DEVELOPING A SIMPLE YET RIGOROUS APPROACH FOR OPERATIONAL RISK MANAGEMENT FOR SMALL VESSELS

By

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Dedication

This research is dedicated to God Almighty for his grace, favor, and mercy in all His ways, and to my late grandmother Beatrice Obeng, my dear wife Eunice Benewaa (Effah) Obeng and my lovely children – Calogero Jason Obeng, Francis Benjamin Obeng and Lisa-Marie Dufie Obeng.

Francis Emmanuel Obeng

Abstract

Fishing is seen as one of the most dangerous occupations in the world, and the people affected by the accidents at sea are often among the poorest in the society as found by the International Labor Organization (ILO). About 95% of fishers worldwide are small scale fishers and it is estimated that as much as 40% of the global landings comes from small scale fisheries according to recent studies conducted by the Food and Agricultural Organization (FAO), in partnerships with Duke University and WorldFish. Some studies have in the past documented fishing accidents and spelt out various hazards and consequences relating to outcomes including injury, vessel damage and loss, and death. There is, however, limited information regarding national and global ranking of these hazards and consequences to help identify the patterns associated with the risk, and hence target training resources in the direction of most probable occurrences is difficult. It is therefore essential to study and assess the interactions among the influential risk factors and the management strategies that can be employed to mitigate their impacts and improve training.

This research work seeks to study and develop a simple but rigorous operational risk modelling and management approach for small vessels that are used in fishing and transportation. A comprehensive probabilistic analysis was required to propose a simple applicable method to analyze risk causal factors of small fishing vessel operations. This was followed by the development of an operational risk model for small fishing vessels. The model was further analyzed with expert data along with secondary data from literature using a hybrid quantitative model for operational risk. In completing the research study, a case for an operational risk management approach for small fishing vessel is proposed using the cost per unit risk reduction (CURR) model to select a risk control option. Several small fishing vessel accidental events were attributed to operator error, vessel factors and environmental factors. Based on the findings of the research it is recommended that a combination of administrative and personal protective equipment control measures be adopted by the stakeholders.

Acknowledgments

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CHAPTER ONE

1. INTRODUCTION

1.1. Background to the Study

Maritime nations with rich and diverse coastlines provide many fishing and transportation opportunities for their economies. Associated with this are maritime accidents occurring every year around the world, and significantly affecting the operational safety of vessels that can leads to capsizing, collision/contact, flooding, fire, and sinking. The oceans have proven to be violent and unrelenting, and accidents can result in the loss of human lives, loss of property and environmental pollution. Commercial fishing has been critical to many economies around the world. Vessels requiring less sophisticated equipment and systems, and loose operational requirements are often employed in fishing activities and transportation of passengers in most places around the globe. These boat types are classified as small vessels, defined as a watercraft carrying a small number of crew (i.e., 2-4 crewmen) and not mandated to hold professionally certified licences and to carry a specific number of crew (NRC, 1991; Dyer, 2000).

About 95% of fishers worldwide are small scale fishers and it is estimated that as much as 40% of the global landings come from small scale fisheries. (FAO, Duke University and WorldFish, 2022). The FAO estimates that roughly 30 million fishermen are working aboard 4 million fishing vessels operating in capture fisheries, 1.3 million decked vessels and 2.7 million undecked vessels (FAO, 2006; Gough, et al., 2020).

In Canada, commercial fishing has been vital to most provincial economies, for example the economy of Newfoundland and Labrador relied on commercial fishing for hundreds of years (Davis et al., 2019). Also, a very substantial number of small fishing vessel accidents occur yearly, amongst African and south-east Asian countries. Many of such accidents go unreported in regional or national media, and therefore the information remains at the local level and are often accepted as fate (Merem et al., 2019; Liss, 2011). Hence, the poorly documented records on injuries and fatalities have resulted in limiting lessons learned and the chance of potential improvements.

Fishing is one of the most dangerous occupations in the world, as fishers are exposed to natural risks or hazards such as heavy seas, high winds, and poor visibility. Fishing vessel accidents often originate from related technical failures, organizational failures, or human errors. Additionally, fishing vessel accidents may be triggered also due to use of inappropriate fishing equipment, location, and weather conditions (Wag et al., 2021; Ugurlu et al., 2020; Davis et al., 2019).

1.2. Research Problem

Small sized boats are frequently used for fishing and passenger transportation around the globe. The concern for maritime safety is a worldwide issue and has been the providence of numerous private and government agencies, at regional, national, and international levels. The frequency and severity rates of accidents vary amongst many regions and nations. Like many complex socio-technical systems, commercial and small-scale fishing vessel operations represent a wide variety of individuals and groups that work within their organizational structures with their own set goals, work process and limitations. The dynamics of the interactions within such socio-technical system, i.e., vessel operators, fish buyers, cooperatives, regulators and numerous daily operational outside factors like weather or sea conditions have been investigated (National Research Council, 1991). This study found that commercial fishing could be made safer through systematically mandating an industry-wide attention to professional qualifications; the suitability and physical condition of the fishing vessels and equipment; and safe operational and occupational practices.

Risk management approach is adopted along with more technical solutions when dealing with industrial safety issues, and this has become the preferred option to tackle most safety concerns as the approach to safety has evolved. Most hazardous industries have developed approaches for dealing with safety and loss prevention, from design standards to plant inspections and technical safety, through to safety auditing and human factors (Wang & Pilay' 2003; Trbojevic & Soares, 2000). The NRC report emphasizes the need for regulations in the small fishing vessel industry. Apart from the unified regulatory framework, another key factor required to ensure a safer fishing operation is training, which must be targeted for efficient use of resources. Although, some studies (Kristiansen, 2013; Gander et al., 2011; Windle et al., 2008) have in the past documented fishing accidents and spell out various hazards and consequences relating to outcomes including injury, vessel damage and loss, and death. There is still scarcity of information regarding national and global ranking of these hazards and consequences to identify the risks patterns associated, and hence target training resources in the direction of most probable occurrences.

The main aim of this study is to develop a simple but rigorous operational risk modelling and management for small vessels that find their use in fishing and transportation. A simple approach is developed because the proposed model is expected to be user friendly by fishers who usually have limited education. Also, a rigorous approach such that the model is developed through the scientific method, and it is therefore capable of producing results. This means, methodology should be based on the principles of science or psychology of human factors such that the outcome of its implementation has measurable impacts. Lastly, proposed plans to manage risk should be operational, which means any solution must be dynamic (changing) in nature.

1.3. Research Questions

The investigation into the causal factors of fishing accidents used a hybrid approach of research through combining both qualitative and quantitative methodology.

The questions guiding the study were:

Question 1: Why do small fishing vessel accidents occur and what are the causal factors?

Question 2: How is a typical fishing vessel accident likely to happen and when will it happen?

Question 3: Does the literature and data suggest that human and organizational factors have less impact on commercial fishing vessel accidents than the technical and environmental issues?

Question 4: What contributes to human error accidents and when are they likely to happen?

Question 5: How do we know which hazard(s) to focus on in terms of accident prevention?

1.4. Objectives of the Study

This research is aimed at developing a rigorous operational risk management model for analyzing and improving safety of small fishing vessels and at the same time make it simple to use by the fishery industry. The proposed model framework is to be available in literature for adoption by stakeholders and it captures the complex and non-linear inter-dependencies amongst the various risk factors, which comprise of technical, human and environment systems failure analysis. This research was conducted to meet the following objectives:

(1) To propose a simple method to analyze risk causal factors of small fishing vessel operations.

(2) To develop an operational risk model for small fishing vessels.

(3) To develop a hybrid quantitative model for operational risk analysis of a small fishing vessel using direct field data.

(4) To propose an operational risk management approach for small fishing vessels

In summary, the objectives of the study are designed to address the research questions by developing a model that identifies the causal factors and predicts when and how accidents are likely to occur, and proposing a risk management approach that addresses both technical and human factors to prevent accidents in small fishing vessels.

Objective (1): This objective aligns with research question 1 as it aims to develop a method to identify the causal factors that lead to fishing accidents.

Objective (2): This objective aligns with research question 2 as it aims to develop a model that predicts how and when fishing accidents are likely to occur.

Objective (3): This objective aligns with research questions 1, 2, and 4 as it aims to develop a hybrid model that utilizes both qualitative and quantitative data to identify the causal factors of fishing accidents, predict when they are likely to occur, and identify the contribution of human error.

Objective (4): This objective aligns with research questions 3 and 5 as it aims to develop an approach to manage operational risk that considers the impact of technical and environmental factors, as well as human and organizational factors, and focuses on identifying the most critical hazards to prevent accidents.

The highlighted links and connections between the research questions and the objectives of the current research are illustrated schematically with Figure 1.2.

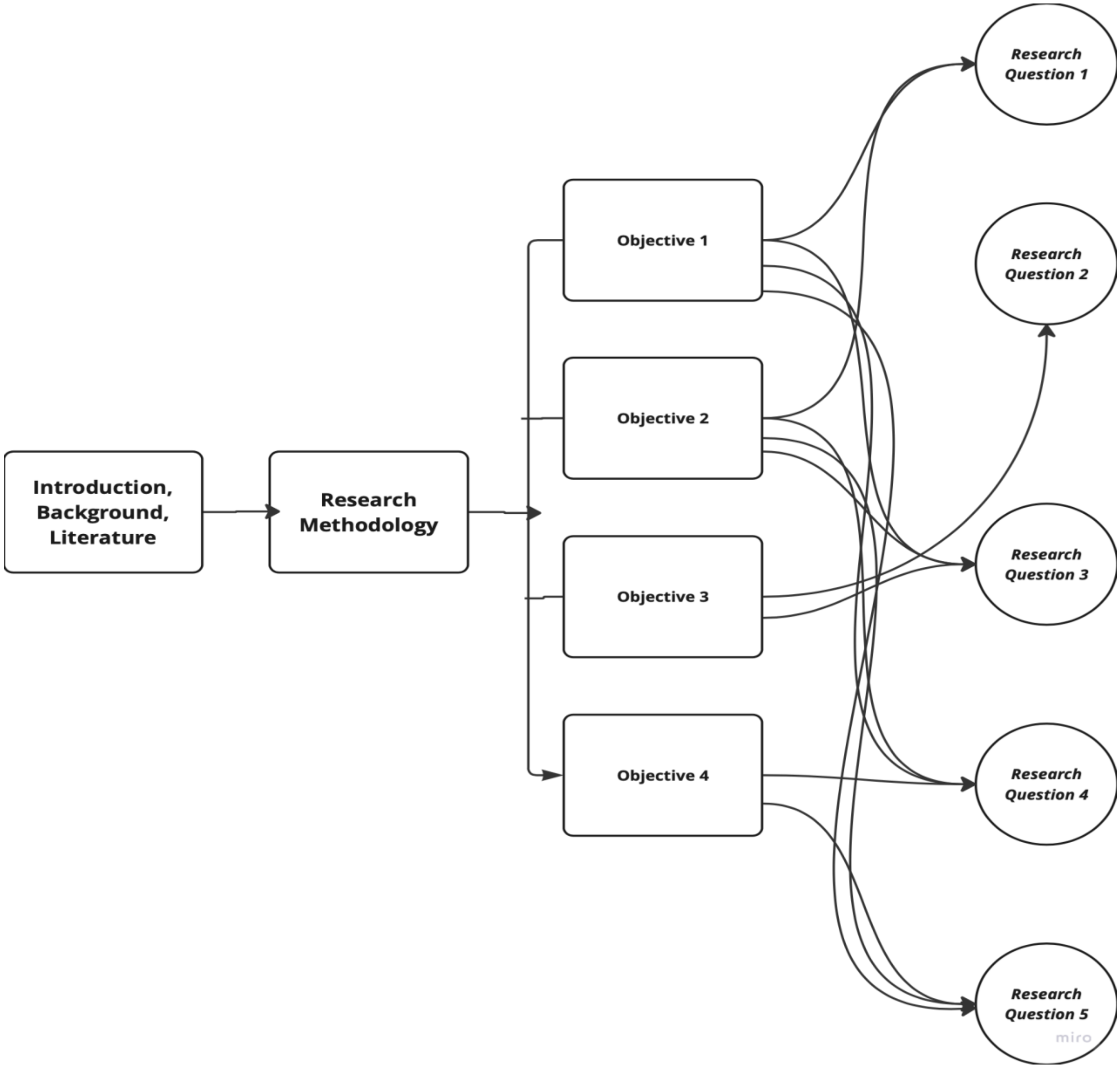

Figure 1.1 Framework of proposed study showing connection between research questions and the study objectives.

1.5. Scope of the Study

The scope of the current study focuses on small fishing vessel accidents and aims to investigate the causal factors contributing to these accidents. It encompasses both qualitative and quantitative research methodologies to provide a comprehensive understanding of the factors involved. The study primarily examines the interplay of technical, human, and environmental factors in the occurrence of accidents.

Assumptions:

1. The study assumes that small fishing vessels refer to boats used for commercial fishing activities with a defined size and capacity.
2. It is assumed that the research will primarily focus on accidents related to small fishing vessels and not extend to other types of maritime accidents or vessel categories.
3. The study assumes that a hybrid approach, that combines qualitative and quantitative methods, is the most effective way to gather data and analyze the causal factors of fishing accidents.
4. It is assumed that the research will be conducted using a sample of fishing vessels, and the findings will be generalized to the wider population of small fishing vessels, considering any limitations and biases of the sample.
5. The study assumes that the proposed operational risk management model will be practical and applicable for the fishery industry, considering its specific needs and requirements.
6. It is assumed that the research will rely on literature reviews, direct field data collection, and analysis of existing data to develop the risk model and management approach.
7. The study assumes that the proposed risk management approach will effectively address both technical and human factors to prevent accidents in small fishing vessels, based on the findings and analysis conducted during the research.

