be a big burden for an officer to consider many different variables to apply to the rules in time-pressed situations [1].

Technologically speaking, many related studies have been conducted. The term "Ship domain" involves that area surrounding a ship that the navigator wants to keep other ships clear of. Ship domain alone is not sufficient, however, for enabling one or more ships to simultaneously determine the collision risk for all of the ships concerned. More advanced methodologies, such as fuzzy theory, and genetic algorithm, have been proposed [40]. Fuzzy theory is useful in helping ships avoid collision in that fuzzy theory may define whether collision risk is based on Distance to Closest Point of Approach (DCPA), Time to Closest Point of Approach (TCPA), or relative bearing - algorithms that are difficult to apply to more than two ships simultaneously [41]. These methods work well in one-on-one situations, but are more difficult to apply in multiple-ship situations.

However, in reality, collisions between ships frequently occur. This is partly due to the ever increasing size and speed of ships each year. A primary cause of ship collisions is officer error. OOW have generally some expertise in finding safe routes that will avoid ship collisions; however, particularly when shipping lanes are crowded and many ships encounter each other simultaneously, finding such routes is especially difficult for officers. The need to repeat this task throughout the voyage multiplies the risk of human error.

Ship collision avoidance involves helping ships find routes that will best enable them to avoid a collision. When more than two ships encounter one another, the procedure becomes more complex since a slight change in course by one ship might cause a “butterfly effect” in the whole system. To support the need to find safe routes for ship traveling in crowded waters, I propose the Distributed Algorithms such as Distributed Local Search Algorithm (DLSA), Distributed Tabu Search Algorithm (DTSA) and Distributed Stochastic Search Algorithm (DSSA). Along with the development of the Distributed Algorithms, I also suggest a new cost function that considers both safety and efficiency. By adjusting a weight factor of the cost function, a ship can consider both.

In this chapter, I explain the background of my work. Furthermore, I show how the Distributed Algorithms is applied to ship collision avoidance, explaining variables, procedures for the proposed algorithm, and experimental results and make comparative analysis between distributed algorithms, finally proposed a computational methodology for collision avoidance.

5.2 Framework and Terminology

5.2.1 Framework

Distributed ship collision avoidance is made up of two procedures: control and search. A framework of these procedures is given in Figure (5-1). When a ship arrives at her destination, this procedure is terminated.

For the control procedure, the ship decides whether to proceed to the next position. If the ship does not have any neighboring ship within a certain area, namely detection range, and also has not yet arrived at her destination, she moves to the next position.

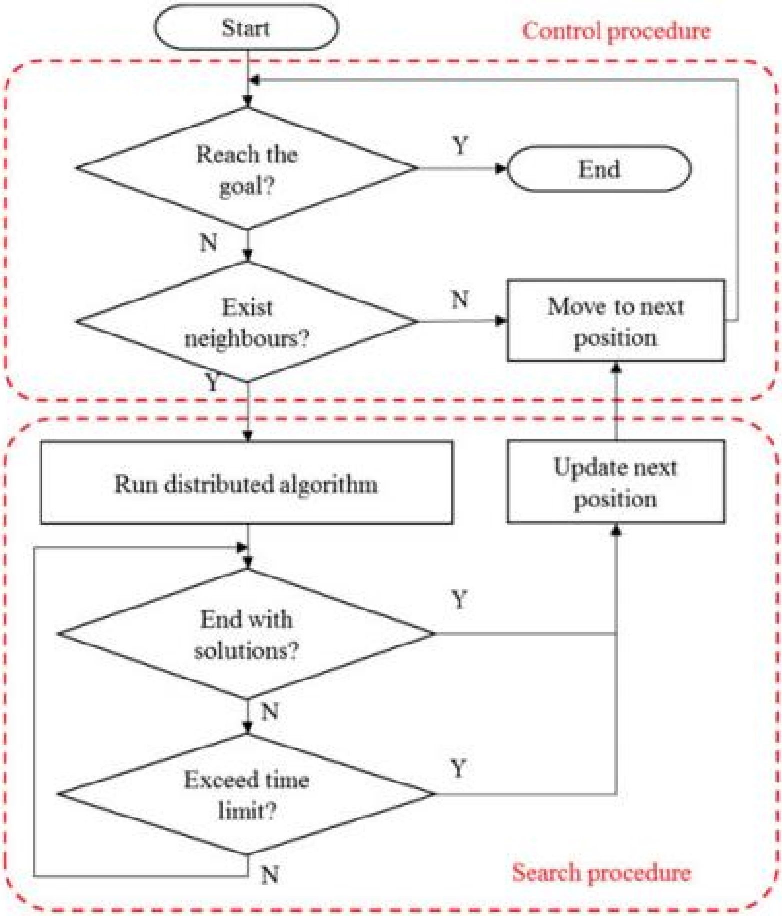

Figure 5-1: Framework of Distributed Ship Collision Avoidance

For the search procedure, a ship tries to avoid collision by running a distributed algorithm when she confirms that there is a collision risk. If every ship finds a solution, or if the computational time exceeds a certain time limit, they move to the next positions. A time limit on the computational time is set for all ships exchange messages with each other to figure out safe courses. When the time has elapsed, they update the next positions (typically, with the courses that may not be safe but have the minimum cost found so far) and all ships move to the next positions to check whether a collision happened on the spot. The ships alternate the search and control procedures until they arrive at their destinations.

5.2.2 Terminology

Figure (5-2) illustrates the basic terms of algorithm. The home ship (own ship) located at the center has a detection range to detect neighboring (target) ships. The home ship can exchange messages with the neighboring ship in the detection range, but not with the ships located outside the detection range. The home ship tries to keep a safety domain between herself and the neighboring ship. The safety domain is a circle with a certain radius depending on ships. If that safety domain is penetrated, it is considered they collide with each other.

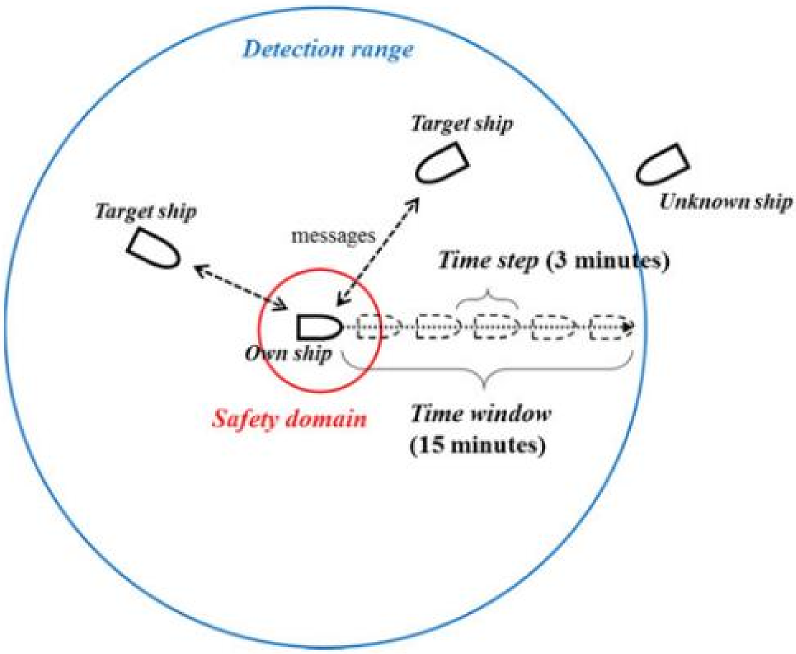

Figure 5-2: Basic Terms

The meaning of the terms are as followings:

- **Home ship:** A ship that focus on.
- **Time step (T):** The maximum length of time (in minutes) for which the home ship plans her future positions.
- **Detection range:** The area in which the home ship can communicate with other ships.
- **Neighbor:** A ship located within the detection range. The home ship can exchange messages only with her neighbors.
- **Safety domain:** The area that the home ship prohibits a neighboring ship from penetrating.
- **Ok? Message:** It includes information of position.
- Improvement message: It includes the number how much the cost is reduced.
- **ID:** Identification is given at initial state. It is used when improvement is same with neighboring ship's one. A ship with higher priority ID has the right to choose next course.
- **Candidate course:** Considering the maneuvering ability of ships, the altering course is restricted as shown in Figure (3-3). It has to be considered with the characteristics of ship, such as speed, tactical circle and the traffic condition.

Due to the characteristics of ship, a ship has a restriction to change maximum course as shown in Figure (5-3). The figures show candidate courses for a ship. For example, when maximum changeable course is 10 degrees, a ship can choose one of them, such as starboard 10 degrees, forward, and port 10 degrees. Figure (5-4) shows the change of neighboring ships depending on the detection range of home. Ship at center. The larger the size of the detection range, the more the number of neighboring ships.

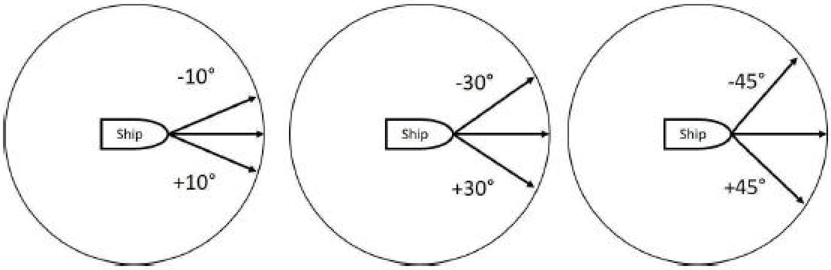

Figure 5-3: Limit of Maneuvering Course.

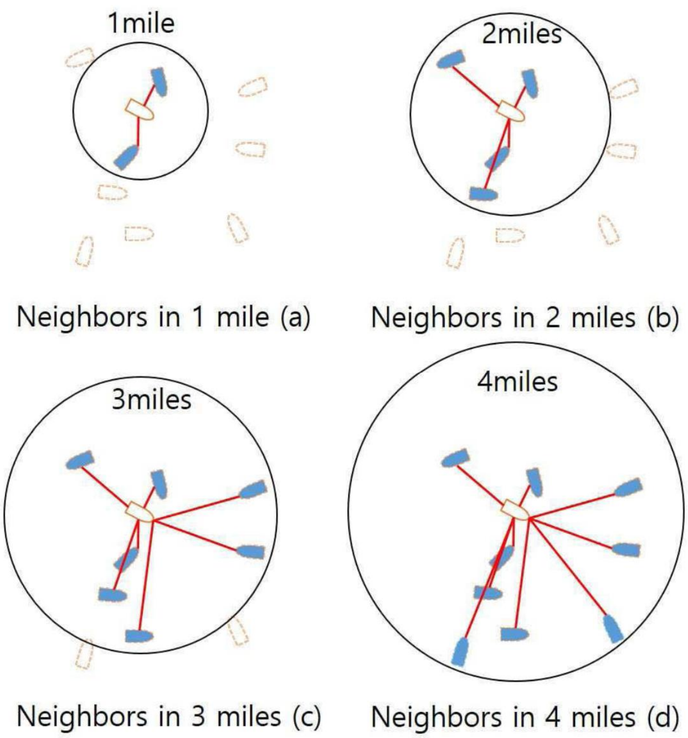

Figure 5-4: Change of Neighboring Ships Dependencies

Figure (5-5) shows multiple-ship situations. Each ship has her own local view called detection range (red circles). The home ship can exchange messages with a neighboring ship, but not with a ship located outside the detection range. To arrive destination, home ship exchanges messages with neighboring ships until she finds a safe course. Then home ship proceeds to next position. Home ship repeats this process until she arrives at the destination.

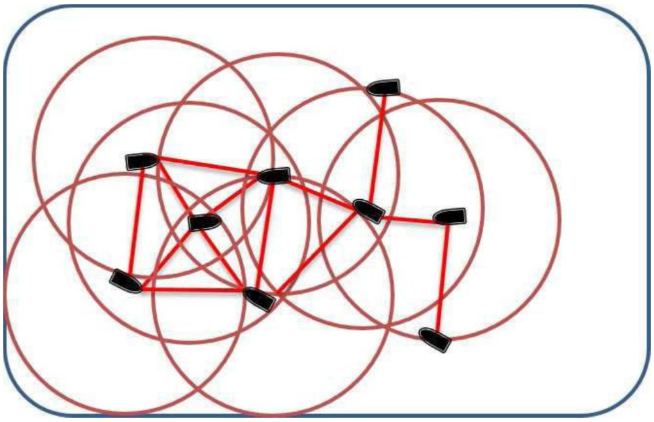

Figure 5-5: Multiple-Ship Situations.