1.6. Study contributions and novelty

The proposed study's novelty lies in its comprehensive approach, incorporating qualitative and quantitative methodologies, developing a tailored risk management model, and addressing the specific challenges of small fishing vessels. The contributions of the study include advancing knowledge on causal factors, providing a practical risk management approach, and enhancing safety practices in the fishery industry, ultimately aiming to reduce accidents and improve the overall well-being of fishing vessel operators and crew members. The concise highlights of these contributions are shown below:

1. Hybrid Methodology: The study adopts a hybrid approach by combining qualitative and quantitative research methods. This integration allows for a comprehensive understanding of the complex interplay between technical, human, and environmental factors in small fishing vessel accidents. This approach is novel and enhances the depth and breadth of the study's findings.
2. Comprehensive Analysis: The study's focus on both technical and human factors distinguishes it from previous research that may have predominantly emphasized one aspect over the other. By considering a broad range of causal factors, including vessel-related issues, human error, and environmental influences, the study provides a comprehensive analysis of small fishing vessel accidents.
3. Operational Risk Management Model: The development of an operational risk management model specific to small fishing vessels is a significant contribution of this study. The proposed model captures the complex and non-linear interdependencies among risk factors, enabling a more accurate assessment of accident risks. Its simplicity and practicality make it accessible and useful for the fishery industry to improve safety practices.

4. Integration of Direct Field Data: The study's utilization of direct field data through surveys, interviews, and focus groups adds a valuable contribution to the research. By gathering information directly from fishermen, vessel operators, and crew members, the study incorporates real-world perspectives and experiences, ensuring the relevance and applicability of the findings.
5. Risk Prevention Approach: The study's proposal for an operational risk management approach tailored to small fishing vessels fills a gap in the literature. This approach addresses both technical and human factors, recognizing their interconnectedness and the need for a holistic approach to accident prevention. The recommendations provided can guide the fishery industry in implementing effective safety measures and training programs.
6. Practical Industry Application: The study's ultimate contribution lies in its practical application to the fishery industry. By providing a rigorous yet simple-to-use operational risk management model, the study offers a valuable tool for analyzing and improving safety in small fishing vessel operations. The findings and recommendations have the potential to enhance safety practices, reduce accidents, and protect the lives and livelihoods of those involved in the industry.

1.7. Limitations to the Study

The study approach relied on data based on past incidents and hence, historical incident data published in journal articles and reports of national and international agencies. The accuracy of the causal factors in the data exported for quantitative analysis is uncertain.

The consideration of any acquired dataset for statistical purposes also depends on the completeness of the data and accuracy in order to provide any meaningful analysis. Meanwhile, accidents that require notifications may be subject to under-reporting for several reasons, which may include responsibility for damages and varied employment consequences.

Even though human error is recognized as a cause of almost all accidents, including fishing vessel accidents, the way all investigators collect and code the data may not be directly applicable to the numerous accident models and frameworks.

The complex nature of socio-technical systems makes it challenging to build models to predict the risk associated with such a system. Several uncertainties with the model and data may introduce subjectivity in the proposed models. The current study is not an attempt to address all research gaps associated with the safety of fishing vessel but an attempt to address some of the research gaps related to quantitative risk assessment and management of small fishing vessels operation considering the human element.

1.8. Overview of Existing Literature

Commercial fishing makes significant contributions to the national and regional economies of many countries around the world. Fishing is presumed to be the most dangerous occupation in the world, and the people who are mostly affected by accidents at sea are often among the poorest in the society (ILO, 1999). Fishers are often exposed to natural risks or hazards such as heavy seas, high winds, and poor visibility. Risk is measured in terms of human injury, environmental damage, or economic loss as a function of the failure probability and the consequence of failure (CPQRA., 1999). According to the National Research Council, (1991), records showed that in 1989, 10.7 billion pounds of fish were landed by U.S. vessels, representing a fifth in total world harvest which came behind Japan, the Soviet Union, China, and Peru (National Oceanic and Atmospheric Administration [NOAA], 1990) as cited by NRC. (1991). Further studies in the recent past (Lincoln & Lucas, 2010; Case et al., 2018) found that the United States in 2008 also recorded a fishing fatality rate of 129 deaths per 100,000 fishermen which exceeded the 2016 fatality rate for all workers by 23 times.

According to (Drudi, 1998) evidence of corpses of fishermen washed ashore many times to Newfoundland beaches during the 19th century.

Studies conducted by the Food and Agricultural Organization of the United Nations has found that about 98 percent of the 4 million fishing vessels identified as operating in capture fisheries, are under 24 m in length and most are not covered by any international rules and regulations (FAO, 2006). Fishing vessel accidents have often originated from related technical and organizational failures, or human errors. The interactions of the technical and organizational factors along with environmental factors constitute the main causes of accident (Nan. and Sansavini, 2016; Reason, 2008). The environmental factors may involve physical surroundings of the operators or equipment that could adversely affect performance as weather conditions, noise, and lighting. The technical failure of a component and equipment malfunction and failures resulting from design flaws have been well researched. There have therefore been improvements in prevention of such failures and increased reliability of equipment.

Some research studies (Wang et al., 2021; Ugurlu et al., 2020; Davis et al., 2019), found accidents may also be triggered due to use of inappropriate fishing equipment, location, and weather conditions. Additionally, other studies have shown that most fishing accidents occurred during the actual activity of fishing, since the vessel loading, and stability are altered during this period (Havold, 2009). Safety barriers are introduced to the scheme of operations to offer a form of protection to marine systems and structures from the negative consequences of functional failures and human errors.

Furthermore, studies conducted by Jin and Thunberg (2005) found wind speeds increased the probability of fishing vessel accidents and incidents. The study found that accidents are more likely to occur in coastal waters and numbers are higher in winter conditions. The impact and severity of vessel damage is also key and provides an idea of the consequence. The damage severity has been found to be inversely proportional to the length of the vessel (Jin, 2014; Ugurlu et al., 2020). The studies also showed that severity of the crew's injury was directly proportional to the loss of stability and sinking of the vessel. Wang et al., (2005) found that the risk of accidents on fishing vessels increases as vessel length decreases.

Davis et al., (2019) studied the effect of crew's knowledge of stability on capsizing of fishing boats. The authors state, commercial fishing has been vital to the economy of Newfoundland and Labrador for hundreds of years in Canada, and fishing for several species has remained a major industrial activity in the province despite a 1992 imposed moratorium to preserve cod stocks. As of 2016, commercial fishing directly accounted for 3,100 jobs in the province and an additional 3,000 indirect jobs (Newfoundland and Labrador Statistics Agency, 2017) as cited by Davies et al., (2019). The Transportation Safety Board of Canada (TSB) is responsible for acquiring incident and accident data and to use obtained transportation incident/accident occurrence data during the process of its investigations to analyze safety deficiencies and to identify risk in the Canadian marine transportation system.

For instance, 267 marine accidents were reported to the TSB, in the year 2019, which was down from the 2018 total of 289 and below the 10-year (2009–2018) average of 298 (TSB, 2020). In 2019 the proportion of shipping accidents (78%) of which most shipping accidents involved fishing vessels (29%), followed by solid-cargo vessels (27%). Additionally, 12 of the 17 marine fatalities in 2019 were fishing related. The data compiled and analyzed in this study indicate that more needs to be done to improve safety in the commercial fishing industry.

A substantial number of small fishing vessel accidents do occur yearly, amongst African and south-east Asian countries, and many of these incidents go unreported in the regional or national media. Such accidents, hence, remain at the local level and are often accepted as fate. Moreover, the poorly documented records on injuries and fatalities limits lessons learned and chance of potential improvements. In Ghana, which has one of Africa's most promising political systems and is an economic heavy weight, small-scale fishing is one of the most predominant occupations amongst the local folk and peasants. There are more than 200 coastal and inland villages in the country that rely on fisheries as their primary source of income and have few alternative sources of livelihood or employment (Eriksen, 2019).

According to a study by Doyi (1984), Ghana is deemed to have a long history as a small-scale fishing country dating back to the 1700's and 1800's. The industry is well developed and produced approximately 70% of the total fish production of the country whereby the small-scale fishing industries' total catch increased considerably in the late 1960's from 105,100 tons of marine fish caught in 1967 to 230,100 tons in 1971. In 1982, the yield was 234,100 tons composed of 199,100 tons of marine varieties and 35,000 tons of freshwater fish from the lake Volta (Doyi, 1984). It is worthy of note that not only does fishing provide a significant source of employment in all these mentioned nations, but they form a fundamental part of the culture and identity of the people.

There's been some improvement in the accident situation of fishing vessels in developed nations and calls have been made encouraging the International Maritime Organisation (IMO) to publish a comprehensive regulatory framework capturing all aspects of fishing with the objective of making the industry more resilient and to minimise accidents and their consequences significantly (Piniella and Fernández-Engo 2009; Francisco Piniella 2007). The challenges associated with fishing voyages in the North Atlantic Ocean including the hazards and their resulting tragedies while operating in harsh environmental conditions are discussed by Junger (1997). The work discusses amongst other issues the importance of teamwork while moving fishing gear and working with dangerous tools on wet and slippery decks in a variety of sea-states and adverse weather conditions.

Some recent studies on maritime safety have tried to propose recommendations to address fishing safety. Most maritime accident analysis studies in the recent past have relied on subjective experts' knowledge to reveal and predict the causal relations amongst the process of accidents, as well as data-driven methodologies (Fan et al., 2020). Especially, causal relations have been connected to one type of accidents through accident analysis methods, specifically for grounding or collision (Macrae, 2009; Hanninen & Kujala, 2012; Ugurlu et al., 2015). The frequency or probability of accident occurrence is another important component for determining the risk, and studies such as (Fabiano et al., 2010; Pristrom et al., 2016) have focused on the occurrence probability of maritime accidents. Fabiano et al. (2010), for example, investigated the occupational accident frequency affected by the organization, job experience, and productivity. Meanwhile, consequence and their impact have been studied, and most such studies have concentrated on the severity or the consequence of maritime accidents. As shown in (Zhang et al., 2016), which predicted the accident consequences in the Tianjin port by statistical analysis of historical accident data. Wang & Yang (2018) analyzed the key risk factors influencing waterway accident severity by using Bayesian networks (BNs).

A further review of existing literature on commercial fishing safety publications also helps identify the predominant accident causal factors or events in fishing vessel operations. In Perez-Labajos (2008), the study categorizes fishing incidents under accidents and illness of fishermen; attitudes towards safety by fishers; material damage to vessels and equipment. Other categorizations such as probabilistic models of accidents; decisive variables of accidents; means and mechanisms of prevention; procedures of survival and rescue resources; and concentration of accidents on fishermen and fleet, were pointed out.

Fan et al., (2020) have investigated how different risk factors singularly or in combination impacted different types of maritime accidents in terms of their likelihood. The study explores by manually analyzing on a case-by-case basis, records of maritime accidents from the Marine Accident Investigation Branch (MAIB) and Transportation Safety Board of Canada (TSB) that occurred between period of 2012 and 2017, to develop a primary database that support a BN-based approach to help analyze accident types in maritime transport. Evidence shows that past disasters such as Chernobyl, the Challenger crash and Deepwater Horizon oil spill, brought considerable awareness to the contribution made by organizational factors to an accident (Kimes et al., 2014; von Thaden et al., 2006). These organizational factors also included inadequate procedures and training; insufficient standards, requirements, and processes; and management induced pressure.

In general, human errors are said to contribute the highest to maritime accidents and this contribution is estimated to be in the range of 75-96% (Portela, 2005). Human causal factors are associated with human error and defined by Reason (1990) as “encompassing all those occasions in which a planned sequence of mental or physical activities fail to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency.” Examples of human error include, but are not limited to, inattention, memory lapses, complacency, and mistakes. Additionally, communication failure, ineffective training, poorly designed equipment, exhaustion or fatigue, situation ignorance, noisy working conditions, and other personal and environmental factors can lead an individual to make errors (Fan et al. 2018).

Some recent research studies have been found to support this assertion; human error has contributed to various types of accidents in the range of 84-88% of tanker accidents, 79% of towing vessel groundings, 89-96% of collisions and 75% of fires and explosions (Chan, et al., 2016). In addition, current studies such as (Ugurlu, et al 2020; Zohorsky, 2020; Domeh, et al., 2021; Obeng, et al., 2022a) have found human error to be a major contributing accident causal factor for fishing vessels.

To provide proper management strategies to reduce risks, investigations are conducted to examine all aspects of fishing accidents to understand the mechanisms and circumstances present, as well as the interaction of the persons, machinery, and working conditions that contributed to the accident (Kuhlman, 1977). While analyzing accidents, consideration should be given to the measures and actions necessary to prevent a similar accident in the future. Furthermore, “the ultimate goal of an investigation is to learn from failure” (p.5, Dekker, 2006).

Under this section, an overview of the available relevant literature has been presented. Further literature specific to the study objectives are provided for further reference. The introduction section under chapter 3 of this thesis contains thorough review of further literature on maritime accidents and safety issues pertaining to fishing and what solutions have been implemented to address them. Attention is focused on fishing vessel capsize accidents and the causal factors and the review presents the identified risk factors. Further literature review on the human factor contributions to small fishing vessel accidents have been undertaken as part of the introduction sections of chapters 4 and 5 of the thesis. Also, specific thorough review on risk management for fishing vessel operation is contained in chapter 6 for further reference. Figure 1.1 shows a schematic diagram summarizing the interacting major factors leading to accidents in the operation of fishing vessels, and the ensuing consequences and impacts. Based on the analysis outcomes corrective measures are then recommended and implemented to mitigate and reduce the risks and impacts. From the review of existing literature, fishing vessel accidents happen because of the complex interaction of technical, human, and environmental factors. This can lead to major accidents of capsizing, collision, flooding, or sinking, which may end up in the loss of life, injury, or damage to property.

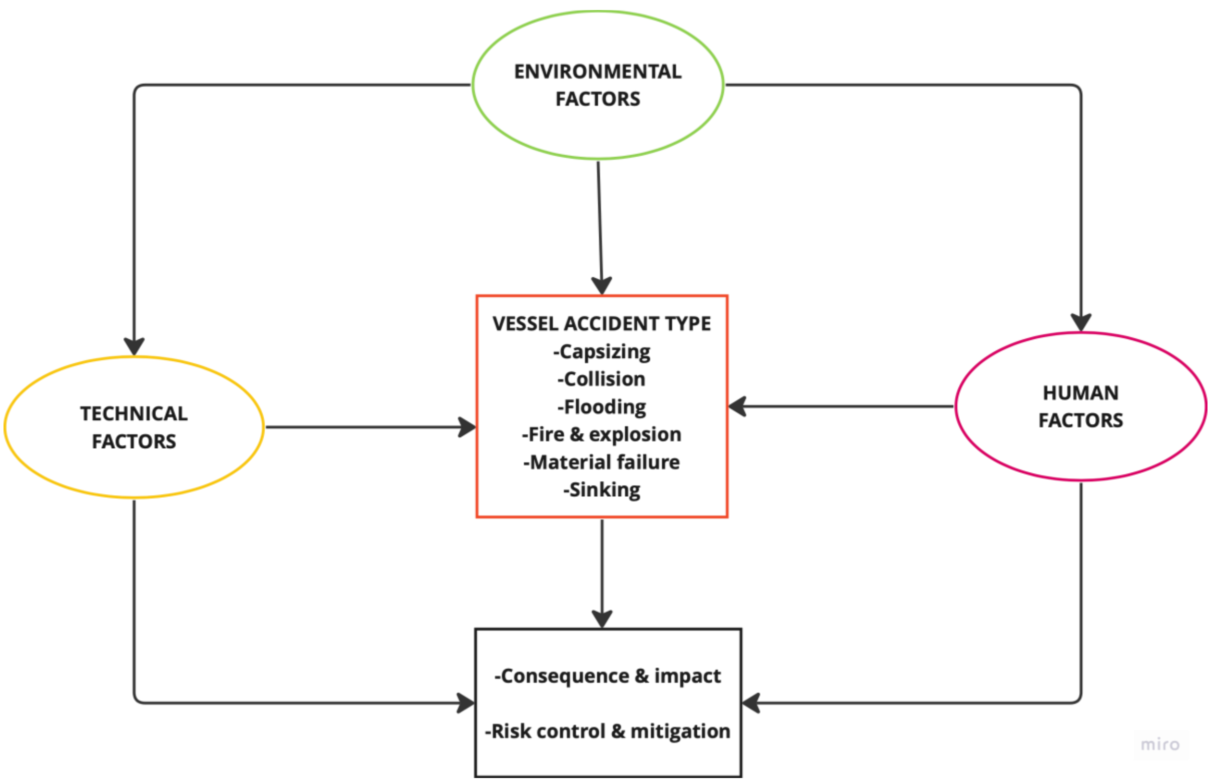

*Figure 1.2.*Schematic of accident causal factors interactions with consequence and mitigation measures.

1.9. Organization of the Thesis

This thesis is written in a manuscript-based format. The overall outcome of this thesis is represented in four peer-reviewed journal papers. Chapter's 1, 2 and 7 present the introduction, research methodology and conclusions, respectively. Chapters 3 to 6 of this thesis are developed based on the paper submissions to peer-reviewed journals.

Chapter 2 highlights the research methodology and general study methods for both the analysis of the selected journal publications and accident investigation reports and discussions with subject-matter experts. For interviews with experts, the results are collected in qualitative form and later transformed into quantitative data. These results supplemented the quantitative data from the analysis of investigation reports.

Chapter 3 presents a capsizing accident scenario model for small fishing trawler. This chapter is published in *Safety Science 2022; 145: 105500.*

Chapter 4 presents a model for analyzing operational risk for small fishing vessels considering crew effectiveness. This chapter is published in *Ocean Engineering 2022; 249: 110512.* Chapter 5 presents a hybrid Bayesian network model for operational risk analysis of a small fishing vessel. This chapter has been reviewed and come for revisions and re-submitted to *Ocean Engineering.*

Chapter 6 presents an operational risk management approach for small fishing vessel. This chapter is in a draft manuscript form, internally revised and ready to be submitted to a *Journal for publication.*

Chapter 7 presents the study's summary, conclusions, and recommendations.

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CHAPTER TWO

2. RESEARCH METHODOLOGY

2.1. Overview

The intent of this section is to introduce the research methodology applied to solve the research problem in general. This covers the development of models, and the processes of data gathering for the project. To address the research questions and achieve the objectives of the study, a hybrid approach combining qualitative and quantitative research methodologies can be adopted. This approach can provide a holistic understanding of the causal factors of small fishing vessel accidents and offer practical insights for risk management and accident prevention in the fishery industry. The proposed study methodology is structured as follows:

1. Literature Review: Conducting a comprehensive review of existing literature, including academic research papers, industry reports, accident investigations, and relevant regulatory frameworks. This review will provide a theoretical foundation and help identify key factors associated with small fishing vessel accidents.
2. Qualitative Data Collection: Semi-structured Interviews - Conducting interviews with experienced fishermen, vessel operators, safety managers, and relevant stakeholders to gather qualitative data on their perspectives, experiences, and insights regarding small fishing vessel accidents. These interviews could be audio-recorded and transcribed for analysis.
3. Quantitative Data Collection: (a). Field Surveys: Administering structured questionnaires or surveys to a representative sample of small fishing vessel operators and crew members. These surveys can capture quantitative data on accident incidents, fishing practices, vessel characteristics, operational procedures, and human factors. The surveys may be conducted in person or online, depending on the accessibility of the target population. (b). Analysis of Existing Data: Analyze historical accident data provided by relevant authorities, coast guard

agencies, or insurance companies. This data can provide insights into accident patterns, time of occurrence, contributing factors, and severity.

4. Data Analysis: (a). Qualitative Analysis: Transcribe and analyze interview data and focus group discussions using qualitative analysis techniques such as thematic analysis. Identify recurring themes, patterns, and causal factors related to small fishing vessel accidents. (b). Quantitative Analysis: Analyze the collected survey data using appropriate statistical methods, such as regression analysis, to identify correlations between variables and determine the relative importance of different factors in accident occurrence.
5. Model Development: Based on the findings from the qualitative and quantitative data analysis, develop an operational risk management model for small fishing vessels. This model should consider the complex interdependencies between technical, human, and environmental factors in accident causation. The model will be practical, easy to understand, and adaptable to the fishery industry's needs.
6. Risk Management Approach: Propose an operational risk management approach that integrates the identified causal factors and preventive measures. This approach should address both technical and human factors, considering the specific context and constraints of small fishing vessel operations. Recommendations for accident prevention, safety enhancements, and training programs shall be provided.
7. Validation and Evaluation: Validate the developed operational risk management model and the proposed risk management approach through expert reviews, industry consultations, and pilot testing. Evaluate the effectiveness and feasibility of the model and approach by assessing their practicality, usability, and potential impact on safety outcomes.

The current study begins by conducting a comprehensive review of existing literature on small fishing vessel accidents and risk factors. This helps in understanding of the existing research and literature on small fishing vessel accidents and risk factors, and also helps identify key themes, trends, and gaps in the literature. The introduction chapter of this PhD thesis presents the results of this task in the background section. Further literature review is contained in the introduction of sections of chapter 3, 4, 5, and 6 in the thesis.

Next is the collection of both qualitative and quantitative data from primary and secondary sources. This is done by conducting semi-structured interviews with experienced fishermen, vessel operators, safety managers, and stakeholders. For quantitative data we administer structured questionnaires or surveys to a representative sample of small fishing vessel operators and crew members. Additionally, we analyze existing data on small fishing vessel accidents, obtained from relevant authorities or agencies. This aspect of the methodology is implemented under chapter 3, 4, 5, and 6 in this thesis.

The collected data is next analyzed using qualitative and quantitative analysis techniques to identify correlations, determine the importance of different factors, and generate probability data. This aspect of the methodology is implemented under chapter 3, 4, 5, and 6 in this thesis.

The model's development and risk management approach phases are implemented to propose an operational risk management approach that integrates identified causal factors and preventive measures. This aspect of the methodology is implemented under chapter 3, 4, and 6 in this thesis.

Next, is to validate the developed model and approach through expert reviews, industry consultations, and pilot testing to evaluate their effectiveness and feasibility. This aspect of the methodology is implemented under chapter 3, 4, 5, and 6 in this thesis. The manuscripts generated from the current study were submitted for publications in peer-reviewed journals.

A presentation of the results and findings of the study is done by summarizing the results of the data analysis, model development, and risk management approach. This aspect of the methodology is implemented under chapter 3, 4, 5, 6, and 7 in this thesis.

Lastly, discussions to Interpret the findings, their implications and provide recommendations for the fishery industry are undertaken, and conclusions drawn to end study. This aspect of the methodology is implemented under chapter 3, 4, 5, 6, and 7 in this thesis.

Figure 2.1 outlines the various steps involved in the study methodology and Figure 2.2 shows the methodology steps and the expected outcomes from a specific step.

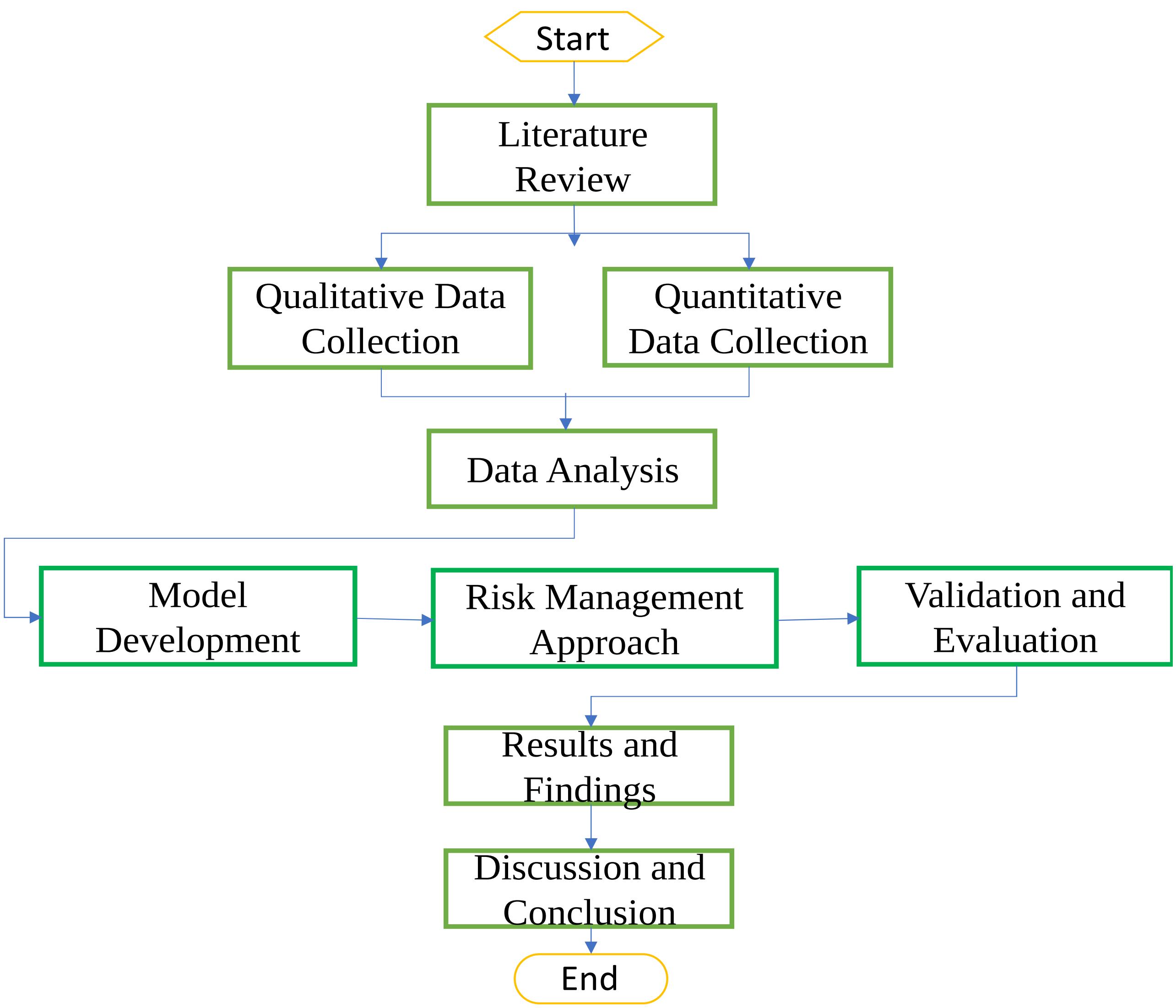

Figure 2.1. Framework of study methodology for operational risk management of small vessel.

Figure 2.2. Study Methodology and their expected outcomes.

The rest of this chapter outlines the nature or strategy of the study, the methods of data collection, the kind of data analysis, the ethical considerations, and the research limitations.

2.2. Nature of Study

The current research combines both qualitative and quantitative methods (i.e., hybrid approach), whereby accidents occurrence and viable strategies adopted to mitigate their consequences in fishing vessel operation, is the study focus. The design of research methods is related to research questions and the research problems (Kumar et al., 2018; Hatch & Lazaraton, 1991; Silverman & Seale, 2005). This study seeks to identify the most high-risk (critical) operational activities during a fishing operation/voyage, and would be trying to deal with research questions of What? Why? and How (much)? Questions like What? And How? will normally represent the nature of qualitative inquiry research which aims at describing what is going on in the research, and a question like Why? can help explore a comparison between groups or seeks out relationships between variables for items studied (Creswell, 1998, p. 17). The research study involves the computation of risk for major causes of fishing accidents during operations and the analysis and proposal of risk management options to mitigate, reduce and control the calculated risk.

2.3. Gathering of Documentation/ Data Collection

An initial and a very important component of this study is to determine the primary causes of fishing vessel accidents/incidents. For many countries, accidents that result in death, injury, significant loss of property, or damage to environment will lead to an investigation and an accompanying report by the respective governmental agency of the country. The study method for this research uses the analysis of historical and literature data on accidents from the artisanal and commercial fishing activities and their incident/accident reports worldwide. This process constituted a secondary data source approach, whereby the quest was to search for data from published literature on reported accidents, identifying the dominant causes, and consequence (injury & fatality) of these accidents from the mentioned sources. To undertake this task, the data sources search was segmented into four regions for the purpose of convenience and simplicity (ie. Europe, America, Africa, and Australia & Asia Pacific), with publications spanning over a range of years, although where possible to rely on recent data. Additionally, the data analyzed also covered various ranges of fishing vessels although the majority involved the small-scale or artisanal fishing vessels. Through google search engine via the internet, major reports from studies and investigations by organizations such as: International Maritime Organization (IMO), Food and Agriculture Organization (FAO), Marine Accident Investigation Board (MAIB, UK), Transportation Safety Board (TSB, Canada), National Research Council (NRC, US), European Maritime Safety Authority (EMSA), and relevant technical papers were obtained from journal publication on the regions. The results of the exercise yielded a list of contributing causal factors of the fishing vessel accidents and their occurrence probabilities. The first and second objectives were addressed using the data obtained from the secondary data sources. The published data are found in chapters 3 and 4.