Suppose, for example, that a ship sails the ocean at 12 nautical miles per hour. Due to the restriction on ship movement, a sailing ship cannot change her course abruptly. Once she selects a course, she must follow it for a certain period. The ship is required to consider changing her course every three minutes (every 0.6 nautical miles). The ship plans her future positions in 15 minutes based on current positions, headings, and speeds of herself and her neighbors. Note that this is done every three minutes through communication with neighboring ships. The *Ok?* Message includes the information for position. The improvement message includes the number how much the cost is reduced. The ship exchanges both messages with neighboring ships. When (T) gets larger, a ship becomes more proactive.

5.2.3 Cost and Improvement

For a candidate course, two things have to be considered, i.e. collision risk against a neighboring ship and relative angle between a candidate course and destination as shown in Figure (5-6)-(a). I propose a cost function considering both of them. The cost function is used for all distributed algorithms that will be shown in the following sections. Given current positions, headings, and speeds of neighboring ships, a ship computes the cost for each candidate course. A candidate course is chosen from a discrete set of angles as shown in Figure (5-6)-(b). In consideration of typical ship maneuvering, it ranges from 45 degree on the port side (-45 degrees) to 45 degrees on the starboard side (+45 degrees) in step of 5 degrees. If the angle heading for a destination exists in these bounds, it is also included as a candidate course.

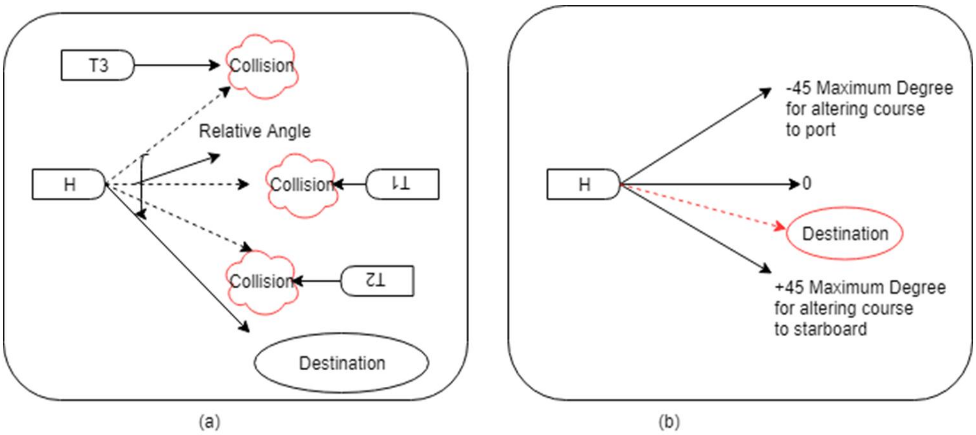

Figure 5-6: (a) Collision risk and relative angle **(b)** candidate courses and heading angle for destination

I propose a cost function that is comprised of the collision risk against a target ship and the relative angle between a candidate course and a destination.

Equation 5.1 shows the collision risk, where *crs* and *j* mean a candidate course and a neighboring ship, respectively, and *self* means the home ship. It *self* will collide with ship *j* in *T* when choosing a course *crs*, and CR_{self} for *crs* and *j* is computed as *T* divided by *TCPA*. It becomes zero, otherwise.

$$CR\ self(crs,j) \equiv \frac{T}{TCPA_{self}(crs,j)} \tag{5.1}$$

Equation 5.2 computes the *COST* for a course *crs*, which is made up of two parts: first, the sum of CR_{self} over the neighboring ships at risk for *crs*, and second, the relative angle between *crs* and a destination. α is a weight factor that controls the relationship between the safety and efficiency. In equation 5.2, the front part, CR_{self}, is for the safety against target ships, and the rest part is for the efficiency, considering the destination. If α gets larger, a ship places more emphasis on safety than efficiency. On the other hand, the ship goes long way round. For all distributed algorithms, I set the value of α to one. During the search, a ship tentatively selects one course as her next-intended course that causes some cost computed by equation 5.2. However, she may be able to reduce the cost by changing it to another course.

$$COST_{self}(crs) \equiv \alpha \sum_{j \in Neighbors} CR\ self(crs,j) + \frac{\theta_{dest} - \theta_{self}(crs)}{180^{\circ}} \tag{5.2}$$

Equation 5.3 computes the largest reduction in costs as $improvement_{self}$. A ship always tries to select the course that gives the largest reduction in costs. A ship is always aware of absolute angles $\theta_{heading}$ and θ_{dest} for her heading and destination, respectively. As shown in Equation 5.4, a course for the destination is computed by$\theta_{dest} - \theta_{heading}$ to be added into a set of candidate courses only if the course is within the bounds on alterable angles.

$$improvement_{self} = \max(COST_{self}(next\ intended\ course) - COST_{self}(crs)) \tag{5.3}$$

$$\theta_{dest} = \theta_{dest} - \theta_{heading} \quad if\ |\theta_{dest} - \theta_{heading}| < 45^{\circ} \tag{5.4}$$

Figure (5-7) is an example of how to compute $COST_{self}$ and $improvement_{self}$ for the home ship (H). Ships T1 and T2 are neighboring ships of the home ship. Ship T2 is contented with the current course. However, the home ship will collide with ship T1 after 12 minutes (four time steps) later with her current course. The cost for 000° is computed by COST(000°) = 5/4 + 18°/180° = 1.35, while the cost for 045° is COST(045°) = 0 + 27°/180° = 0.15, and the cost for 018° (the course for the destination) is COST(018°) = 0 + 0°/180° = 0. The $improvement_{self}$ for the home ship is thus computed by $improvement_{self}$=max *crs* {*COST* (000°) −COST (crs)} = 1.35, since the cost for 018° is clearly minimum among the candidate courses. Ship T2 is ruled out for computing the cost because ship T2 has nothing to do with any collision.

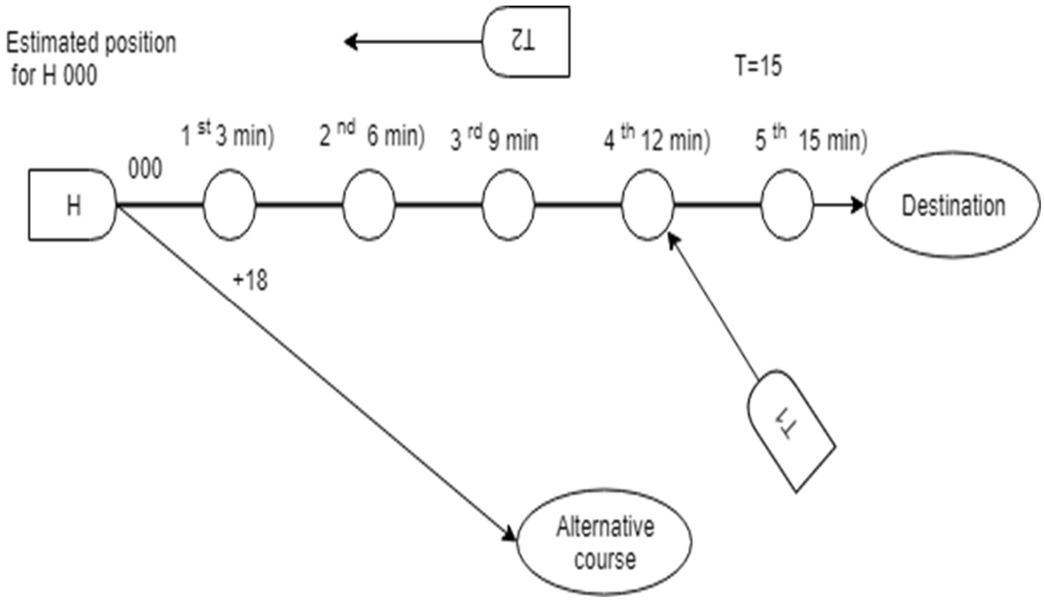

Figure 5-7: Numerical Example for Computing Costs and Improvements

5.3 Distributed Local Search Algorithm

5.3.1 Reason of selection

The algorithms from a regulations point of view such as COLREGs and the others from technological point of view such as ship domain, fuzzy theory, ant colony algorithm and neural networks define collision risk mostly in one-to-one ship situations, however, and are computed by using only local information without online communication among ships [42]. In this sense, it is said that most precedent algorithms are suited to a centralized system in which every computation is done by a server without online communication among participants, i.e., ship personnel. To deal with multiple-ship situations, which are more complex, however, algorithms must be suited to distributed systems that enable individual ships to exchange information online with neighboring ships. Indeed, exchanging such information online is important, but one further important consideration for individual ships is to know the intentions of other ships because individual ships otherwise cannot respond promptly to actions by other ships. Therefore I consider it important to enable individual ships to exchange information on both facts and intentions to avoid collisions in multiple-ship situations. I assume that individual ships exchange intentions with neighboring ships using an AIS. The AIS is a machine used on board to displays information such as the speed, bearing, and position of neighboring ships in real time. Based on AIS, I introduce a Distributed Local Search Algorithm (DLSA) for solving the ship collision problem effectively in multiple ship situations by taking into account the intentions of neighboring ships [43].

Local search is a met heuristic method for solving optimization problems and incompletely algorithms. It may find the solution to a problem or fail even if the problem is incomplete. Local search is applied to many problems, e.g., the traveling salesman problem or the nurse scheduling problem. The local search is a centralized system in which every computation is done at a central location or computer. It is easy to design a whole system if a server knows all information for all agents. The LS is an iterative improvement algorithm that keeps a ‘current’ state and tries to improve it [44], [45]. This process is repeated until no further improvement solution can be found.

If, for some reason, e.g. a server is broken, it is not possible to maintain a system. Compared to a local search, the DLSA searches locally for an approximation solution by different agents. The DLSA does not have a server and need not use a computer. This means that individual agents may solve a certain problem by satisfying constraints. This is why it is flexible in a system failure and adds less load in computation.

5.3.2 DLSA Procedure

The DLSA, is a distributed constraint satisfaction problem (DisCSP) which is a mathematical problem defined as a set of objects that are consistent with the assignment of values to variables or satisfying all constraints by multiple agents [46]. The DisCSP is consists of a set of agents, (1, 2. . . K) and a set of (CSPs, P1, P2.....Pk).

Figure (5-8) is the flowchart for DLSA. First, a ship sets current course as next intended course. Each ship exchanges information to compute ($COST_{self}$) and ($improvement_{self}$). If every ship is contented with next-intended course, then this process ends. Otherwise, they exchange an (improvement $_{self}$) message with neighboring ships. A ship which has the largest value of improvement chooses new *next-intended course* [47].