In the next stage of the research, individual questionnaires/interviews were conducted with fishing vessel operators. The original motivation for this approach was to supplement the data obtained from literature sources (i.e., investigation reports, historic data, journals, etc.) with expert opinion data. It is worth noting that the challenge of insufficient to almost no-existence of accident database should be no excuse for not conducting sound risk assessment for small fishing vessel operations. Rather, with less knowledge and minimal understanding of the subject of this research, the need for risk assessment and management becomes more imperative. Therefore, the objective of the current study aligns with today's risk-based approaches in decision-making to deal with uncertainties within socio-technical systems and processes.

The questionnaire/interview portions of the study were approved by Memorial University's Interdisciplinary Committee on Ethics in Human Research (ICEHR). Prior to the interview/ questionnaire administering taking place, all participants signed a consent form.

Participants were recruited (drawn) from a group of experts from maritime safety and accident investigation boards, small vessel operators' association and regulatory agencies, with over five years' experience in the design and operation of small vessel (i.e., fishing, passenger, and transport goods), and with knowledge about causal factors of maritime accident/incident were used in the data collection exercise. The purpose of the survey was to collect information from participants to help estimate the likelihood (i.e., probability) of accident triggering factors for small fishing vessel operations. The experts rated risk factors and barriers of safety for the proposed accident scenario, and in addition recommend management strategies. The results and analysis of the field studies are captured under chapter 5, a publication in Journal of Ocean Engineering.

2.4. Limitation of the Methodology

The limitation of the methodology lies in the style of extracting information on both the frequency and consequence of an accident from the data sources. It is usually difficult to gather information on both accidental event frequency and the consequence of an accident from a single data source. A published work would mostly focus on the frequency or likelihood of an accident solely or the consequence only. As explained by Wright and van der Schaaf (2004), accidents are rare compared to near misses, hence if accidents could be supplemented by a much greater number of near misses, common causes could be identified with greater confidence (Davis et al., 2019).

2.5. Ethical Considerations

The nature of the current study would usually be subjected to certain ethical issues and MUN ethics approval was obtained. At the same time, participants were asked to sign a Debriefing and

Withdrawal Letter. However, the current study has an inherent ethical consideration since it deals with historic data already collected through acceptable means.

2.6. Data Analysis

The reported accidents/incidents of fishing vessel operations and the accompanying consequences under the regional categories in the literature are analyzed and the occurrence likelihood's (i.e., probability or frequency) of an accident were extracted from the literature and historic incidents. For the maritime transportation industry, the historical approach has been applied by (Abkowitz and Galarraga, 1985), although it is often difficult to acquire straightforward frequency information. According to American Institute of Chemical Engineers (2000), there is no specific way to measure risk or present an estimate of the risk of an event taking place, but it is usually determined from information and available resources and the audience for which it is intended for. The risk can be computed as a function of the historical frequency and the historical consequence. After which a qualitative ranking may be applied to classify the severity of the various accidents analyzed.

The data management and numerical analysis aspect of the research were done using quantitative modeling tools as enumerated in the steps above, i.e., fault tree analysis (FTA); Bayesian network (BN), and evidence theory (translate verbal data to numeric).

2.6.1. Fault Tree Analysis (FTA)

It is one of the distinct methods of quantitative risk analysis that is used to develop a logical relationship amongst the causal factors of an accident and then estimate the associated risk. The FT is developed by a top-down approach while considering the causes or events at levels that are below the top level (IMO, 2013). It presents the causal relationship between accident events which individually or in combination happens to cause a higher-level accidental event occurrence. As an example, if any one of two or more lower events can cause the next higher event, this scenario can be shown by a logic "or" gate. The logic gates determine the addition or multiplication of probabilities (by assuming independence) to obtain the values for the top event. Fig. 2.3 illustrates this example,

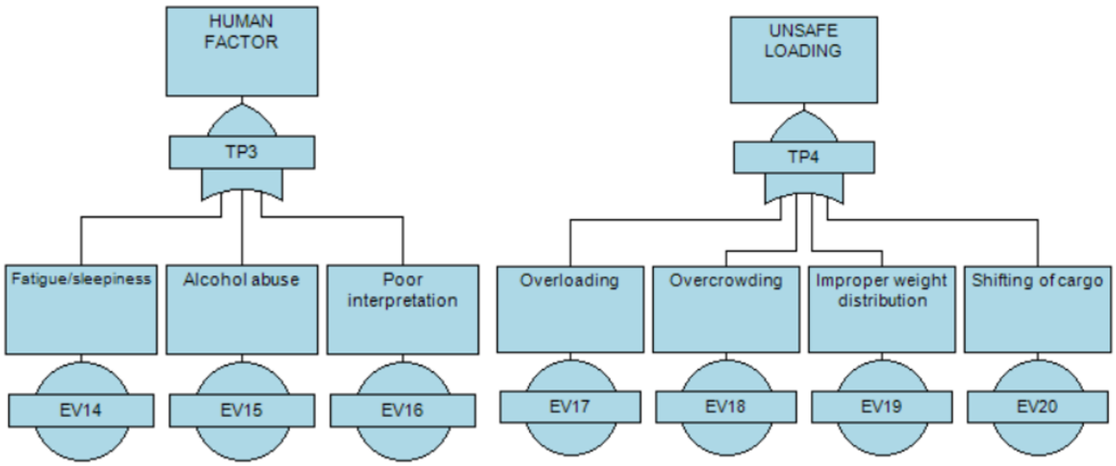

Figure 2.3. Example of fault tree with top event human factor or unsafe loading and basic event such as fatigue.

2.6.2. Bayesian Network (BN)

Even though BNs are applied to many diverse subject areas, according to (Pearl, 1986) it emerged from the artificial intelligence community. The method is a probabilistic graphical approach that represents the interaction of parameters using a directed acyclic graph (DAG), and for which the nodes represent random variables. The arc is directed from a "parent" node to a "child" node. In studies conducted by Fenton & Neil, (2013) the authors introduce the BN approach in the context of risk assessment. Sometimes arc direction may give a clue about causal relationship. As stated by Hanea, et al., (2022) the arc direction may also be selected based on what combination of marginal and conditional probability distribution is the easiest to acquire. In general, the BN variables are either discrete or continuous, but a hybrid of the two is also possible. The discrete variables are however the most commonly used approach. To solve conditional probability tables (CPTs) are used to represent probability distribution for child nodes, this CPTs can become complex as the number of entries required grow exponentially. The parent nodes which constitute the basic event will be entered with the event's prior probability data except they also form child node in the network chain. The BN method uses a conditional probability approach, which is based on the Bayes theorem, and which has found its roots in many studies that are probabilistically based. Utilizing directional arrows (i.e., edges), the statistical relationship between the developed network variables depicts the real events.

The accident network for the sample scenario was formed using the causal factors which depict events from the developed logic diagram. The mapping approach used is described by Khakzad et al. (2011) and Khakzad et al. (2013): mapping of primary events to root nodes; intermediate events to intermediate nodes; top event to leaf node; event occurrence probability to prior probability; and Boolean gates to conditional probability tables (CPTs). Boolean logic is used to build the conditional probability table (CPT) to evaluate the occurrence probability of the leaf node. For purpose of analysis the fault tree diagram (FTD) is mapped into a Bayesian network (BN).

An assumption of the non-dependence of the root node is implemented, and the chain rule is then applied to develop the joint probability distribution (JPD) between the child node and the parent nodes (Bielza and Larrañaga, 2014).

$$P(U) = \prod_{i=1}^{n} P\left(P_a(A_i)\right) \tag{2.1}$$

Where, $U = variables\ (A_1, A_2, \dots., A_N)$

$P\ _a(A_i) = parents\ of\ Ai\ in\ the\ BN$

$P(U) = reflects\ the\ properties\ of\ the\ BN$

2.6.3. Evidence Theory.

Also called belief functions theory, evidence theory was initiated by Dempster with his works on milestones superior and inferior bounds of a family of probability distributions (Dempster, 1967) which was then reinforced by Shafer (Shafer, 1976). There exist varied processing models of imperfect information in the literature (Smets, 2004). Probability based belief function theories such as, upper and lower model (Walley & Moral, 1999); Dempster-Shafer theory), and couple non-probabilistic belief function theory (the theory discussed in Shafer's book, Shafer, 1976; Transferable Belief Model by Smets 1990, 1994).

2.6.4. *Dempster-Shafer (D-S) evidence theory*

The Dempster-Shafer theory (DST), sometimes called the evidence theory, was initially proposed by Dempster in 1967 whiles studying lower and upper limits of probability (Dempster, 1967) and later formalized by Shafer in 1976 (Shafer, 1976). The literature on D-S theory promotes it as a useful and convenient framework for modeling epistemic uncertainty and combining evidence from multiple sources.

The theory constitutes a set of propositions (*bpa*'s) and then assigns to each of them an interval of [***belief***, ***plausibility***], and the *bpa* is defined mathematically by the belief function m: $2^{\Theta} \rightarrow [0, 1]$ over a frame of discernment Θ, that satisfies the relations below; (Wang et al., 2022; Omid & Assefa, 2016)

$$\sum_{A \in \Theta} m(A) = 1 \qquad (2.2)$$

$$m(\emptyset) = 0. \quad (2.3)$$

$$m(\Theta) = 1 \quad (2.4)$$

Where, the number of all subsets of Θ is 2^{Θ}. If $m(A) > 0$, then A is the focal element.

The mass function $m(A)$ represents the degree of support given to proposition A. The mass $m(\Theta)$ also represents the uncertainty of the evidence for proposition A. If $m(A) = 1$, then the evidence does not provide valuable information (Wang et al., 2022).

The plausibility (Pl) function P: $2^{\Theta} \rightarrow [0,1]$ is defined by using the belief (Bel) function as

$$Pl\,(A) = 1 - Bel\,(\tilde{A}). \quad (2.5)$$

The *Bel* and *Pl* functions are the lower and upper envelopes of a class of probability assignments about A so that $Bel(A) \leq Pl(A)$ (Omid & Assefa, 2016). The precise probability of an event (in the classical sense) would lie within the lower and upper bounds of Belief and Plausibility, respectively (Sentz & Ferson, 2002).

$$Bel(A) = P(A) = Pl(A). \quad (2.6)$$

The plausibility and belief functions of the D-S evidence theory help us obtain information about the uncertainty in the knowledge and understanding of experts.

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CHAPTER THREE

3. Capsizing Accident Scenario Model for Small Fishing Trawler

Preface

A version of this chapter is published in the Journal of Safety Science, 145 (2022) 105500. I am the primary author along with the Co-authors, Vindex Domeh, Faisal Khan, Neil Bose, and Elizabeth Sanli. I developed the conceptual framework, methodology and investigation for the capsizing accident scenario and reviewed the literature along with implementing the model with a case study. I prepared the original draft of the manuscript and subsequently revised the manuscript based on the co-authors' and peer review feedback and comments. Co-author Faisal Khan helped in the concept development, method, formal analysis, of model, reviewing and revising the manuscript. Co-author Neil Bose helped in the methodology, formal analysis, of model, reviewing and revising the manuscript. Co-author Elizabeth Sanli helped in the formal analysis of model, reviewing, and revising the manuscript. Co-author Vindex Domeh helped in the concept development, methodology, reviewing and revising the manuscript.

Abstract

Fishing is considered one of the most dangerous occupations globally. Small-scale fisheries, which make up about 90% of the entire industry worldwide, are done using small boats with little onboard shelter and limited navigation and safety equipment. Small-scale fishing uses small fishing vessels such as small trawlers, which are prone to accidents, such as capsize. This paper proposes applying the Object-Oriented Bayesian Network (OOBN) to capture the risk influencing factors of the capsizing accident scenario under different operating conditions for a small fishing trawler, a sub-class of fishing vessels. The model dynamically assesses the probability of capsizing occurrence, considering the complex interaction among critical influencing parameters. The application of the proposed model is demonstrated on a small fishing trawler. To enhance the applicability of the model, uncertainty analysis was also conducted. The probability of capsize is estimated as 0.092 ± 0.003. A study considering the most critical contributing factors was also performed to identify key risk-reducing measures. The most critical measure identified are the human elements (training and experience). The proposed model would serve as a tool for the maritime industry and governmental regulatory bodies for decision making.

Keywords: Accident; Capsize; Small trawler; Sensitivity; Bayesian Network; Risk control; likelihood

3.1. Introduction

Marine accident reporting has been receiving much attention in the developed world. Most documented incidents (or accidents) indicate a high proportion of fishing vessel involvement. Fishing is an inherently dangerous occupation and, for many years, has been seen globally as one of the riskiest occupations, with some staggering and alarming occurrence incidents for commercial fisheries. The United States, for example, in 2008, recorded a fishing fatality rate of 129 deaths per 100,000 fishers, and that exceeded the 2016 fatality rate for all workers in the United States and all industries by 23 times (Case et al. 2018; Lincoln and Lucas 2010). Quite often, fishers' corpses were strewn onto Newfoundland beaches in the 19th century (Drudi 1998). The small fishing vessel industry worldwide has reported over 1,000 fatalities on average annually since the 1960s, according to Lloyd's Register Foundation (2018), with many occurrences in Africa and Asia. Current reports from the International Labour Organization (ILO) and Food and Agriculture Organization (FAO) of the United Nations (UN) estimate that between 24,000 and 32,000 deaths occur annually in the pursuit of fishing. The safety of fishing vessels should be prioritized, as proper safety measures will save lives, protect vessels from damage, prevent severe accidents and injuries, protect the environment and contribute to profitable fisheries, thus, according to (FAO 2019).

It is common knowledge that fishers depend on their vessels for survival, and this becomes compromised if their boat is lost. There is even the likelihood that some or all the crew will lose their lives too. The most common causes of fishing vessel casualties include capsizing, foundering, fire/explosion, and collision. FAO (2001, 2019) has summarised the leading accident causes as fire on board, a man falling overboard, loss of water tightness, machinery failure or damage, bad weather, loss of communication, loss of steering system, loss of propeller, collision, running aground and explosions. Furthermore, from the fishermen's perspective, the listed causes have their roots in economic pressure, luck, uncertain weather, lack of knowledge about equipment fatigue, and stress (Costa 1996; FAO, 2001). Small fishing vessels, especially, risk capsizing during a large catch, getting submerged in heavy seas, and sometimes get run down by a more massive ship.

The term "capsize" is used to describe a vessel heeling over to an angle from which it cannot return upright unless assisted by an external force (Borlase 2003). Vessels capsize incident is among the accidents leading to the loss of life and property in marine casualty investigations. Studies have revealed ship capsize frequency per 5027 fishing vessel accident rates of 4.4% for fishing boats from 2004 to 2017 (Davis et al. 2019). Further studies also show frequencies of 0.264 for ferry boats capsize from 1991 to 2000 (Sigua and Aguilar 2003) and 0.08 for ocean-going ships capsize from 1995 to 1999 (Toffoli et al. 2005) in Newfoundland and Labrador, Philippines, and worldwide shipping respectively. The increase in maritime accidents resulting in capsizes also brought about the need for sustainable maritime search and rescue since 2011. For instance, the Canadian Coast Guard investment plan for 2011-2015 shows 98% (TEC) going to SAR and 2% (TEC) for Aids to Navigation (CCG, 2019). Another typical example is the 6100 marine SAR incidents recorded in Canada's 2017 fiscal year (Manning and Gold 2018). Davis et al. (2019) confirm that small fishing trawlers capsize as one type of maritime SAR incidents encountered in Europe and North America. Dickey (2008) further confirmed the vessel capsize incident as a leading global maritime accident with a high fatality rate.

In developing countries such as those in Africa and Southeast Asia, advanced fishing equipment is lacking, and fishing activities are done using small boats with little onboard shelter and limited navigation and safety equipment. The small-scale fishing practices in these regions have also been heavily linked to poverty and deprivation, which characterizes individual households and communities (Béné 2003). However, there are well-documented articles by Berkes et al. (2001); Delgado et al. (2003); and Kittinger et al. (2013), which have shown evidence of small-scale fisheries accounting for more than 90% of the world's fishing occupation in terms of people involved. The small fishing trawler, a subclass of fishing vessels, are popular types of vessels used for small-scale and commercial fishing activities in Europe and most developed nations. These vessels are difficult to access and usually will not have sophisticated navigation and communication installations to help limit or prevent avoidable accidents. As a result, research interest has heightened in vessel capsize, focusing on small fishing trawlers (Taguchi et al., 2013; Davis et al. 2019; Papanikolaou et al. 2000). Ugurlu et al. (2020) studies identified that 73 out of the 226-fishing vessel accidents which met the criteria of the studies were trawlers, and these fishing vessels were involved in combined accidents of a collision, sinking, and grounding. Windle et al. (2008) proposed a conceptual model that identified potential sources of direct and indirect risks to fishing health and safety, which helped throw light on possible pathways from regulation to fishing safety.

The International Maritime Organization (IMO) has enacted conventions that have provided benchmarks for improving safety, and many fishing nations have adopted its measures into their marine safety programs. The IMO’s Document for Guidance on Fishermen's Training and Certification (IMO, 1988) and the Code of Safety for Fishermen and Fishing Vessels (IMO, 1975a) addresses fishing vessels. Other IMO codes and guidelines include the voluntary guidelines for the design, construction, and equipment of small fishing vessels (IMO, 1980) and the code of safety for fishers and vessel design and construction (IMO, 1975b). These guide training and education and detailed curriculum development. The IMO has, over the years, also assisted developing countries in its area of expertise, such as preparing model maritime legislation that suits countries for adoption. Other examples can be found in the setting up of regional coordination offices in Ghana, Kenya, Ivory Coast, and the Philippines, and meeting the unique needs of Africa through the IMO's Integrated Technical Co-operation Program (ITCP) ("IMO achievements," 2020). The IMO, ILO, and FAO have documented varied challenges facing the small-scale fishing industry. The Yearbook of Labour series published by the International Labour Organization (ILO) relating to total employment (i.e., paid employment plus self-employment) and persons in paid employment worldwide generally classify fisheries together with agriculture, hunting, and forestry, and therefore, fishers are not separately identified. Statistically, fisheries encompass not only fishers but also workers in fish processing and aquaculture. However, the FAO is a repository of the most comprehensive data concerning the number of persons engaged in fishing and roughly estimates about 15 million fishers aboard decked or undecked fishing vessels worldwide. The FAO's manual on safety at sea for small-scale fishers (FAO 2019), is also a document that aims to contribute to a culture of safety awareness among fisherfolk and reduce the number of accidents while increasing the chances of survival if accidents occur. The manual guides on safety matters related to the workings of a small-scale fishing vessel (e.g., fire safety, deck safety, lifesaving equipment, lighting, and ventilation), personal safety, and navigation safety.

Research has generically studied factors that contribute to boat capsizing, among this, the operational state of the vessel, adverse weather conditions, and human errors are found to play critical roles, see (Jin et al., 2001; Wang et al., 2005; Peters, 2019; Ugurlu et al., 2020). However, there is also significant work being done to understand and minimize vessel capsize accidents. Peters (2019) studied ship capsize but focused on tolerable risk margins applicable to naval vessels. Another study (Sur and Kim, 2020) centered on estimating frequency and consequence measures without recourse to a risk factors analysis. Uğurlu et al. (2020), on the other hand, carried out a probabilistic risk assessment on causal factors to a fishing vessel sinking and collision accidents. The reviewed literature shows that the subject of fishing vessel capsize assessment using Bayesian network (BN) modeling is yet to be thoroughly studied. Thus, to study and answer the questions of how a small fishing trawler capsize is likely to happen and when it happens, the object-oriented Bayesian network (OOBN) is adopted here to fragment the causative factors in a complex formulated network.

The current paper presents a comprehensive study on the critical contributing parameters for small fishing vessel capsize accident scenarios and dynamically models the likelihood of occurrence under different operational scenarios via the OOBN. The present study's objectives are to (i) identify the critical/basic parameters and intermediate parameters leading to a small fishing trawler capsize, (ii) understand the dependencies and interdependencies among these parameters, (iii) assess the probabilities of the risk factors from historical data, literature, and subject matter experts' knowledge, (iv) establish the most probable path toward small vessel capsize under multiple operational scenarios and provide a best practice risk reduction strategy and, (v) develop a robust dynamic model, an object-oriented Bayesian network (OOBN), to estimate the probability of capsizing accident scenarios for a small fishing trawler.

The remaining part of the research work discusses as follows: Section 2 explains the proposed methodology, section 3 is devoted to research results and discussion. Section 4 concludes the findings of this work and makes recommendations.

3.2. The Research Methodology

Fishing vessel accidents occur due to a complex combination of influencing factors. To capture these factors for risk prediction requires a robust and dynamic methodology. Fig. 3.1 shows the proposed methodology for a small trawler capsizes accident scenario.

The proposed methodology starts with the characterization of the vessel type and the identification of accidental events and contributing risk factors. Next, accident events and risk factors are used to develop a logical safety structure for the capsizing accident scenario using the fault tree diagram (FTD). The developed fault tree is next mapped into a BN and OOBN for numerical analyses. Risk factor probability acquisition (in this case, literature data) and assigning failure probabilities to the factor states. Afterward, the numerical analyses of the BN model are performed to estimate the occurrence likelihood of trawler capsizing, and further sensitivity and uncertainty analysis assist in the selection of the critical risk contributing factor which needs attention in a risk control measure. The systematic stages of the method are further explained in the following sections.

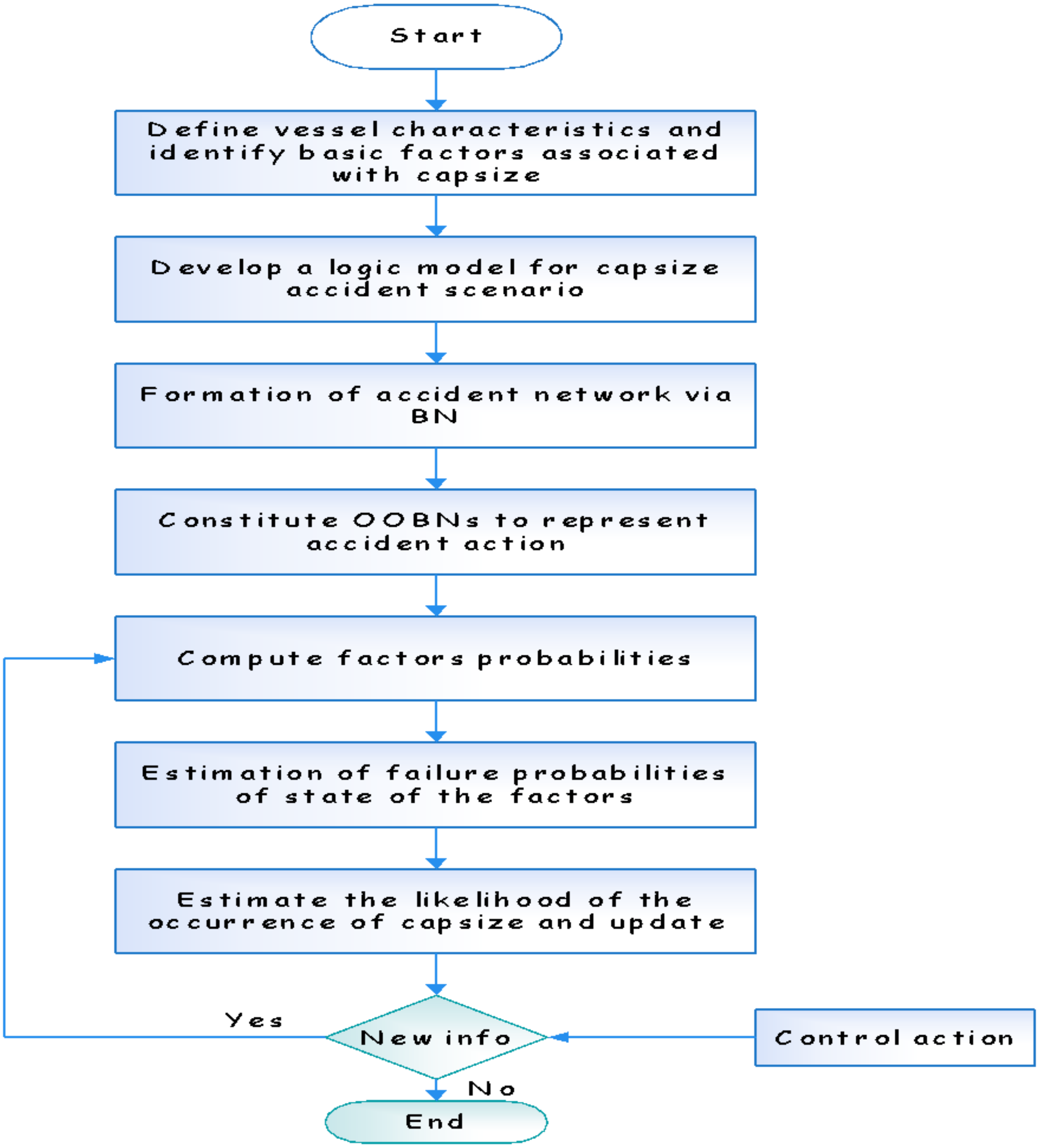

Figure 3.1 Small trawler capsizes likelihood estimation model.

3.2.1. Capsizing Scenario Model

Identification of Conditions and Parameters Leading to Capsize

In this study, a small fishing vessel (trawler) will be classified as a decked or undecked fishing vessel of length (LOA) less than 24 m, and which makes use of trawls as their fishing gear with less advanced navigational and safety equipment installed on-board. The capsizing of small trawlers, as observed from accident reports and published literature, is attributed to major accidental events involving flooding, loss of boat stability, and loss of boat control. Additionally, the effects of adverse weather and human error also play contributing roles in vessel capsize. Studies conducted by Taguchi et al. (2013) and Borlase (2003) have analyzed the effect of freeboard on the stability of the fishing vessel and flooding stability, which are concluded to be significant causes leading to the possibility of capsizing. The primary events of the major parameters or factors associated with the major contributing conditions are shown summarised in Table 3.1, based on the reviews of the following studies: (NRC (1991); Köse et al. (1998) Jin et al. (2001); Wang et al. (2005); McKnight et al. (2007); Kum and Sahin (2015); Ugurlu et al. (2015); Ung (2019); Davis et al. (2019); Ugurlu et al. 2020).

Table 3-1 Major parameters (accidental events) and risk factors for small fishing trawler capsize

Number	**A condition that leads to an accident**	**Parameters or factors of accident condition**
1	Flooding	Hull integrity, human factors, machinery failure, communication failure, environmental factors, failure of echo sounder, failure of GPS, steering gear failure, vessel squat, boats, small-scale design flaws, poor maintenance, corrosion, route plan, failure of echo sounder,

2	Boat Stability (Static and dynamic)	Unsafe loading, human factors, free surface effect, trim, overloading, overcrowding, improper weight distribution, shifting of cargo
3	Boat Control	Navigation system failure (GPS and binoculars failure), maneuvering system failure, loss of directional stability, weather, human factors, rudder failure, machinery failure, bow thruster failure, unsafe loading (static loading, fish on deck, shifting of cargo), boat speed, steering (Helmsman) failure, mechanical failure, corrosion, defective design, poor maintenance, fatigue failures, excessive wear, corrosion, faulty design, and lack of maintenance.
4	Weather	High wind, high sea current, rough waves, high tides
5	Human Error	Not closing the sea-chest, not blocking scuppers during heavy catch, fatigue, alcohol abuse, poor interpretation (judgement), insufficient experience, inadequate training, inattention failures, supervision failures, boat speed, steering handling failure, carelessness, failure to use the equipment, improper route observation, improper lookout, sleepiness, OOW handling failures, OOW inattention failures, supervision failures, verification failures.

Logic Diagram representing Capsize influencing parameters' dependencies.

The current studies focus on small trawlers, a popular fishing vessel type mostly in Europe that is prevalent in use for small-scale fishing. The European Maritime Safety Agency (EMSA, 2014) reports for the periods 2011, 2012, and 2013 identified marine casualties and incidents involving trawlers 102/184, 153/272, and 171/367 (trawler/total fishing vessels). The event sequences leading to a capsize accident for a small trawler are presented as a fault tree diagram (FTD). The FTD can be analyzed qualitatively and quantitatively using Boolean algebra (i.e., logic gates of OR- and AND). It is traditionally used to estimate the top event of fault tree analysis (FTA). The deductive approach of the FTA, with its binary-based analysis nature, makes it highly subjective. To limit variability in the prediction of the occurrence probability for the outcome of an accident scenario and reduce the level of uncertainty in the results for different analysts, a probabilistic model such as the Bayesian network (BN) is more appropriate.