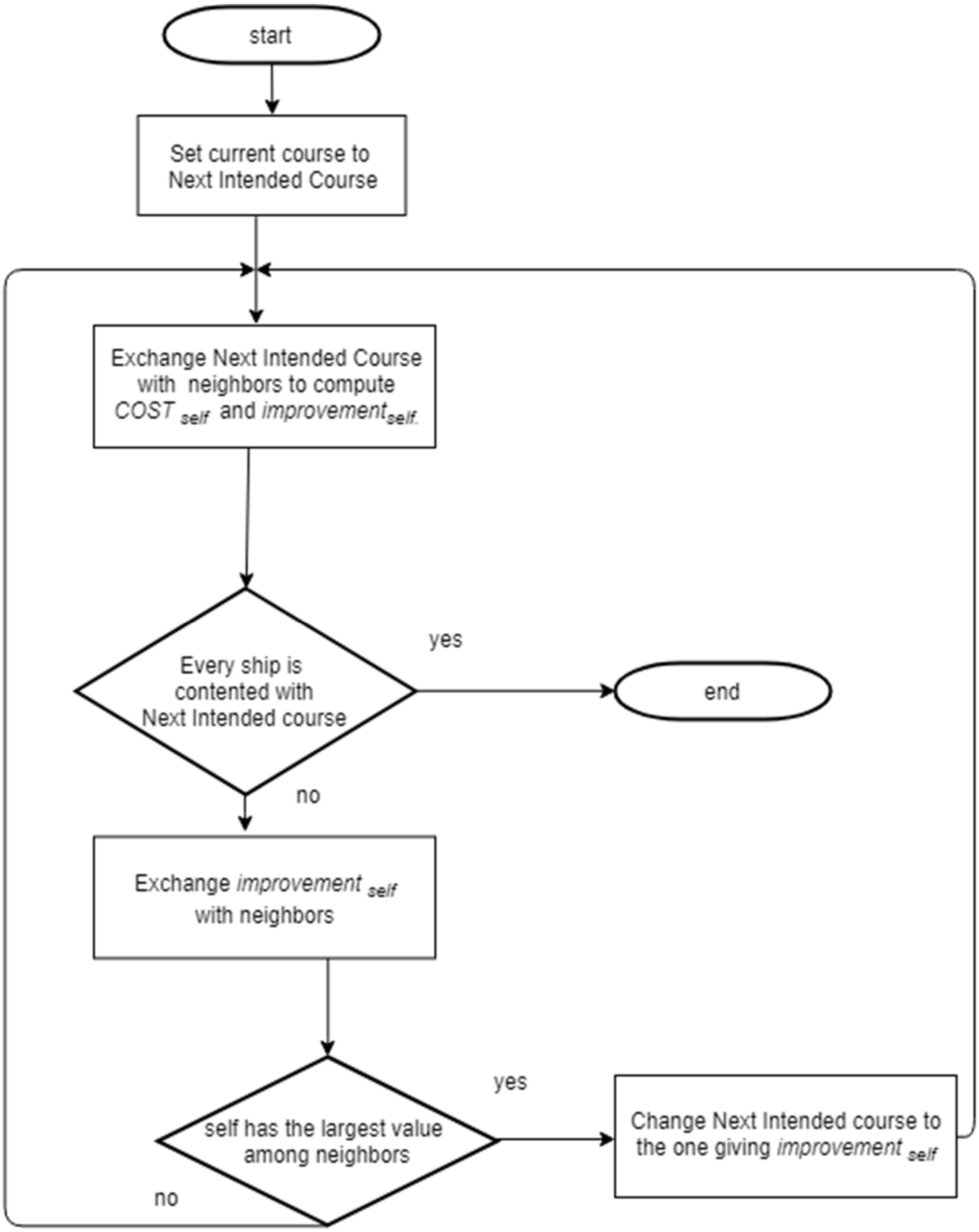

Figure 5-8: Flowchart of Distributed Local Search Algorithm

Figure (5-9) shows the process of the DLSA. This describes how to exchange messages and decides highest priority ship among ships. Assume three ships are encountered as shown in Figure (5-9)-(a).

A ship checks her position for whether she has arrived at a destination. The process will be repeated until a ship arrives at her destination. A ship searches a vicinity whether target ships exist. If so, target ships are added in the neighboring list. Each ship exchanges *ok?* Message with target ships. They compute the cost for each candidate course as shown in Figure (5-9)-(b).

If there are collision risks between ships, they exchange $improvement_{self}$ message as shown Figure (5-9)-(c). Each ship compares the value of improvement of herself and target ships. A ship that has the biggest improvement has a right to choose next-intended course. Otherwise, she keeps the current course as shown in Figure (5-9)-(d).

If more than two ships have same the value of improvement, the ties are broken by the ID of ships that is given randomly in an initial situation. This process continues until the collision risks disappear. If collision risk has disappeared, a ship proceeds to the next position and checks whether its position is the destination.

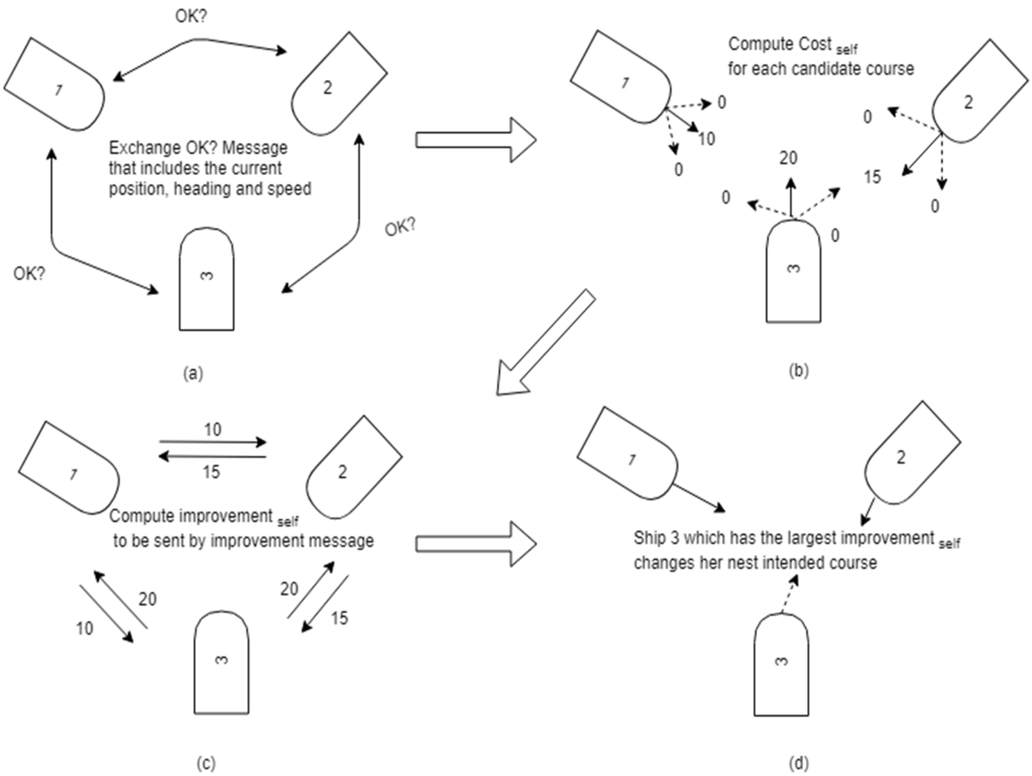

Figure 5-9: Flowchart Showing the Process of DLSA.

5.3.3 Results

DLSA is flexible during a system failure as If, for some reason, e.g. a server is broken, it is not possible to maintain a system. Compared to a local search, the DLSA searches locally for an approximation solution by different agents. The DLSA does not have a server and need not use a computer. This means that individual agents may solve a certain problem by satisfying constraints. This is why it is flexible in a system failure and adds less load in computation. DLSA is easily applied to ship collision avoidance in multiple-ships situations. All ships can chart their course freely. They prefer a course that will allow them to reach their destination safely and quickly. A certain sea area, such as an entry port, crossing area, or narrow area has no option but to be crowded because all ships will travel in a similar pattern. In addition, each individual ship must find a solution by itself using local information. However, according to the recent study, it is sometimes trapped in Quasi Local Minimum (QLM) that prevents a ship from changing course even when at risk of collision.

5.4 Distributed Tabu Search Algorithm

5.4.1 Reason of Selection

I suggested DLSA in the previous section. DLSA is flexible during a system failure. DLSA is easily applied to ship collision avoidance in multiple-ships situations. All ships can chart their course freely. They prefer a course that will allow them to reach their destination safely and quickly. A certain sea area, such as an entry port, crossing area, or narrow area has no option but to be crowded because all ships will travel in a similar pattern. In addition, each individual ship must find a solution by itself using local information. However, according to the recent study, it is sometimes trapped in Quasi Local Minimum (QLM) that prevents a ship from changing course even when at risk of collision. To deal with this issue, I propose a new distributed algorithm called the Distributed Tabu Search Algorithm (DTSA) [48]. DTSA enables a ship to search for a new course compulsorily when trapped in QLM, to allow it to escape.

Tabu search (TS) technique was invented by Glover in 1986 [49].TS was proposed to overcome Local optima and it has been made to meta-heuristic search method along with genetic algorithm, simulated annealing and ant colony algorithm. TS is being used in integer programming, scheduling, routing, and the traveling sales-man problem. By using memory to prohibit certain moves, TS searches for global optimization rather than local optimization. There are several kinds of memory structures, such as short, intermediate, and long-term memory. The short-term memory prohibits a solution (move) from being selected in the tabu list. The intermediate term memory may lead to bias moves toward promising areas. The long-term memory guides to new search areas for diversity. In conventional problems, application of the short-term memory only is sufficient.

This method enables precedent local search to overcome local minimum. To solve the problem of QLM, we applied tabu search technique, where the ship in QLM puts her current course in a tabu list to prohibit herself from selecting that course for a certain period of time. DTSA enables individual ships to choose another course compulsorily

5.4.2 DTSA Procedure

Figure (5-10) shows the procedure for DTSA. The whole framework is essentially the same as DLSA; only the QLM procedure (dotted red box) is added. All ships repeat this process until they arrive at their destination. Each ship checks for whether it has arrived the destination. If not, the ship searches the vicinity to find a neighboring ship. The ship exchanges an *ok?* And improvement messages with its neighbors. The ship with the highest improvement chooses the next-intended course. If there is no collision, all individuals move to the next position. If not, the ship exchanges the exchanged information with its neighboring ship. This process is repeated until all ships are contended with their next-intended courses. If QLM occurs, a ship calls the QLM procedure, in which she randomly chooses an alternative course excepting any courses in the tabu list. This process will be recurred until QLM is resolved. If the collision risk has disappeared, all ships move to the next position.

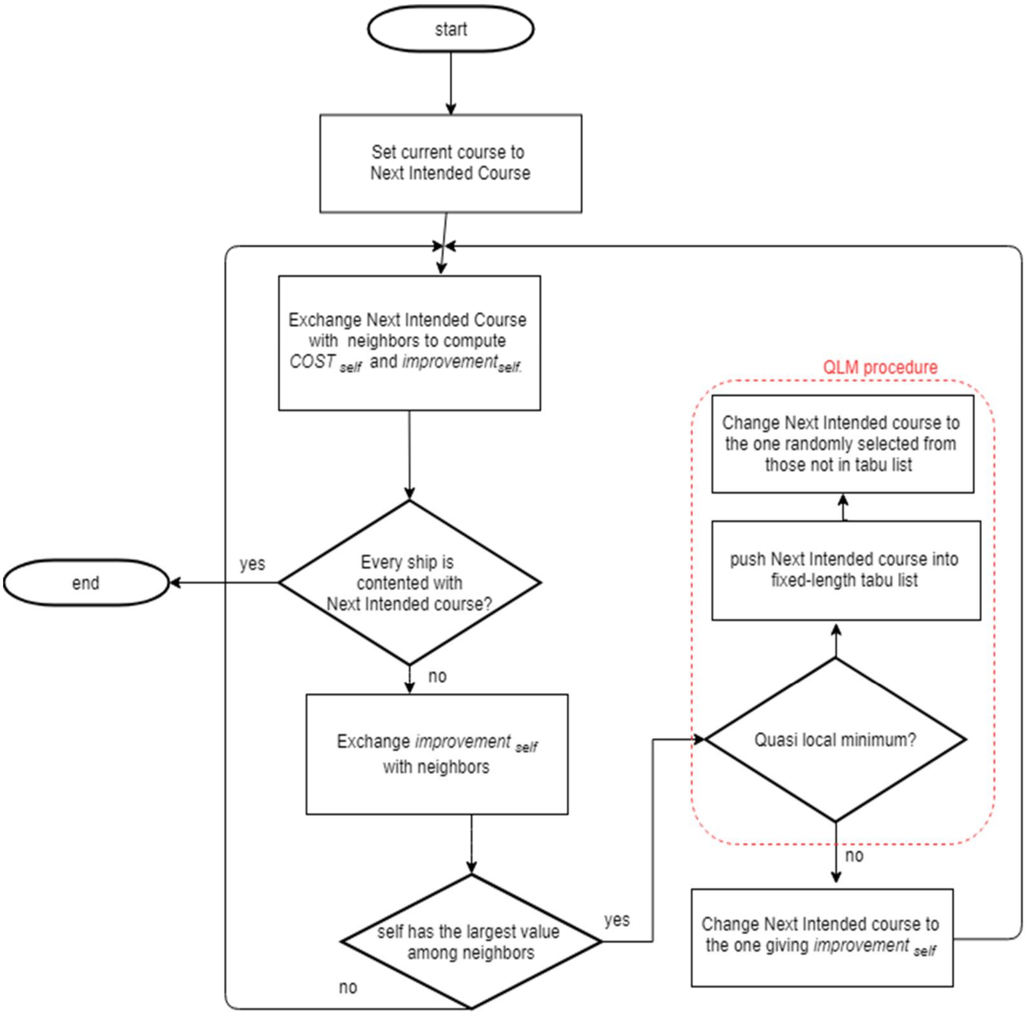

Figure 5-10: Flowchart Showing the Procedure of DTSA

Figure (5-11) shows the process of DTSA. Assume four ships encounter with each other as shown in Figure (5-11)- (a). Ships 2 and 4 are now satisfying current course. Ships 1 and 3 have the risk of collision at current course. Even though ships 1 and 3 alter their course to avoid collision, there still exist collision risk with ships 2 and 4. The current courses of ships 1 and 3 are recorded in the tabu list to prevent a ship from choosing current course as shown in Figure (5-11) - (b). Ships 1 and 3 choose a course randomly except tabu list as shown in Figure (5-11) - (c). After exchanging messages with each other, ships 2 and 4 start to search a course with minimum cost as shown in Figure (5-11) - (d).