In this work, a fault tree was developed to illustrate the interrelationships existing between the capsizing incident and the causal factors that are responsible for its occurrence. Intermediate accidental events of flooding, loss of stability, and loss of control come next at a level below the top event. These intermediate events were further developed into the most basic events at the lowest level for which data is readily available or data could be acquired in the future. Fig. 3.2. illustrates a summary example of the logic diagram representing small fishing trawler capsizing. It was built based on the major parameters and risk factors listed in table1. In the FTD events such as loss of hull integrity (GT5), the human factor (GT6), unsafe loading (GT7), navigation and maneuver failures (GT8), and harsh weather (GT9), which have transfer-out symbols are developed further until the lower-level basic events. See supplementary material for a completely developed fault tree representing the small fishing trawler capsize. The causal factors which represent the intermediate and basic events have been gathered from potential hazardous events relating to the vessel, weather and environment, and human actions from literature and reports.

The fault tree was developed by reviewing relevant articles that were obtained through searches conducted on Google Scholar and ScienceDirect. Our focus was on journal articles and technical reports from governmental agencies and NGO’s using keywords or combinations of keywords of small, commercial, fishing, vessel, safety, and capsize. In all, fifty-five (55) primary events were identified, representing the failure of components, environmental conditions, human errors, and some operational functions bound to happen during the life of a vessel. The logic diagram presented also helped identify almost all the possible combinations of the primary event that may lead the small trawler to capsize. For a quantitative computation and dynamic analysis of these interrelationships of the primary events and the top event, the fault tree was then mapped into Bayesian networks (henceforth referred to as a Bayesian network-based accident network model).

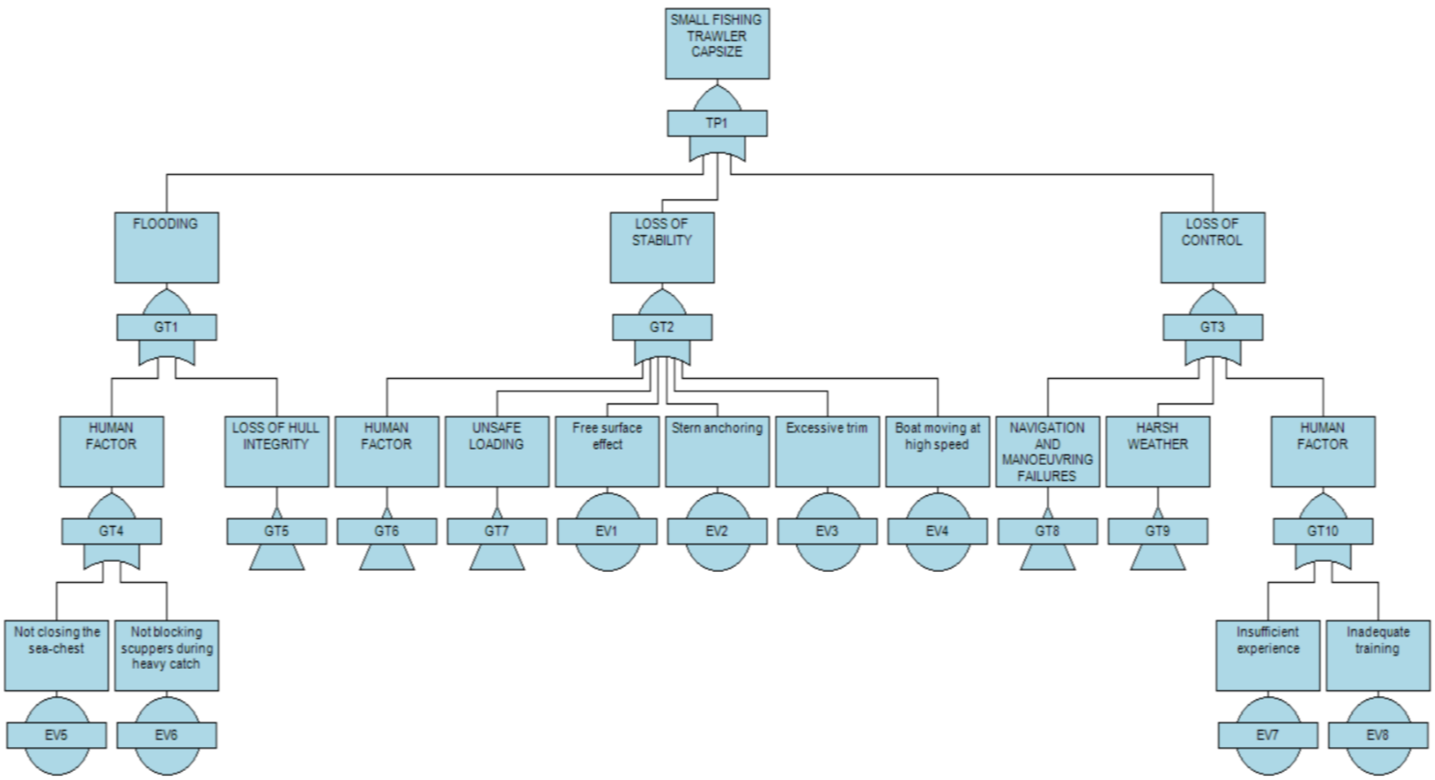

Figure 3.2 A schematic of the developed fault tree for a small fishing vessel (trawler) capsizes accident.

3.2.2. The Bayesian Network-based Accident Model

In this section, the capsize scenario of the small trawler is formed into an accident network by mapping the developed accident logic diagram (FTD) into a Bayesian network (BN). The BN is an emerging artificial intelligence (AI) algorithm, which has seen its implementation in risk assessment (Li et al., 2018). The BN approach is implemented for a dynamic analysis capability for the developed accident model. Updated knowledge in the form of future incidents occurrence rates data could be captured to update the small fishing vessel capsize occurrence probability. This capability also helps address the challenges associated with the availability and correctness of the primary causal events data, even when data may exist.

The BN method uses a conditional probability approach, which is based on the Bayes theorem, and which has found its roots in many studies that are probabilistically based. The BNs are directed acyclic graphs for which the nodes represent variables. Utilizing directional arrows (i.e., edges), the statistical relationship between the developed network variables depicts the real events.

Table 3-2 Risk causal factors (technical) for Small Fishing Trawler used to constitute BN.

No.	***Technical causal factors***	***Symbol***	***Prior Probability***
1	Free Surface effect	**A3**	1.16E-05
2	Stern anchoring	**A4**	1.42E-04
3	Excessive trim	**A5**	0.00001
4	Boat moving at high speed	**A6**	1.78E-05
5	Failure of echo sounder	**A10**	3.08E-04
6	Failure of GPS	**A11**	4.07E-05
7	Steering gear failure	**A12**	6.71E-05
8	Vessel squat	**A13**	8.14E-05
9	Small-scale design flaws	**A14**	2.01E-04
10	Main engine failure	**A16**	6.71E-05
11	Lack of VRM communication	**A17**	7.32E-05
12	VTS failure	**A19**	2.24E-08
13	Low material resistance	**A29**	1.07E-02

14	Shifting of cargo	**A39**	0.00001
15	Binocular failure	**A42**	6.71E-05
16	Rudder failure	**A43**	6.70E-05
17	Bow thruster failure	**A44**	2.03E-04
18	Static loading	**A45**	0.00001
19	Fish on deck	**A46**	0.00001
20	Excessive wear	**A55**	0.00001

Table 3-3 Risk causal factors (human errors) for Small Fishing Trawler used to constitute BN.

No.	***Human causal factors***	***Symbol***	***Prior Probability***
1	Not closing the sea-chest	**A1**	1.80E-02
2	Not blocking scuppers during heavy catch	**A2**	4.26E-04
3	Insufficient experience	**A7**	2.30E-02
4	Inadequate training	**A8**	2.50E-02
5	Improper route plan	**A9**	1.01E-03
6	Poor/lack of maintenance	**A15**	3.48E-05
7	Lack of communication between ships	**A18**	9.84E-04
8	Improper watchkeeping	**A22**	9.45E-04
9	Fatigue/sleepiness	**A33**	2.07E-04
10	Alcohol abuse	**A34**	6.70E-05
11	Poor interpretation	**A35**	1.33E-03
12	Overloading	**A36**	1.55E-04
13	Overcrowding	**A37**	1.55E-04
14	Improper weight distribution	**A38**	1.55E-04
15	Carelessness	**A40**	5.85E-05
16	Failure to use equipment	**A41**	6.09E-04
17	OOW handling failures	**A51**	6.52E-04
18	OOW inattention failures	**A52**	6.59E-04

19	Supervision failures	**A53**	9.01E-04
20	Verification failures	**A54**	1.00E-02

Table 3-4 Risk causal factors (environmental) for Small Fishing Trawler used to constitute BN.

No.	***Human causal factors***	***Symbol***	***Prior Probability***
1	Poor vision (A20)	**A20**	1.59E-03
2	High traffic density (A21)	**A21**	5.82E-04
3	Iceberg present (A23)	**A23**	5.82E-04
4	Contaminants (A24)	**A24**	0.00001
5	CO2 (A25)	**A25**	4.86E-02
6	C12H24 (A26)	**A26**	2.60E-03
7	O2 (A27)	**A27**	5.52E-03
8	With water (A28)	**A28**	1.77E-03
9	High salt (A30)	**A30**	2.17E-03
10	Bacteria (A31)	**A31**	1.12E-04
11	Low pH (A32)	**A32**	5.80E-03
12	High tides (A47)	**A47**	7.33E-04
13	High wind (A48)	**A48**	0.00057
14	Rough waves (A49)	**A49**	0.00057
15	High sea current (A50)	**A50**	0.00057

The accident network for the small trawler capsizes scenario was formed using the causal factors as summarised in tables 3.2 through 3.4, which depict events from the developed logic diagram. The tables categorize the capsizing risk causal factors under three (3) key subgroups, technical factors, human factors, and environmental factors. The mapping approach used is described by Khakzad et al. (2011) and Khakzad et al. (2013): mapping of primary events to root nodes;

intermediate events to intermediate nodes; top event to leaf node; event occurrence probability to prior probability; and Boolean gates to conditional probability tables (CPTs). Boolean logic is used to build the conditional probability table (CPT) to evaluate the occurrence probability of the leaf node. Figures 3 and 4 show the complex and a simplified BN model, respectively, for small trawlers after mapping the fault tree diagram (FTD) into a Bayesian network (BN). The primary risk causal factors are represented with symbols of A1 through A55 and embedded within the BN in figure 3.3, with their definitions illustrated in table 3.3.

An assumption of the non-dependence of the root node is implemented, and the chain rule is then applied to develop the joint probability distribution (JPD) between the child node and the parent nodes (Bielza and Larrañaga, 2014).

$$P(U) = \prod_{i=1}^{n} P\left(P_a(A_i)\right) \tag{3.1}$$

Where, $U = variables\ (A_1, A_2, \ldots., A_N)$

$P_{\ a}(A_i) = parents\ of\ Ai\ in\ the\ BN$

$P(U) = reflects\ the\ properties\ of\ the\ B$

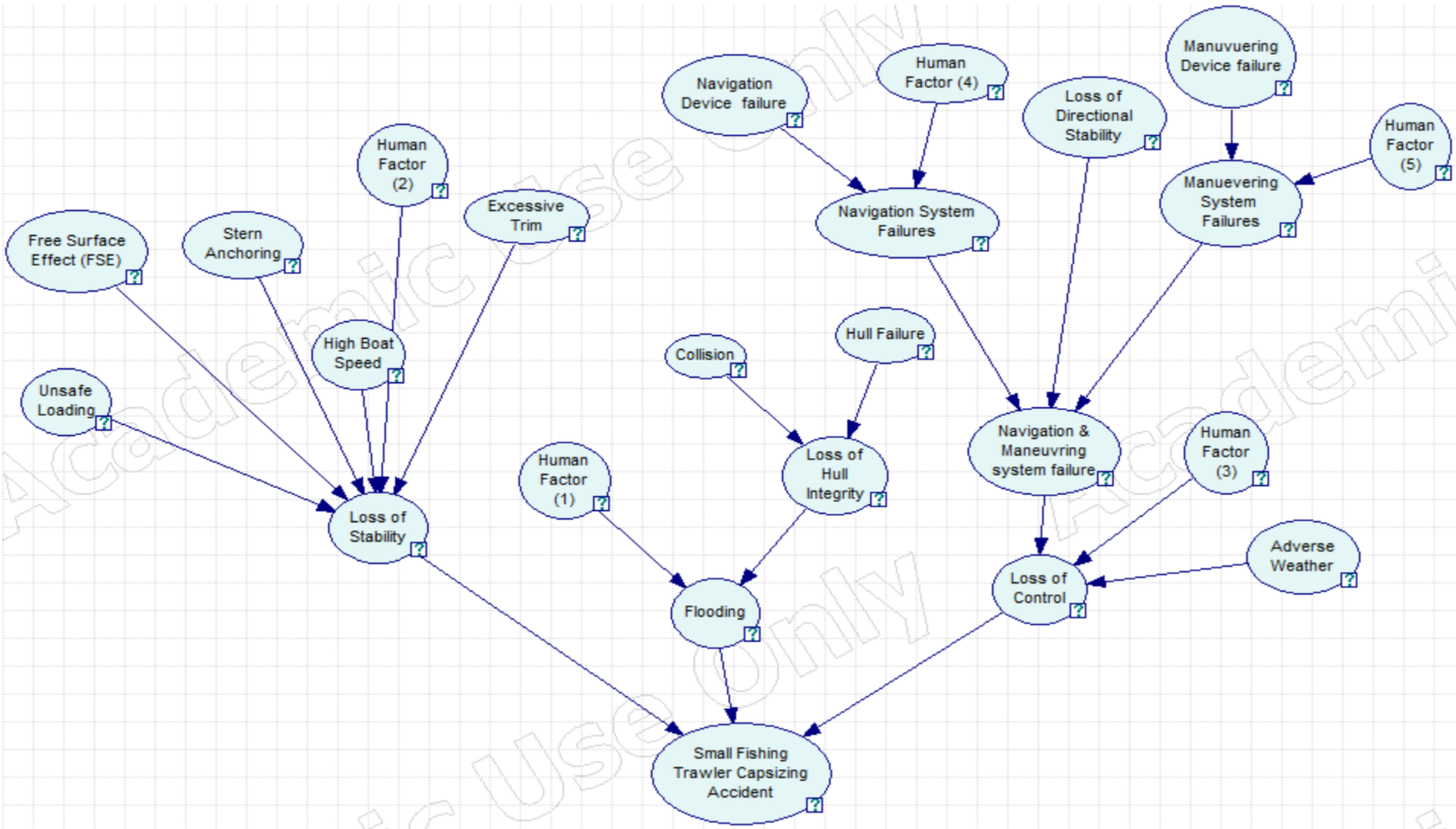

Figure 3.3A simplified Bayesian Network-based accident model for a small fishing trawler.

3.2.3. Simplification of Bayesian Network using Object Oriented Concept

The Bayesian network (BN) is a powerful tool in modeling maritime risk, which have preliminarily applied to risk analysis of strategic marine logistic and the risk assessment for ship-bridge collision (Li et al., 2018), operational risk analysis of marine transportation in Arctic waters (Khan et al., 2018), and analysis of fishing vessel accidents (Ugurlu et al., 2020). However, the standard BN is rendered impractical or insufficient, 1) when the developed network contains so many nodes that it becomes too difficult to conceptualize, and 2) when the network includes many similar repeated fragments. In both cases, it is challenging to comprehend and visualize network representation, and therefore the need to decompose the model into smaller component models. These component models are known as object-oriented Bayesian Networks (OOBNs).

The accident causal factors (parameters) listed in Table.3.1 can have grouped in sub-models to constitute small component models that are OOBNs: (1) Flooding state, (2) Boat stability state, (3) Boat control state, (4) Loss of hull integrity, and (5) Navigation and maneuvering. These constituted OOBNs then combine to form the (6) Trawler capsize model (see Fig. 3.4).

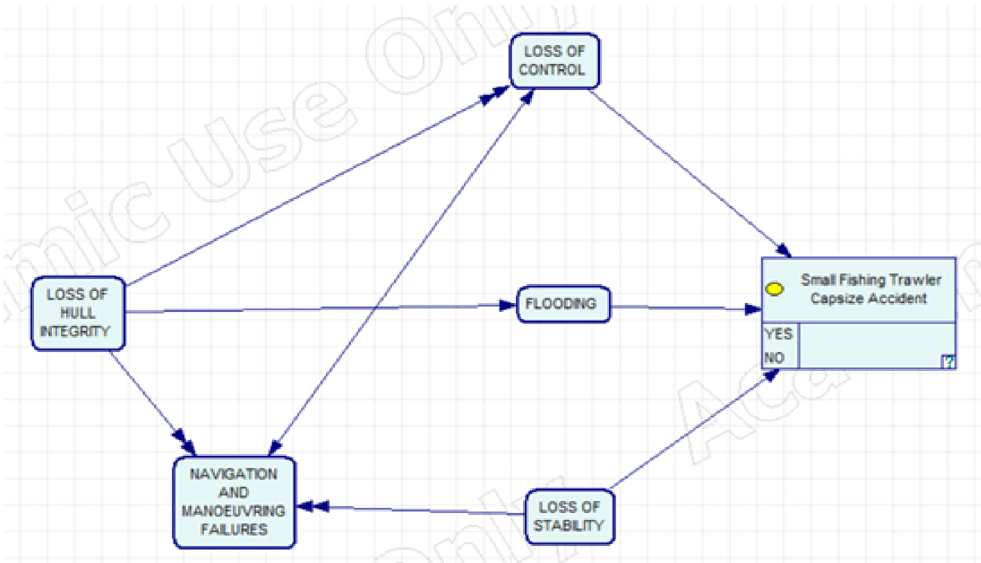

Figure 3.4 OOBN model for small trawler capsize.

The sub-model tool in the GeNIe software was used to simplify the original BN into OOBNs. To this end, the causal factors of small trawler capsize, which are represented by the accident parameters, were reorganized under the major accidental events leading to the leaf node (main accident). From knowledge of classical naval architecture and accident investigation reports on vessel capsize, there seems to be significant evidence that the vessel's stability, adverse weather conditions, and human judgment play major roles. Also, reduced maintenance and unfavorable environmental conditions, which mostly lead to loss of hull integrity, expose the vessel to flooding. Harsh weather, coupled with improper loading and loss of dynamic stability, ultimately will cause the loss of control (steerage control). As a result, the combination of the sub-models of; loss of hull integrity, flooding, loss of stability, navigation, and maneuver failure, and the loss of control constitute the OOBN, as shown in Fig. 3.4.

3.2.4. Capsize Occurrence Probability Estimation

As observed from the analysis of small trawler capsize, our dynamic accident model constitutes the root causes of flooding (intake of water), loss of stability, loss of control, and human error. These root causes were analyzed with the causal factors as outlined in Tables 3.2 thru 3.4 and the environmental conditions of harsh weather. A forward analysis is performed using prior probabilities to estimate the capsizing accident occurrence probability. The initial occurrence probabilities used for primary events in BN are the prior probabilities, which are probability data usually available on the basic events.

3.2.5. Probability Updating and Diagnostic Analysis

The BN can perform probability updating given new evidence, aside from the traditional estimations obtained from logic diagrams (Bobboi et al. 2001). Bayesian updating, also sometimes known as belief updating, is an analysis based on abductive reasoning, which computes the posterior marginal probabilities of the root nodes when the top event is assumed to have occurred. This capability introduces some form of dynamism into the accident scenario modeling. In updating probabilities, the leaf node in BN is set to the occurrence (i.e., evidence of 100 % probability) and generating new probability values for the root nodes constituting the posterior probability.

A diagnostics analysis of the BN model for vessel capsize can be undertaken via query such as: "given the top event has occurred, what are the occurrence probabilities of the primary events", and this helps to estimate the posterior probabilities of primary events are, i.e., $P(EVi|TE)$.

During the BN diagnostics, the most probable configuration that identifies the weakest link in the accident model by searching the state space of each variable can be determined by finding the difference between the prior and posterior probabilities for the root nodes. One of the most important reasons for undertaking a risk assessment is identifying the critical contributors of an accident scenario, not necessarily the numerical value of the measured risk.

The events with the highest or most significant 'difference values' will be selected to constitute the most probable set—the occurrence probability calculated using Bayes' theorem, as shown in Equation (3.2).

$$P(C) = \frac{P(A)\times P(A)}{P(C)} \tag{3.2}$$

where $P(A|C) = \ Posterior\ probability$;

$$P(A) = \ Prior\ probability, P(A) = \ Likelihood\ probability,$$

$$P(C) = \ Total\ probability;$$

$P(C|A) \times P(A)$ = Joint probability.

3.2.6. Sensitivity Analysis

The impact of the changes in the data on the modelling results can be observed through various approaches such as a nonconformity analysis, accuracy analysis, and sensitivity analysis (Ugurlu et al., 2020). A sensitivity analysis is conducted on the prior probabilities data used to evaluate the variation contributions per root node to the overall uncertainty measure in the leaf node (i.e., small trawler capsizes).

The techniques used for the sensitivity analysis in this study were the importance index (I_i), which uses a global variance approach to rank root nodes according to the degree of impact on the vessel capsize probability. The theory underpinning the importance index, as explained by Qian and Mahdi (2020), is summarised in Equation (3.3).

$$I_i = \frac{\sigma_{xi}^2}{\sigma_Y^2} \quad (3.3)$$

where, I_i = Improvement index.

σ_{xi}^2= Variance of the data set for every change in a root node.

σ_Y^2 = Variance of the original data for all root nodes.

The importance index ranking only attests to the risk factor effect on model output variability; it does not give knowledge about unidentifiable risk factors for small trawler capsize probability estimation. In addressing this knowledge gap, factor screening is vital, and the elementary effect (EE) method (Qian and Mahdi 2020; Saltelli et al. 2008) is one such sensitivity analysis technique. In the screening process, the elementary effect method categorizes the model input factors into high, medium, and low elementary effects. The high elementary effect factors are crucial to realizing the model output estimation, followed by a medium elementary effect category; low elementary effect factors intuitively have no significant effect on the output results. This presents the opportunity of simplifying the model by representing all such factors as a constant. By applying Equation (3.4)-(3.7), the EE method is used to screen the OOBN model risk factors.

$$EE_a = \frac{Y(a_i) - Y(a)}{\Delta} \quad (3.4)$$

where, EE_a = Elementary effect; $Y(a)$ = Original model output; and $Y(a_i)$ = New model output after a change in the primary event, 'a.'

$$Stepwise\ or\ increment\ (\Delta) = \frac{n}{2(n-1)} \tag{3.5}$$

where n = number of factors.

$$\mu_i = \frac{\sum_{k=1}^{k=r} \quad (EE_i)}{r} \tag{3.6}$$

where r = number of times EE_i was estimated per primary event; and μ_i = Mean for a set of EE_i estimated 'r' times per primary event.

$$\sigma_i = \sqrt{\frac{\sum_{k=1}^{k=r} \quad \left(EE_i^k -\right)^2}{r-1}} \tag{3.7}$$

where, σ_i = Standard deviation for a set of EE_i estimated 'r' times per primary event.

3.2.7. Control Measure Analysis

From the sensitivity analysis and improvement measure, the most probable explanation is to be explored through demonstration in a case study. This analysis is primarily aimed at minimizing the associated risk with an accident. For proper risk management, an attempt at control measures must be applied to reduce the occurrence probability of the small trawler's capsizing incident.

In this study, we have implemented the so-called proactive or frequency reducing measure. Furthermore, this was used to lower the occurrence probability of small fishing trawler capsize by focusing on the basic events of inadequate training and insufficient experience. While in operation, the only factor that can be controlled is the human factor. These are the basic or primary human error events having substantial probability values amongst the critical primary event.

3.3. Application of the Developed Model

The sequence of events leading to a capsizing accident scenario of a small trawler is demonstrated here by using an example of a hypothetical wooden fishing vessel with the following specifications: length (LOA) = 13.3m (43ft 7in), beam = 4.14m (13ft 6in), draft = 2.05m (6ft 8in), and displacement = 38 tonnes; operating in Atlantic Canada waters (NL). The accidental intermediate events were broken down to the basic events for which there was data available, or data could easily be obtained in the immediate future. Meanwhile, due to the under-reporting of incidents, the amount of data relating to fishing vessel accidents is limited. The data used for the prior probabilities of the causal risk factors were adopted from the literature (Wang et al. (2005); Woodward (2014); Ugurlu et al. (2015); Ung (2018); Yadzi et al. (2018); Ung (2019); Davis et al. (2019)) and are shown in Tables 2.2 thru 2.4. A forward and updating analyses are performed on the OOBN model for capsizing accident using the GeNIe Modeler software. Further sensitivity and uncertainty analyses are also undertaking, and the results of case implementation are discussed in the section that follows.

3.4. Results and Discussion

Fishing vessel accidents and safety issues have been an age-old problem. The international community and individual countries have, over the years, held various fora to help address issues of fishing vessel safety. The main objective of the current work is to dynamically model the capsize accident scenario for small fishing trawlers using a Bayesian Network. The section presents the results of the case study and discusses the observations and patterns in the output results. The numerical results are based on the object-oriented BN (OOBN).

3.4.1. Capsize probability estimation.

An occurrence probability value of 0.073 for small fishing trawler capsize was realized through a forward analysis performed on the OOBN model in the software solver after incorporating the prior probabilities shown in table 3.3. The blue shaded color in the yellow-colored leaf node (Fig. 3.5.), which represents the capsizing accident, indicates a 7 percent chance of this accident happening. This estimate is in the probability range of available data on fishing vessels capsize accidents. For example, in a recent study by Sur and Kim (2020), fishing vessel capsize frequency was estimated for nine (9) vessel types from 1988-2016; the records revealed 0.010 and 0.063 minimum and maximum capsize probability, respectively, with a standard deviation of 0.014. This finding provides an initial validation for the proposed model. Figure 3.6 shows the BN results for the contributions of loss of control and flooding to the top accident of capsizing. These major events contributing probabilities are 5% and 2%, respectively, and comes mainly from the human factor events. This indicates the capsizing of small fishing vessels is caused by human (operator) error.

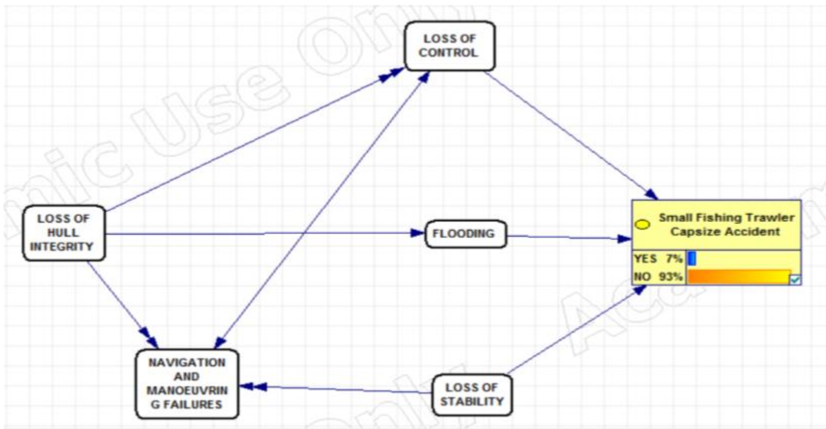

Figure 3.5 OOBN model with probability estimation result for small trawler capsize.

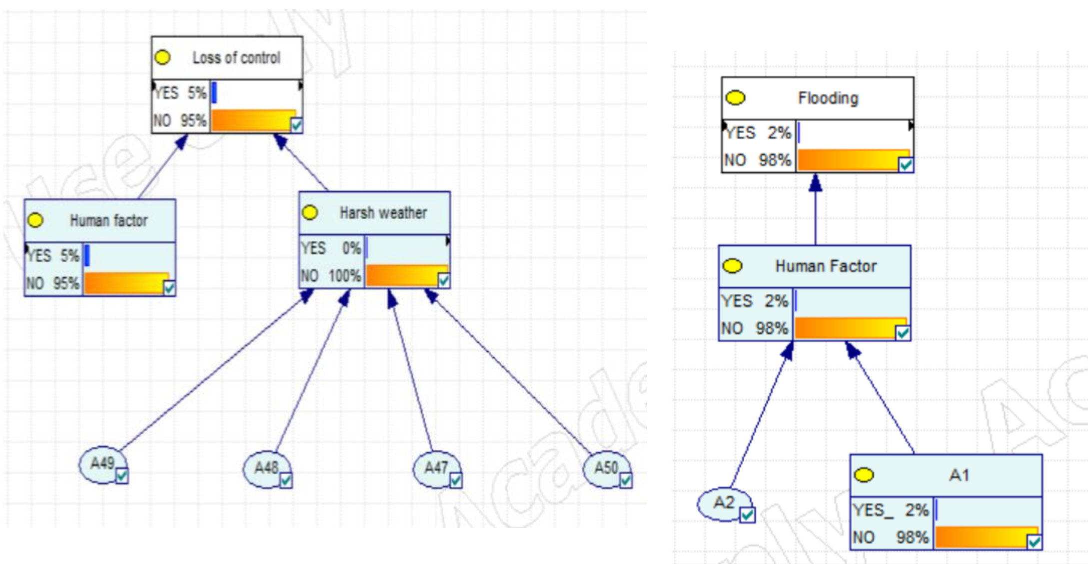

Figure 3.6 Results showing contribution by (a) loss of control and (b) flooding to capsize accident.