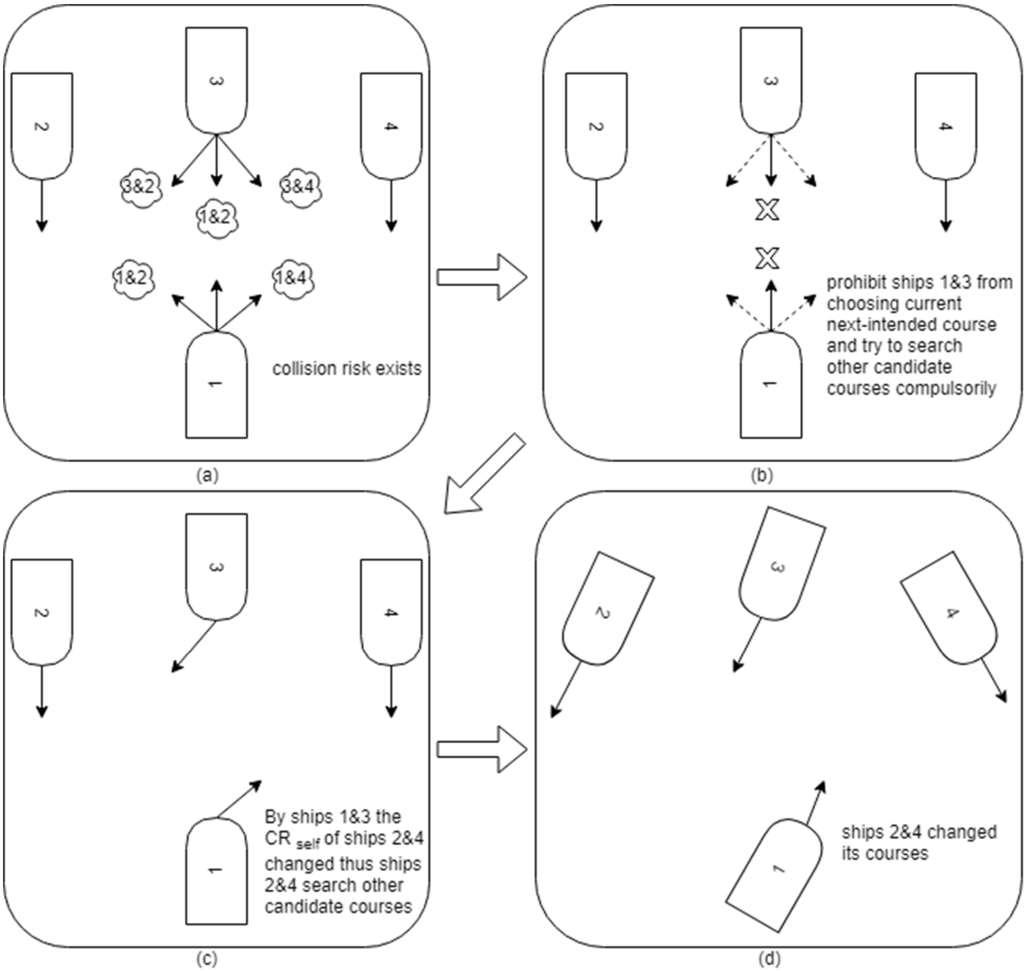

Figure 5-11: Flowchart Showing the Process of Distributed Tabu Search Algorithm

5.4.3 Simulation

The experiments are done with three different situations depending on the number of ships and various origins and destinations to test the performance of DTSA compared to DLSA. A ship has the following given values: Safety domain = {0.5, 1} nautical miles, Detection range = {10, 20} nautical miles, and Speed = {12} knots. The minus and plus signs indicate the port and starboard, respectively. To evaluate the performance, the success percentage and average distance are computed.

- **Success ratio:** The meaning of success is that all ships arrive at their destination without collision. The success ratio is the ratio between the number of successful results and total number of experiments.

- **Average distance**: The sailing distance is a ship's route from origin to destination. The average distance is the figure that the sum of the sailing distance for all experiments divided by the number of situations that result in success.

Table 5-1 shows the meaning of the index used in the experimental results.

Table 5-1: Candidate Course by Index used in Experiments

Index	Candidate course
15	{-15°,0°,+15°}
30	{-30°,0°,+30°}
45	{-45°,0°,+45°}
ALL	{-45°,-30°,-15°,0°,+15°,+30°,+45°)

1st Simulation

I experimented with six ships with four variables. Figure (5-12) illustrates the situation for experiment 1. Table (5-2) shows the neighboring ship list. Each ship records its neighboring ships in the list. That is, ship 1 recognizes ships 2 and 3. Ship 2 recognizes ships 1, 3, and 5. There is no collision risk for ships 1, 3, 4, and

6, but ships 2 and 5 are at risk of collision. All variables are used by changing their values in one situation. In total, sixteen experiments were conducted.

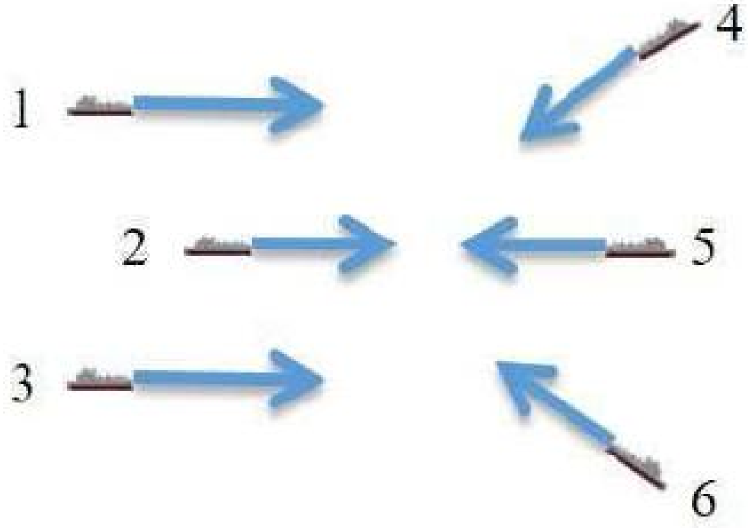

Figure 5-12: Situation for 1st Experiment

Table 5-2: List of Neighboring Ships For Experiment 1

Number of ships	1	2	3	4	5	6
1	X	O	O	X	X	X
2	O	X	O	X	O	X
3	O	O	X	X	X	X
4	X	X	X	X	O	O
5	X	O	X	O	X	O
6	X	X	X	O	O	X

Figure (5-13) shows the result for experiment 1. Compared with DLSA, DTSA has a better result. In case of 15, DTSA recorded higher success percentage than DLSA. The cases of ALL DTSA showed the best results, which were no failures and low average distance.

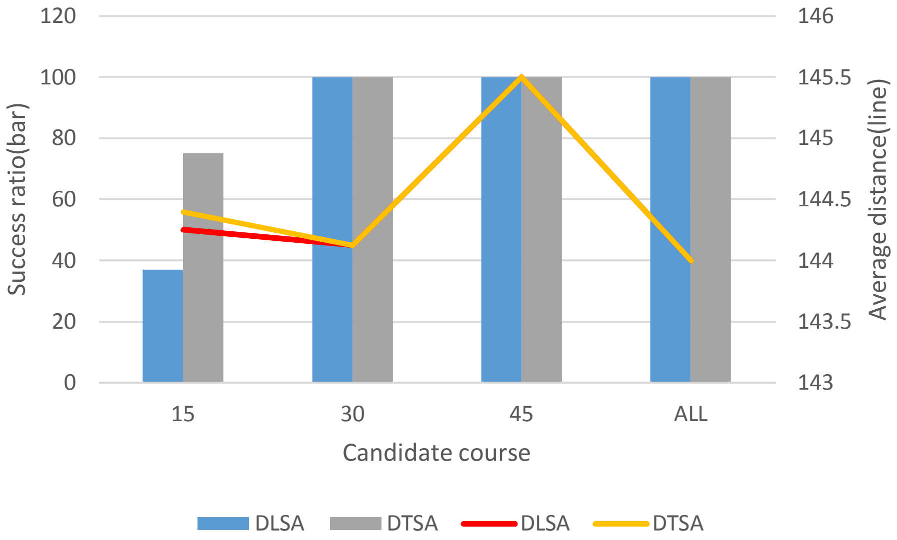

Figure 5-13: Result for 1st Experiment

2nd Simulation

In experiment 2, I experimented with five ships that individual ships encounter, as shown in Figure 5-14. The tracks of ships 1, 2, 3, and 4 produced an X shape. Ship 5 cuts across the space simultaneously.

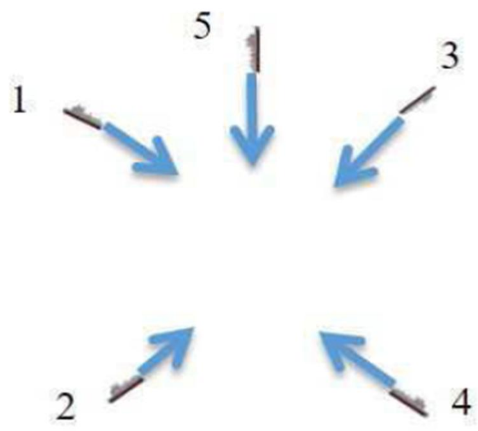

Figure 5-14: Situation for 2nd Experiment

Figure (5-15) shows the result for experiment 2. In the experimental result, except for 15 DLSA, the average distance showed similar figures. The cases of 30, 45 and ALL DTSA recorded no failures and low average distance. 15 DLSA had the drawback in terms of success percentage.

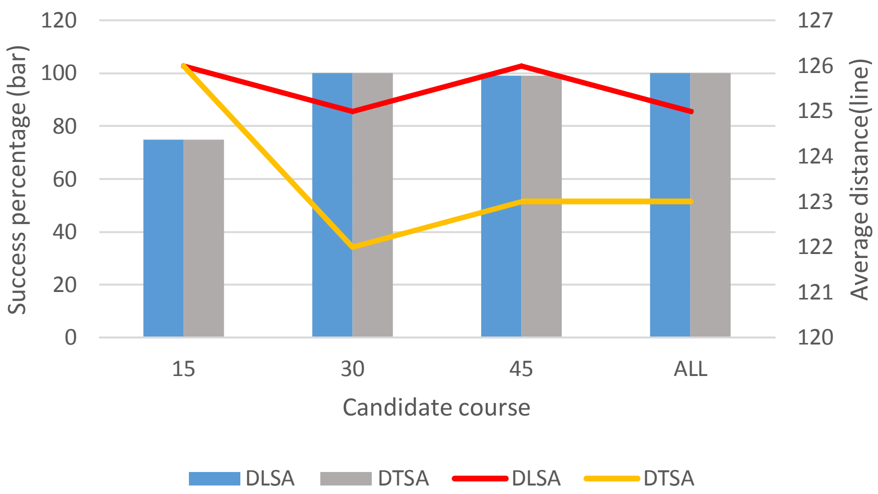

Figure 5-15: Result for 2nd Experiment.

3rd Simulation

I experimented with ten ships traveling in the same direction toward the destination from left to right, as shown in Figure (5-16). Figure (5-17) shows the result for experiment-3.Compared with DLSA, DTSA demonstrated better performance overall. All DTSA showed low and uniform average distance.

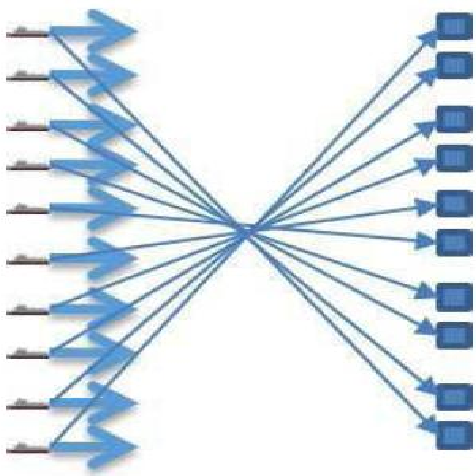

Figure 5-16: Situation for 3rd Experiment

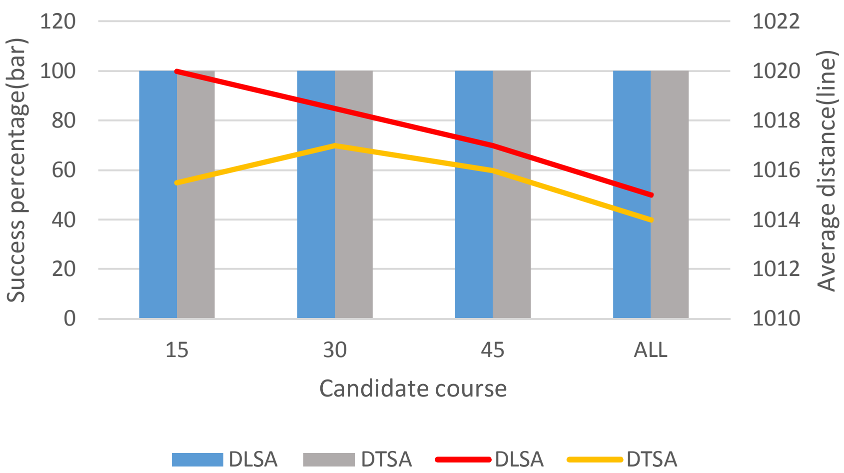

Figure 5-17: Result for 3rd Experiment

5.4.4 Results

I explained earlier that several algorithms work in specific situations, such as one-on- one situations. To avoid ship collisions in multiple-ship situations, I applied DTSA and DLSA. I used the tabu search algorithm to avoid the QLM problem. The experiments demonstrated how individual ships can avoid collisions in multiple-ship situations. In the experimental results, DTSA outperformed DLSA. Some experiments showed similar patterns: The more the number of candidate courses is increased, the shorter the average distance; the less the size of the degree of the candidate course, the greater the failure count. This is because a ship can bore of quickly if it drastically alters its course. ALL DTSA showed the lowest average distance in most cases. This means that the more candidate solutions, the better the performance.

5.5 Distributed Stochastic Search Algorithm

5.5.1 Reason of Selection

For many-to-many situations, few methods have been suggested such as DLSA and DTSA in section 3 and 4, respectively. Both algorithms can provide a safe course to ships in distributed system well. However, it should be taken into consideration in respect of limited range and transmission distance of frequency. In other words, the number of messages between ships needs to be reduced. In DLSA and DTSA, the mutual exclusion to prevent endless loop is one of the reasons that increases the number of messages between ships. In DLSA, each ship searches for a safer course within her own local view by exchanging intentions with neighboring ships. The DTSA enhances DLSA with the tabu search technique to escape from a QLM in which DLSA sometimes becomes trapped. One common drawback of these algorithms is that a relatively large number of messages need to be sent in order for the ships to coordinate their actions. Since message exchange accounts for the largest part of the cost of distributed algorithms, this could be fatal, especially in cases of emergency, where quick decisions should be made. In this section, I introduce the Distributed Stochastic Search Algorithm (DSSA), where each ship changes her next-intended course in a stochastic manner immediately after receiving all of the intentions from the neighboring ships. In DSSA, the probability is adopted to prevent ship collision. A ship may choose new next intended course with probability p, otherwise she will keep currently selected next intended course with probability $1-p$ [50].

In the context of distributed constraint optimization, the Distributed Stochastic Algorithm has been proposed to reduce the number of messages by allowing neighboring agents to perform simultaneous changes in a stochastic manner. They reveal that these simultaneous changes often lead to faster convergence to a sub-optimal solution; furthermore, its stochastic nature excludes the need for a specific method to escape from QLM. The basic idea of this algorithm can be applied in the context of distributed ship collision avoidance [51].

5.5.2 DSSA Procedure

The procedure for the DSSA for ship collision avoidance can be presented in Figure 5-18 which shows. First, a ship selects her current course as the next-intended course. After exchanging next-intended courses with neighboring ships, an agent computes $COST_{self}$ and $improvement_{self}$. If some ships are not contented with the next-intended course, she changes her course by following rules A or B, which are described below. This process is repeated until all ships are satisfied with their current next-intended courses. The next-intended course is chosen stochastically as follows. A certain ship, which depends on rule A or B, chooses the course giving $improvement_{self}$ with probability p, but does not change with probability $1-p$. In DSSA with rule A (denoted by DSSA-A), only the ships with positive $improvement_{self}$ can change the next-intended courses stochastically. On the other hand, in DSSA with rule B (denoted by DSSA-B), the ships with zero $improvement_{self}$ can also change the next-intended courses if they have positive costs. This is because the change in next-intended course of a ship may produce better results at the next step, even if it does not reduce the cost presently. Therefore, the new next-intended course may be chosen with the probability p.

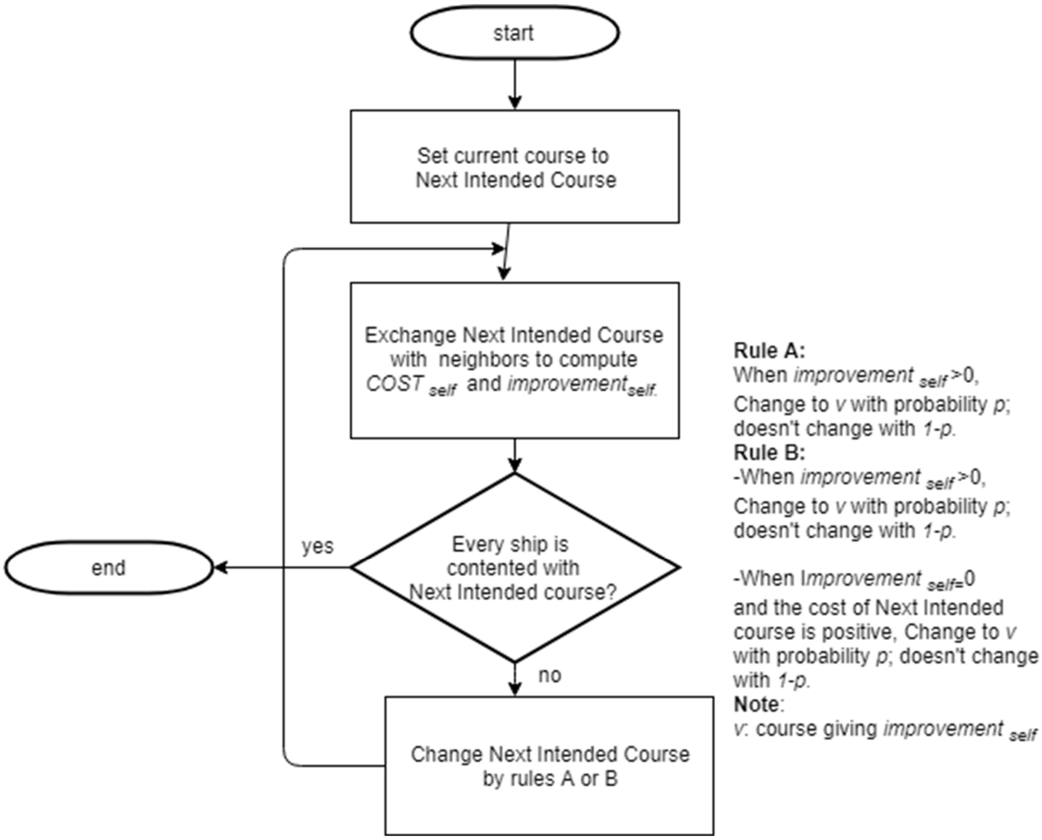

Figure 5-18: Flowchart Showing the Procedure of DSSA

5.5.3 Simulation

In distributed ship collision avoidance, individual ships all cooperate with each other. To clarify the importance of such cooperation, I show a simple result before conducting comprehensive experiments using DLSA, DTSA, and DSSA. So, I compare the performance of DLSA, DTSA, and DSSA for the twelve-ship encounter instance.

Total twelve ships are used, as shown in Figure 5-19. This is one of the simulated trajectories of twelve ships by DSSA-A. All ships arrived at their destinations without collision. It also demonstrates how much the home ship's decision is affected by the target ships. The ships in the middle that are surrounded by many target ships altered their courses significantly while other ships altered their courses only a little. Figure (5-20) shows the average distance and the number of messages for the twelve-ship encounter instance. In terms of average distance, all algorithms showed a similar result. In terms of the number of messages, DSSA had much fewer than DLSA and DTSA.

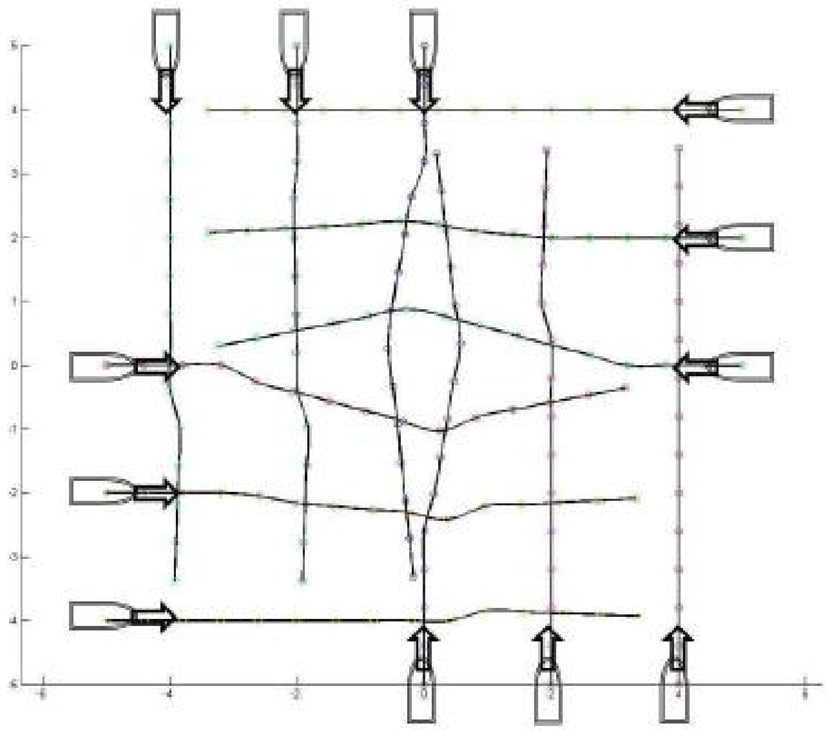

Figure 5-19: Simulated Trajectories of Twelve-Ship by DSSA-A

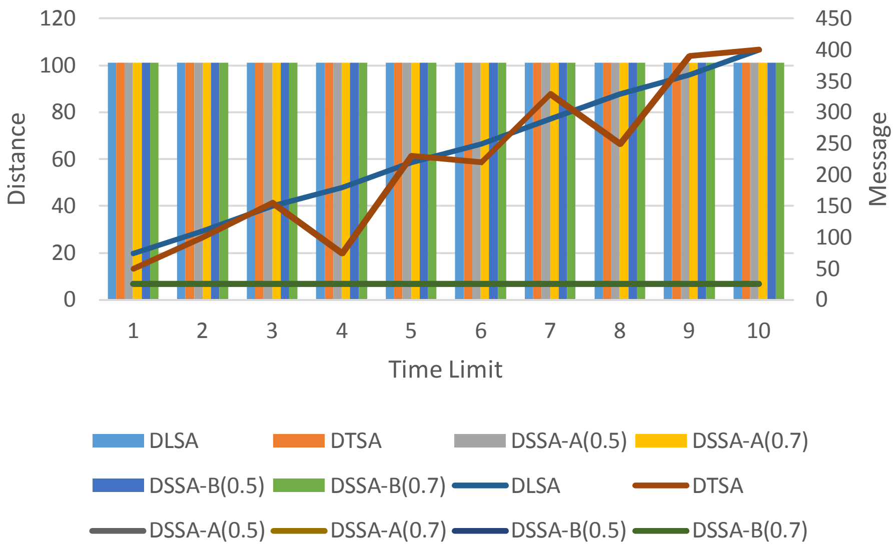

Figure 5-20: Result of Simulation for Twelve-Ship Encounter

5.5.4 Results

In section 5.5, I proposed Distributed Stochastic Search Algorithm for ship collision avoidance. There are five types of DSSA depending on the probability and the improvement. Depending on the probability, a ship chooses a next-intended course. This manner can solve a QLM problem and reduce the number of messages. This simplified the algorithm. In experimental results, compared to DLSA and DTSA, DSSA-A and B recorded lowest average distance and messages. Figure 5-19 shows that how much a ship's decision is affected by neighboring ships. I demonstrated that Distributed Algorithms can be applied to multiple-ship situations. Note that all experiments are recorded no collision.

For future work, it needs to consider the characteristics of ships. Some of variables, such as detection range, safety domain may be sensitive to a distributed algorithm for ship collision avoidance. It needs to be able to cope with various situations.

5.6 Comparative Analysis between Distributed Algorithms

Figure (5-21) and (5-22) show the different communication method among DLSA, DTSA and DSSA. Let me suppose three ships are encountered with each other. If all ships proceed to current course, a collision will happen at the center. To prevent the collision, ships exchange messages with neighbors such as *ok?* Message as shown in Figure (5-21)-(1). They exchange messages again such as *improvement* message as shown in Figure (5-21)-(2). If ship A has highest improvement, than she alters next intended course as shown in Figure (5-21)-(3). While ships B and C do nothing, because of the prevention for endless loop. Thus the collision between ships B and C still remains, they exchange messages with neighbors as shown in Figure (5-21)-(4, 5). Finally, ships A and B alter their courses. And the collision disappeared. At that time, the total number of messages are 24 times.

For DSSA, the total number of messages are 6 times. Because all ships send messages to neighbors. And each ship changes next intended course by probability *p*. By the stochastic nature, there is no need to wait for the decision of neighbors or send *improvement* message.

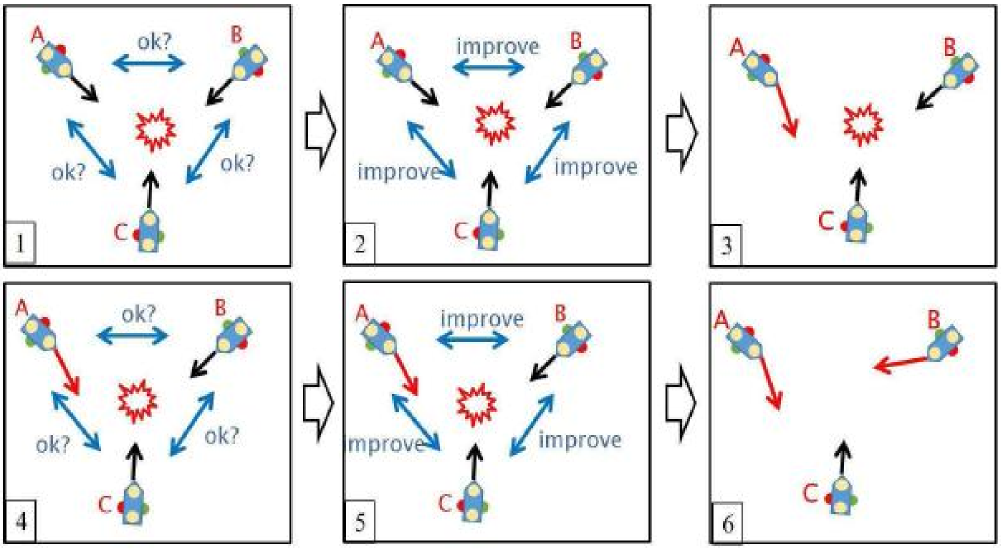

Figure 5-21: Method of Exchange Messages for DLSA and DTSA

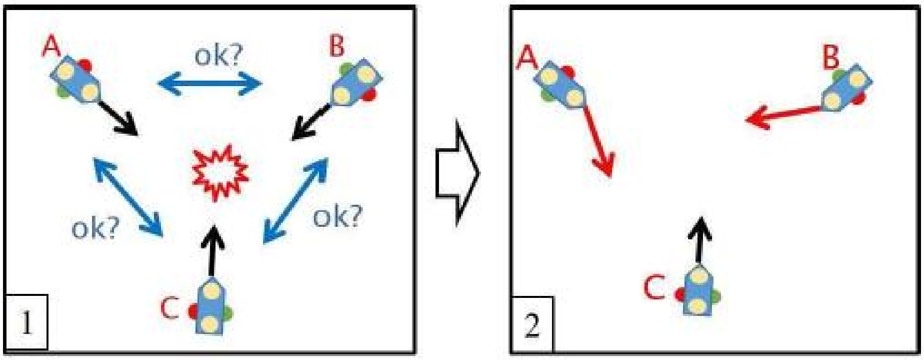

Figure 5-22: Method of Exchange Messages for DSSA

We should point out that both DLSA and DTSA require two cycles of message exchange for some of the ships to change intentions. Namely, they require one cycle for *ok?* Messages and another cycle for improve messages. However, in DSSA, one cycle suffices for some ships to change intentions since there is no need to exchange *improvement* $_{self}$.

The comparison of the results among the tested algorithms show the followings:

1) No collision occurs in this experiment.
2) All algorithms showed a similar result.
3) There is little difference among these distributed algorithms.
4) In terms of number of messages shown in lines in Figure (5-20), the followings are indicated:
   - DLSA recorded the highest.
   - DTSA had better results than DLSA.
   - DSSA performed better well than DLSA and DTSA, irrespective of values for time limit.

Table 5-3 summarizes the main features of our distributed algorithms for ship collision avoidance.

Table 5-3: Comparison of DLSA, DTSA and DSSA

Difference	**DLSA**	**DTSA**	**DSSA**
Solution for QLM	None	Tabu	Stochasticity
Solution for endless loop	Mutual exclusion with neighbors		Stochasticity
Number of opportunities of message exchange per round	Two	Two	One
Candidate courses	3 Kinds	User's needs	
Cost Function	Number of expected collisions + remaining time	Number of expected collisions + remaining time + relative bearing from heading to destination	

5.6.1 Results

Three ships collision avoidance algorithms: DLSA, DTSA and DSSA presented, discussed and analyzed. The results of analysis and comparison among these algorithms indicate:

1) DTSA had better results than DLSA.
2) Compared to DLSA and DTSA, DSSA produced good results, such as decreasing the number of messages. Therefore, DSSA enables ships to exchange significantly fewer messages than DLSA and DTSA.
3) DSSA performed better well than DLSA and DTSA, irrespective of values for time limit.
4) DSSA is stochastic nature algorithm, which excludes the need for a specific method to escape from QLM.
5) There is little difference among these distributed algorithms. Where,
   - The more the number of candidate courses is increased, the shorter the average distance.
   - The less the size of the degree of the candidate course, the greater the failure count. This is because a ship can bore off quickly if it drastically alters its course.

Chapter 6 Conclusions and Recommendations

Marine transport has a vital role in people and cargo transport across the world as the ship is a watercraft to transport passenger or cargo from one to another, she has long been used throughout the world. Marine transport industry is considered one of the huge and high-risk industries. As vital transportation carriers in trade, ships have the advantage of stability, economy, and bulk capacity over airplanes, trucks, and trains so more than 90% of the world's cargo transports by merchant ships. Therefore, reducing the associate risks and improving maritime safety are of the essential requirements for main marine transport industry. There are several causes that can rupture the aforementioned transport chain, with undesired consequences. Therefore, this doctoral dissertation has described types and main causes of ship accidents and take special concern to the human error as the main cause of the majority of ship accidents and then described how to avoid a collision between ships by applying Distributed Algorithms. In Chapter 6, I summarize the research.

6.1 Conclusions

The major contribution of the present work is constituted by the following items.

Firstly, I presented the motivation of research, the problem identification, introduced the ship accident types, presented human error definition, presented the objectives of research and presented the structure of the dissertation.

Then, I presented the background and related work in the field of marine safety, presented the review of necessary literature upon which the study revolves around. Several research studies conducted to investigate the causes of different types of ship accidents the conclusion from the studies have shown that following are the main causes for maritime accidents:

- Human failure (lack of training, operational error, negligence)
- Mechanical failure (Lack of maintenance)
- Lack of communication

- Equipment failure
- Fault of design
- Unfavorable and external cause
- Lack of procedures or incomplete procedure implementation
- Operation in hostile waters
- Management failure

As discussed in the studies, human is the main root of marine incidents. Human error is a complicated terms where it involves many parameters. Human error is at the root of most preventable casualties in the maritime field and around 70 to 95% of transportation accidents.

Finally, made a survey of the main accident investigation methods that have been used in marine industry. It gives an explanation of what accident investigation is, and in the case of marine accidents, which are the entities in charge of conducting such investigations and found STEP and step by step methods are applicable for our case study.

Then, I present detailed statistical analysis and investigation of 98 ship accidents happened during 2014-2017 of 30 ships owned to Kuwait Oil Tanker Company "KOTC". KOTC reporting system classifies ships accidents into the following main groups:

[1] Operator Error (OE)
[2] Negligence (N)
[3] Personal Protected Equipment (PPE) Related
[4] Slips, Trips, fall (STF)
[5] Third Party Fault (TPF)
[6] Procedure Failure (PF)
[7] Bad Weather (BW)
[8] Equipment/Material Failure (E/MF)

The study indicated that human error factors represent ~75% of the causes that led to KOTC's ships accidents. The analysis of human error factors identified that many factors affecting the occurrence of human errors, which tend to occur because of technologies, working environments, non-familiarity or working procedures, lack of training and experiences, and management systems. Accordingly, human errors could be reduced significantly by taking more concern about improving quality of crew training and capabilities development programs, improving working environment, providing clear job related procedures and implementing regulations to control human error.

I present detailed statistical analysis and investigation over the period 2011-2016 reported by the European Marine Casualty Information Platform (EMCIP), half of the casualties were of a navigational nature, such as contacts, grounding/stranding or collision. Amongst occupational accidents, 40% were attributed to slipping, stumbling and falling of persons. Human erroneous action represented 60% of accidental events and 71% of accidental events were linked to shipboard operations as a contributing factor. The results of survey indicated high contribution of human error to the causes of ships accidents, where it represents:

- 62.2% of the total of 156 accidental events analyzed of service ships
- 60.8% of the total of 781 accidental events analyzed of cargo ships
- 54.4% of the total of 338 accidental events analyzed of fishing vessels
- 51.4% of the total of 319 accidental events analyzed of passenger ships

I present a detailed analysis conducted using step-by-step event analysis method and a systematic process for accident investigation based on comprehensive and multi linear description of events sequences using STEP methodology for the collision which happened between Oil Tanker “Kiafan” and Bulk Carrier “Unison Star” in Chittagong - Bangladesh (24 July 2017), while Kaifan was in the Chittagong - Bangladesh anchorage area. As per the illustrated events of the accident and the investigation result, the main cause of the accident was the completely loss of control on Unison Star to avoid colliding with a Blue Lotus ship, which caused drifting of Unison Star towards Kiafan oil tanker. However, the tracking of the accidents events and detailed analysis of the actions taken by both ships clearly show that human error is the main cause of this collision.

The analysis of the collision events clearly showed that both ships indicated lack of experiences and knowledge in managing such situation, which highly affected by the short time window of the accident. Moreover, the dispersion and absence of control of the Chittagong port authority contributed as main factor for this accident.

Moreover, the followings are recommendations from the collision case study to reduce risk of collision specifically due to human error in anchorage areas:

- Bridge watch should be continuously maintained, and a vessel's position accurately monitored.
- Close monitoring of the position of the surrounding vessels
- Main engines should always be on standby
- Windlasses should be kept ready with available power to raise the anchor quickly at short notice.
- Anchor chains should not be over-extended, to avoid the swinging of the vessel over a greater-than-normal arc, increasing the risk of collision.
- Contact should be maintained with the Port Authority to view the latest advisories and updates regarding tide, current and wind conditions.
- In a crossing situation, continue to keep a proper lookout in order to judge the risk of collision properly.
- If the other vessel does not take action to avoid a collision, immediately give a warning signal.

The common parts for the distributed algorithms are explained in chapter 5. This chapter presented framework, terminology, and new cost function. The framework is made up of two procedures: control and search. For terminology, I defined the meaning of terms for distributed collision avoidance. To compute the collision risk, I suggested the new cost function and demonstrated an example how to compute it. The cost function is comprised of two parts, such as the collision risk against a neighboring ship and the relative angle between a candidate course and destination.

Then I described Distributed Local Search Algorithm. This method is first trial in the field of ship collision especially when many ships are encountered. I presented the process of DLSA and showed how to exchange messages with neighboring ships.

Then I proposed Distributed Tabu Search Algorithm. To solve the problem of DLSA, tabu search is applied. DLSA is sometimes trapped in QLM that prevents a ship from changing course. DTSA enables a ship to search for other course compulsorily when trapped in QLM. The framework of DTSA is the same as DLSA, essentially. The QLM procedure is added. I described the process of DTSA. I made total three experiments by changing the number of ships and the variables. In the experimental results, DTSA outperformed DLSA. Some experiments showed similar patterns: The more the number of candidate courses is increased, the shorter the average distance; the less the size of the degree of the candidate course, the greater the failure count. ALL DTSA showed the lowest average distance in most cases. This means that the more candidate solutions, the better the performance.

I proposed Distributed Stochastic Search Algorithm (DSSA). I applied Distributed Stochastic Algorithm that proposed by Zhang to ship collision avoidance. In DSSA, ships have no ID to distinguish one another. All processes are done synchronically. To choose next-intended course, a probability is applied. This stochastic manner can reduce the number of messages and solve QLM. Furthermore, in experimental results, compared to DLSA and DTSA, DSSA-A and B recorded lowest average distance and messages.

The results of analysis and comparison among these algorithms indicate:

[1] DTSA had better results than DLSA.

[2] Compared to DLSA and DTSA, DSSA produced good results, such as decreasing the number of messages. Therefore, DSSA enables ships to exchange significantly fewer messages than DLSA and DTSA.

[3] DSSA performed better well than DLSA and DTSA, irrespective of values for time limit.

[4] DSSA is stochastic nature algorithm, which excludes the need for a specific method to escape from QLM.

[5] There is little difference among these distributed algorithms. Where, the more the number of candidate courses is increased, the shorter the average distance and the less the size of the degree of the candidate course, the greater the failure count. This is because a ship can bore off quickly if it drastically alters its course.

Then, I developed a mathematical algorithm for the risk assessment and collision avoidance and calculating collision risk index and present a criteria to be applied. The application of this algorithm is simulated by using MATLAB code in Appendix (A) which calculate collision risk index of each ship with another.

6.2 Recommendation

In this section, several considerations which are of interest and of importance in relation to the present thesis are presented. However, they are not conducted due to the time constraints. These may be the subjects for future studies. Several recommendations can be made to help strengthen various aspects of shipping safety standards. These recommendation are summarized in the followings:

- There is a need to encourage countries to ratify and implement IMO Conventions and regulations as well as international regulations that govern behavior and operations whilst at sea, and monitor shipping performance. It is important that this information is made publicly available so that business decisions can be made in an informed way and operated on a level playing field.

- Working in high-risk navigation areas require regular review of the emergency response and procedures of these areas. This is to ensure the awareness and knowledge of all the concerned crew. Training courses and well-established emergency operational guidelines for high-risk areas will highly assist in reducing human errors.

- Encourage a more global and cohesive approach towards shipping safety through support for the IMO in its pragmatic approach.

- Investment in research and design to develop a global frame work for a standardized reporting system to enable commonality of data collection, monitoring and reporting of shipping accidents and detentions at various levels. This would help to achieve common, global metrics with the use of clear, simple language, which could be adapted to various levels of reporting.

- Shipping companies should seriously consider the experience of the captain and crew when working is high-risk areas. Captain should accompanied with expert crew when assigned to work in such area for the first time. This will reduce the risk of bad judgment.

- Consider research of the human elements associated to shipping accidents. Where focus should be on Personal Safety. The majority of major hazard sites still tend to focus on occupational safety rather than process safety and those sites that do consider human factors issues rarely focus on those aspects that are relevant to the control of major accident hazards.

- Management should pay more attention toward improving safety culture and environment. If culture well understood and endorsed, it will be the key to preventing major accidents.

- Management Procedure is required that every major hazard will be identified and controlled and a management commitment to make available whatever resources are necessary to ensure that the workplace is safe. It is important to keep the pressure focused on this trend for improvement and clearly understand the factors which are most significant in contributing to accidents at sea.

- The multiple destinations or waypoints for ships need to be considered. In this doctoral dissertation, all ships have only one destination. In real situation, however, there are many waypoints on the way to the destination from origin.

- All ships have different maneuvering characteristics. Considering that, the parameters, e.g. detection range, safety domain, time step and the weight factor α have to be adjusted.

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Appendix (A) Mathematical Collision Avoidance Algorithm

Collision assessment is the basis of a crash detection and prevention system. It is very important to avoid collisions through the timely detection and immediate warning of the collision risk, thus ensuring maritime safety and avoiding casualties. This assessment is based on the development of a collision risk index (CRI). The value of the CRI is influenced by a variety of factors. The time to closest point of approach (TCPA), the distance at the closest point of approach (DCPA), the distance from the target vessel, and the relative bearing are the most significant influence factors.

In the collision avoidance algorithm, it is important to determine the movement parameters of the ship compared to the target vessel, which is the basis of the calculation type and case judgment [52]. The following is a series of ship motion calculations based on the Descartes coordinate system: The speeds of the master and target ships on the axle component is [53]:

$$\begin{Bmatrix} v_{x_o} = v_o \sin \emptyset_o & v_{x_t} = v_t \sin \emptyset_t \\ v_{y_o} = v_o \cos \emptyset_o & v_{y_t} = v_t \cos \emptyset_t \end{Bmatrix} \quad \text{(A.1)}$$

Where (x_o, y_o) are the geographic coordinates of the ship with the velocity ofv_o, and the direction of$\emptyset_o$. (x_t, y_t) are the coordinates of the target vessel with a velocity ofv_t, and a direction of$\emptyset_t$. The relative velocities of the two ships on the *x* and *y* axes are given by [53]:

$$\begin{Bmatrix} v_{x_R} = v_{x_t} - v_{x_o} \\ v_{y_R} = v_{y_t} - v_{y_o} \end{Bmatrix} \quad \text{(A.2)}$$

The magnitude of the relative speed is [53]:

$$v_R = \sqrt{v_{x_R}^2 + v_{y_R}^2} \tag{A.3}$$

The relative direction is:

$$\emptyset_R = arctan\frac{v_{x_R}}{v_{y_R}} + \alpha \tag{A.4}$$

Where:

$$\alpha = \begin{Bmatrix} 0 & v_{x_R} \geq 0, & v_{y_R} \geq 0 \\ \pi & v_{x_R} < 0, & v_{y_R} < 0 \\ 2\pi & v_{x_R} < 0, & v_{y_R} \geq 0 \end{Bmatrix} \tag{A.5}$$

The relative distance between the two ships is:

$$R = \sqrt{(x_t - x_o)^2 + (y_t - y_o)^2} \tag{A.6}$$

The bearing direction of the master ship with the target vessel is:

$$\alpha_o = arctan\frac{x_o - x_t}{y_o - y_t} + \alpha \tag{A.7}$$

The DCPA between the two ships is [54]:

$$DCPA = |R\sin(\emptyset_R - \alpha_T - \pi)| \tag{A.8}$$

The TCPA between the two ships is:

$$TCPA = \left|\frac{R\cos(\emptyset_R - \alpha_T - \pi)}{v_R}\right| \quad (A.9)$$

The azimuth between the ship and the target ship can be expressed as:

$$\Delta B = B_t - B_o \quad (A.10)$$

Where$B_o = C_o$. The speed factor is given by:

$$K = \frac{V_o}{V_t} \quad (A.11)$$

When the TCPA is less than or equal to zero, it means that the two vessels have passed the closest approach, which is defined as the presence of a collision. DCPA, TCPA, R, ΔB and K, are components of the mathematical model of collision risk assessment. R and DCPA represent the collision space, TCPA represents the collision time, and K represents the difficulty of the collision avoidance. The values of ΔB and K affect the avoidance behavior when they are considered to be at a high or low risk of collision. These parameters in the mathematical model and the simulation program of crash risk are called functional functions [55].

The functional function of DCPA is:

$$U_{DCPA} = \left\{\begin{array}{cc} 1 & DCPA \leq d_1 \\ \frac{1}{2} - \frac{1}{2}\sin\left(\frac{\pi}{d_2 - d_1}\left(DCPA - \frac{d_1 + d_2}{2}\right)\right) & d_1 < DCPA \leq d_2 \\ 0 & d_2 < DCPA \end{array}\right\} \quad (A.12)$$

Where d_1 is the minimum safe pass distance, and d_2 is the safe encounter distance. d_1 and d_2 can be expressed as:

$$d_1 = SDA \times N \tag{A.13}$$

$$d_2 = K \times d_1$$

Where the ship safe distance of approach (SDA) is the fuzzy distance when the sailor operates. N is the relative value representing the instantaneous visibility, for the AIS system, N = 1. In addition, the SDA is calculated according to the Goodwin model as follows [56]:

$$SDA = D(\Delta B) + K_1 + K_2 \tag{A.14}$$

Where K1 is the systemic sensitivity effect to SDA, and K1 = 0 for AIS. K2 is the effect of the maritime area to SDA. The weight is small, and it can be considered equal to 0. The values of D (ΔB) corresponds to the following:

$$D(\Delta B) = \begin{cases} 1.1 - 0.2\dfrac{\Delta B}{180°} & 0° \le \Delta B \le 112.5° \\ 1 - 0.4\dfrac{\Delta B}{180°} & 112.5° < \Delta B \le 180° \\ 1 - 0.4\dfrac{360° - \Delta B}{180°} & 180° < \Delta B \le 247.5° \end{cases} \tag{A.15}$$

The functional function of R is:

$$U_R = \begin{cases} 1 & R \le r_1 \\ \dfrac{1}{2} - \dfrac{1}{2}\sin\left(\dfrac{\pi}{r_2 - r_1}\left(R - \dfrac{r_1 + r_2}{2}\right)\right) & r_1 < R \le r_2 \\ 0 & R > r_2 \end{cases} \tag{A.16}$$

Where r_1 = distance for latest actions (DLA) indicates the collision distance of the vessels and the latest action to avoid collision. This distance is not fixed, which depends on the size, speed, type of the ship, the weather condition, the operational ability of officers, and so on. In fact, the traveled distance is safe in the range of 0.4 to 1 nautical mile. In simulation calculations, the article selects r_1 = 1. r_2 Indicates the distance from the ship to the target ship in the danger zone. If r_2 is not in the safe range, it can be considered to be safe. So, $r_2 = r_1 + d_2$.

The functional function of TCPA is:

$$U_{TCPA} = \begin{cases} 1 & TCPA \leq t_1 \\ \left|\frac{t_2 - TCPA}{t_2}\right| & t_1 < TCPA \leq t_2 \\ 0 & t_2 < TCPA \end{cases} \quad (A.17)$$

Where t_1 is the time of arrival to the collision, t_2 is the time of arrival to the destination. Normally, 6–8 nautical miles between ships is usually considered the auto driving stage when using autopilot. For the sake of safety, this article set 8 nautical miles as the distance between ships beginning to form a collision situation. Then, we set the time required to sail from 8 nautical miles between ships to the closest point of approach ast_2. Next, the TCPA was set to correspond tot_2. t_1 and t_2 are given by:

$$t_1 = \begin{cases} \sqrt{\frac{DLA^2 - DCPA^2}{V_{ot}}} & DCPA \leq DLA \\ \frac{DCPA - DLA}{V_{ot}} & DCPA > DLA \end{cases} \quad (A.18)$$

$$t_2 = \frac{\sqrt{8^2 + DCPA^2}}{V_{ot}}$$

The functional function of ΔB is:

$$U_{\Delta B}=\frac{1}{2}\left[\cos(\Delta B-19°)+\sqrt{\frac{440}{289}+cos^2(\Delta B-19°)}\right]-\frac{5}{17} \quad \text{(A.19)}$$

So, the algorithm of collision avoidance, namely the collision-risk index (CRI), is calculated as follows:

$$CRI=\alpha_{DCPA}U_{DCPA}+\alpha_{TCPA}U_{TCPA}+\alpha_R U_R+\alpha_{\Delta B}U_{\Delta B} \quad \text{(A.20)}$$

WhereU_{DCPA}, U_{TCPA}, U_R, and $U_{\Delta B}$ are membership functions that represent the distance at the closest point of approach, the time to the closest point of approach, and the distance and the azimuth of the ship and target ship, respectively. Each factor has different effects on the collision risk. The numbersα_{DCPA},α_{TCPA},α_R, $\alpha_{\Delta B}$ are the weights ranging from 0 to 1, and they have a total of 1, which indicates the effects to collision capability of each membership function to the collision risk. The criteria for calculating the CRI and issuing a warning are as follows: when CRI ≥0.6667, there is a high probability of collision, so the vessel needs to take immediate action to avoid the collision. When 0.3333 ≤CRI < 0.6667, it is likely to collide, and so the vessel needs to be noted. When CRI < 0.3333, there is a low probability of collision, so the vessel needs to be tracked.

The general procedure for the proposed approach is shown in Figure (A-1), and the information from the AIS was calculated. If the collision probability of the ship and the target ship is high, the system will issue a warning and ask the crew to consider the situation, then the crew needs to take action to avoid

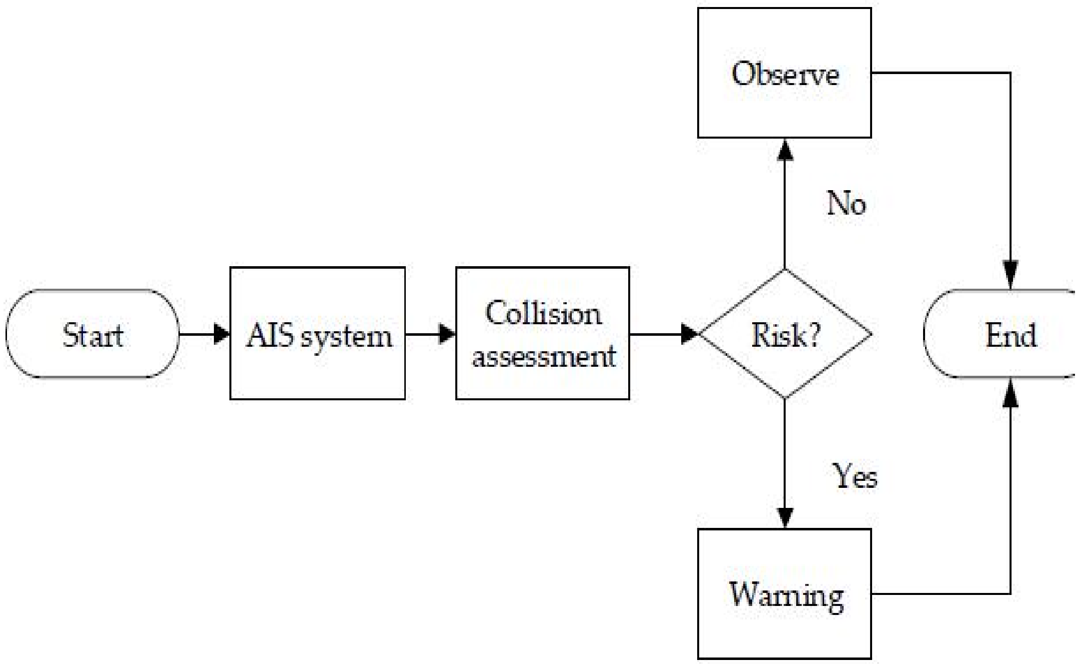

Figure A-1: General Procedure for the Proposed Approach

<u>Mathematical Simulation of collision avoidance algorithm</u>

The following mathematical simulation is influenced by (TCPA) and (DCPA). In the collision avoidance algorithm, it is important to determine the movement parameters of the ship compared to the target vessel, which is the basis of the calculation type and case judgment as discussed above in equation (A.1-3).
The relative distance between the two ships is:

$$R = \sqrt{(x_t - x_o)^2 + (y_t - y_o)^2} \tag{A.21}$$

Angle between the line connecting two neighbouring ships and the horizontal axis:

$$\alpha_T = \sin^{-1}\left(\frac{Y_t - Y_o}{R}\right) \tag{A.22}$$

The relative direction:

$$\emptyset_R = \sin^{-1}\left(\frac{v_{y_t} - v_{y_o}}{v_R}\right) \tag{A.23}$$

The DCPA between the two ships is:

$$DCPA = |R\sin(\alpha_T - \emptyset_R)| \tag{A.24}$$

The TCPA between the two ships is:

$$TCPA = \left|\frac{R\cos(\alpha_T - \emptyset_R)}{v_R}\right| \tag{A.25}$$

So, the algorithm of collision avoidance, namely the collision-risk index (CRI), is calculated as follows:

$$CRI = \frac{T}{TCPA} \tag{A.26}$$

Where T is the Maximum length of time for which the home ship plans her future position.

Simulation

I made the simulation by using five ships. All Ship has the following given values: Safety domain = 0.5 nautical miles, Detection range = 12 nautical miles, and Maximum length of time for which the home ship plans her future position (T) =500.

Table (A-1) illustrates the variables for simulation and description of simulated ships.

Table A-1: Description of Simulated Ships

Ship	Velocity (kts)	Heading (deg)	Pos-X (Nm)	Pos-Y (Nm)
A	24	0	0	0
B	24	240	3	2
C	24	135	4	-2
D	24	45	-7	-9
E	24	90	-5	-10

The following is presented the MATLAB code for the simulation.

```
%INPUT
DetRng = 12;         %Detection range in nautical miles
SafeDomain = 0.5;    %Safety domain in nautical miles
T = 500;              %Maximum length of time for which the home ship plans her future position
V = [24 24 24 24 24];          %Ship velocities in Knots
theta = [0 240 135 45 90];    %Ship heading in degrees
X = [0 3 4 -7 -5];        %Ship X position in nautical miles
Y = [0 2 -2 -9 -10];                %Ship Y position in nautical miles
N = size(V,2);            %Number of ships
Vx = V.*cosd(theta);      %Ship velocity component in X-direction
Vy = V.*sind(theta);      %Ship velocity component in Y-direction
%INITIALIZING OUTPUT VARIABLES
CR = zeros(N);            %Initializing Collision Risk matrix
Neighbor = zeros(N);      %Initializing Neighbor matrix
%CALCULATION
for n=1:1:N
    for ship=1:1:N
        if (ship ~= n)
            Distance = sqrt((X(ship)-X(n))^2+(Y(ship)-Y(n))^2); %Distance between two ships in nautical miles
            if (Distance < DetRng) %If the distance between the two ships is less than detection range then the two ships are neighbors
                Neighbor(n,ship) = 1;
    end
    for j=1:1:N
        if Neighbor(n,j)
            DistanceRel = sqrt((X(j)-X(n))^2+(Y(j)-Y(n))^2);
%Distance between two neighboring ships in nautical miles
            thetaRel = asin(abs(Y(j)-Y(n))/DistanceRel);
%Angle between the line connecting two neighboring ships and the horizontal axis in rads
            VRel=sqrt((Vy(j)-Vy(n))^2+(Vx(j)-Vx(n))^2);
%Relative velocity between two neighboring ships in knots
            if VRel ~= 0
                thetaRML = asin(abs(Vy(j)-Vy(n))/VRel);                  %Angle between the Relative Motion Line and the horizontal axis in rads
                DCPA = DistanceRel*sin(abs(thetaRel-thetaRML));           %Distance of Closest Point of Approach in nautical miles (Minimum distance between two neighboring ships)
```

```
                TCPA      =      3600*DistanceRel*cos(abs(thetaRel-
thetaRML))/VRel;    %Time of Closest Point of Approach in seconds
                if (TCPA < T) && (DCPA < SafeDomain)
                    CR(n,j)= T/TCPA;
display(CR);
```

Results

Figure (A-2) show the detection range for each ship, Table (A-2) shows the neighboring ship list. Each ship records its neighboring ships in the list.

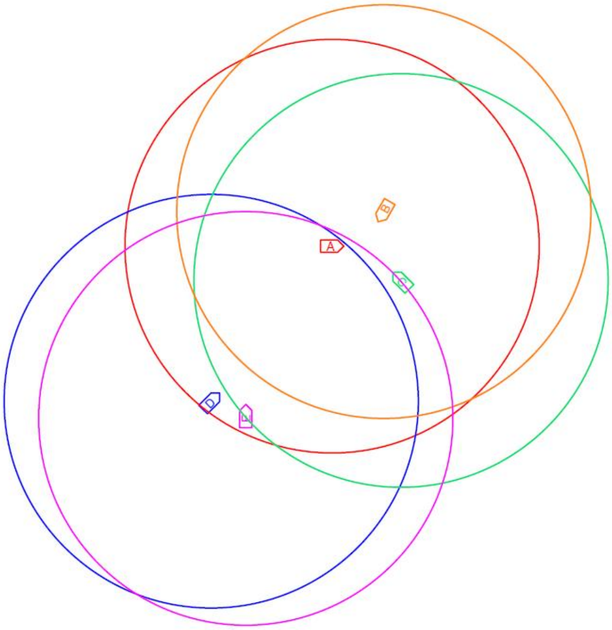

Figure A-2: Detection Range of Five Ships

Table A-2: List of Neighboring Ships for Experiment 1

	A	B	C	D	E
A	0	1	1	1	1
B	1	0	1	0	0
C	1	1	0	0	0
D	1	0	0	0	1
E	1	0	0	1	0

Table (A-3) show the collision risk index which calculated by MATLAB.

Table A-3: Collision Risk Index Calculated by MATLAB

	A	B	C	D	E
A	0	1.6046	1.3807	0	0
B	1.6046	0	1.2911	0	0
C	1.3807	1.2911	0	0	0
D	0	0	0	0	1.1438
E	0	0	0	1.1438	0