3.4.2. Probability updating

To ascertain the certainty state probabilities of risk factors for small trawler capsize, the probability updating of root nodes in the OOBN model is necessary. The updated prior probabilities of the root nodes then become posterior probabilities and reflect the occurrence probabilities of the capsize risk factors if a small trawler capsizes accident happens. To this end, the leaf node (shown as the yellow color in Fig. 3.5) is instantiated to a 'YES' decision state, and the software algorithm runs to solve. The new probabilities for root nodes are shown in column 4 of Table 3.3. By inspection, the prior and posterior probabilities are different in values. This observation further validates the applicability of the model. The top five (5) risk factors to small trawler capsize accidents that have shown the highest updates are: inadequate training, insufficient experience, not closing the sea-chest, poor interpretation of the situation (or judgment), and improper route plan, which are all human-related factors. This result agrees with previous studies (Amir et al., 2014; Talley, 1999).

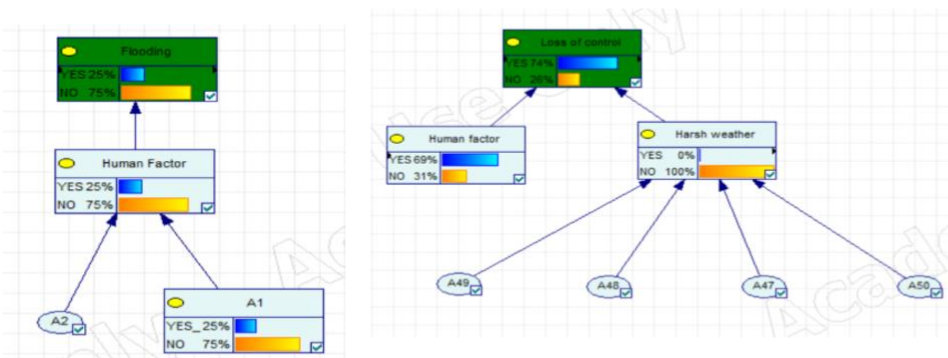

Figure 3.7 Results for human factor probabilities with evidence capsize occurred.

A comparison of the human factor results under forward analysis with the updating analysis yielded a percentage change of 23% and 64% for flooding and loss of control, respectively.

3.4.3. Sensitivity analysis

The techniques used for the sensitivity analysis are as explained in section 4. The importance index (I_i), which uses a global variance approach to rank root nodes according to the degree of impact on the vessel capsize probability was analyzed. The results of the importance index analysis are shown in Table 3.5, column 2. It was observed from table 3, risk factors such as inadequate training, insufficient experience, not closing sea chest, low material resistance to corrosion, and supervision failures, contributed significantly to the leaf node (capsize) occurrence probability. These factors will constitute the riskiest safety factors for small trawler capsize accident occurrence. We note; however, that importance index ranking only attested to the risk factor effect on model output variability and not reveal knowledge about unidentifiable risk factors for small trawler capsize probability estimation.

Furthermore, the factor screening using the elementary effect (EE) method was implemented. By applying equation (4)-(7), the elementary effect method was used to screen the OOBN model risk factors, and the results are shown in column 3 of Table 3. A high EE ($\sigma_i = 0.078$), medium EE ($\sigma_i = 0.002$), and low EE was observed. To reduce the occurrence probability of small trawler capsize, risk factors with high EE must be prioritized since they represent critical risk factors leading the leaf node (capsizing), and followed by medium EE and low EE factors, respectively. However, low EE factors may be ignored since they do not impact small trawler capsize probability significantly.

Table 3-5 Estimates for small fishing trawler capsize.

Symbol	Root Node	Prior Probability (Pr)	Posterior Probability (P)	Standard deviation (σ)
A1	Not closing the sea-chest	1.80E-02	2.48E-01	7.80E-02
A2	Not blocking scuppers during heavy catch	4.26E-05	5.87E-04	7.80E-02
A3	Free Surface effect	1.16E-05	1.60E-04	7.80E-02
A4	Stern anchoring	1.42E-04	1.98E-03	7.80E-02
A5	Excessive trim	0.00001	1.34E-04	7.80E-02
A6	Boat moving at high speed	1.78E-05	2.45E-04	7.80E-02
A7	Insufficient experience	2.30E-02	3.17E-01	7.80E-02
A8	Inadequate training	2.50E-02	3.86E-01	7.80E-02
A9	Improper route plan	1.01E-03	1.39E-02	7.80E-02
A10	Failure of echo sounder	3.08E-04	3.08E-04	2.00E-03
A11	Failure of GPS	4.07E-05	5.61E-04	7.80E-02
A12	Steering gear failure	6.71E-05	8.34E-05	2.00E-03
A13	Vessel squat	8.14E-05	8.14E-05	2.00E-03
A14	Small-scale design flaws	2.01E-04	2.11E-04	0.00E+00
A15	Poor/lack of maintenance	3.48E-05	3.65E-05	0.00E+00
A16	Main engine failure	6.71E-05	9.25E-04	2.00E-03
A17	Lack of VRM communication	7.32E-05	9.09E-05	2.00E-03
A18	Lack of communication between ships	9.84E-04	1.22E-03	2.00E-03
A19	VTS failure	2.24E-08	2.78E-08	2.00E-03
A20	Poor vision	1.59E-03	1.98E-03	2.00E-03
A21	High traffic density	5.82E-04	7.23E-04	2.00E-03
A22	Improper watchkeeping	9.45E-04	1.30E-02	2.00E-03
A23	Iceberg present	5.82E-04	7.23E-04	2.00E-03
A24	Contaminants	0.00001	1.00E-05	0.00E+00

A25	CO_2	4.86E-02	4.86E-02	0.00E+00
A26	C12H24	2.60E-03	2.60E-03	0.00E+00
A27	O2	5.52E-03	5.52E-03	0.00E+00
A28	With water	1.77E-03	1.77E-03	0.00E+00
A29	Low material resistance	1.07E-02	1.12E-02	0.00E+00
A30	High salt	2.17E-03	2.28E-03	0.00E+00
A31	Bacteria	1.12E-04	1.17E-04	0.00E+00
A32	Low pH	5.80E-03	6.08E-03	0.00E+00
A33	Fatigue/sleepiness	2.07E-04	2.85E-03	7.80E-02
A34	Alcohol abuse	6.70E-05	9.24E-04	7.80E-02
A35	Poor interpretation	1.33E-03	1.83E-02	7.80E-02
A36	Overloading	1.55E-04	2.14E-03	7.80E-02
A37	Overcrowding	1.55E-04	2.14E-03	7.80E-02
A38	Improper weight distribution	1.55E-04	2.14E-03	7.80E-02
A39	Shifting of cargo	0.00001	1.38E-04	7.80E-02
A40	Carelessness	5.85E-05	8.07E-04	7.80E-02
A41	Failure to use equipment	6.09E-04	8.40E-03	7.80E-02
A42	Binocular failure	6.71E-05	9.25E-04	7.80E-02
A43	Rudder failure	6.70E-05	9.24E-04	7.80E-02
A44	Bow thruster failure	2.03E-04	2.80E-03	7.80E-02
A45	Static loading	0.00001	1.00E-05	2.00E-03
A46	Fish on deck	0.00001	1.00E-05	2.00E-03
A47	High tides	7.33E-04	7.33E-04	0.00E+00
A48	High wind	0.00057	5.70E-04	0.00E+00
A49	Rough waves	0.00057	5.70E-04	0.00E+00
A50	High sea current	0.00057	5.70E-04	0.00E+00
A51	OOW handling failures	6.52E-04	7.43E-04	0.00E+00
A52	OOW inattention failures	6.59E-04	7.51E-04	0.00E+00
A53	Supervision failures	9.01E-04	9.16E-04	0.00E+00
A54	Verification failures	1.00E-02	1.02E-02	0.00E+00

A55	Excessive wear	0.00001	1.00E-05	7.80E-02

3.4.4. Risk control measures

The control of risky events is a significant step towards accident occurrence prevention. Before outlining safety barriers to prevent small trawlers from capsizing, it is important to identify the most probable configuration (*MPC*) for accident scenario, using the most probable explanation concept. This process constitutes identifying the most hazardous risk factors and capsizes probability estimation, given the combined occurrence of these factors. In the present study, we use sensitivity analysis and probability updating to identify the most hazardous risk factors. The critical risk factors common to these analysis results are inadequate training, insufficient experience, and not closing the sea-chest, and these are human-related faults. It is not surprising the international maritime community has come to the realization in recent times that the human factor played a dominant role in marine casualties' prevention, STCW (1978, 1995 & 2010), and this has reflected in IMO's enactment of STCW 1978 and its subsequent amendments STCW 1995 and STCW 2010. Next, we estimated small trawler capsize occurrence probability when these three factors happen. To do this, we used the concepts of conditional probability (Equation (3.8)), chain rule (Equation (3.9)), marginal probability (Equation (3.10)), and total probability (Equation (3.11)). The computational process is illustrated below.

$$P(A|B) = \frac{P(A,B)}{P(B)} \tag{3.8}$$

where, P(A|B) = conditional probability (probability of event A happening given that event B has happened; P(A, B) = joint probability (probability of events A and B happening together); and P(B) = total probability (probability of all possible outcomes of event B).

The evaluation of joint probability for several events (e.g., A, B, C, D) was carried out as conditional probability statements using the chain rule as follows:

$$P(A,B,C,D) = P(D|A,B,C) \times P(C|A,B) \times P(B|A) \times P(A) \quad (3.9)$$

However, this procedure increases computational cost since the conditional probability tables (CPTs) developed must have probabilities for 2^n (n is the number of events involved) entries. To address this challenge, we assumed marginal independence amongst events to reduce the number of entries required for the CPTs to $2n$. This assumption means taking away the conditional aspect of the statement in Equation (9) to save half the computation time. The result is Equation (10), and once the posterior probabilities of the individual events are known, their joint probability can be estimated.

$$P(A,B,C,D) = P(A) \times P(B) \times P(C) \times P(D) \quad (3.10)$$

Let the probability of the event: inadequate training occurring = P(A8)

Insufficient experience occurring = P(A7)

Closing the sea-chest occurring = P(A1)

Small trawler capsizes occurring = P(C)

Then their respective non-occurrence probabilities are $P(\underline{A8}), P(\underline{A7})$, and $P(\underline{A1})$. From column 5 of Table 3: P(A8) = 3.86E-01, P(A7) = 3.17E-01, P(A1) = 2.48E-01, and $P(\underline{A8}) = 6.14E - 01, P(\underline{A7}) = 6.83E - 01$, and $P(\underline{A1}) = 7.52E - 01$.

$$\text{Hence, } P(A8, A7, A1, C) = 3.86 \times 10^{-1} \times 3.17 \times 10^{-1} \times 2.48 \times 10^{-1} \times 1$$

$$= 0.0303$$

For the total probability, we search the model for all possible combinations of events A8, A7, A1, and C leading to the accident occurrence.

This means:

$$P(C) = [P(A8, A7, A1) \times P(A8, A7, A1)] + [P(A8, A7, \underline{A1}) \times P(A8, A7, \underline{A1})]$$

$$+[P(A8, \underline{A7}, A1) \times P(A8, \underline{A7}, A1)] + [P(C|\underline{A8}, A7, A1) \times P(\underline{A8}, A7, A1)$$

$$+[P(\underline{A8}, \underline{A7}, A1) \times P(\underline{A8}, \underline{A7}, A1)] + [P(\underline{A8}, A7, \underline{A1}) \times P(\underline{A}8, A7, \underline{A1})]$$

$$+[P(A8, \underline{A7}, \underline{A1}) \times P(A8, \underline{A7}, \underline{A1})]$$

To evaluate the conditional probabilities, we turn to the OOBN model and instantiated to the appropriate decision state (see Fig. 3.8 for an example illustrating the) and estimated the capsize probability; this produced the results in Table 3.6 when all the relevant factors are considered. The joint probabilities were calculated using Equation (10).

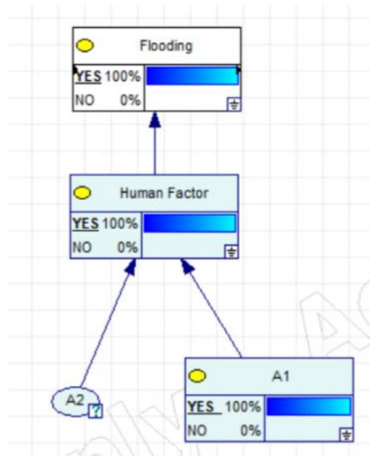

Figure 3.8 Sample instantiating process for risk factor A1(i.e., not closing sea-chest).

Table 3-6 OOBN model results of conditional probability statements

Number	Conditional probability statement	Occurrence probability	Non-occurrence probability
1	P(C|A8, A7,A1)	1	0
2	$\boldsymbol{P(C\|A8, A7, \underline{A1})}$	1	0
3	$\boldsymbol{P(C\|A8, \underline{A7}, A1)}$	1	0
4	$\boldsymbol{P(C\|\underline{A8}, A7, A1)}$	1	0
5	$\boldsymbol{P(C\|\underline{A8}, \underline{A7}, A1)}$	1	0
6	$\boldsymbol{P(C\|\underline{A8}, A7, \underline{A1})}$	1	0
7	$\boldsymbol{P(C\|A8, \underline{A7}, \underline{A1})}$	1	0

A1= not closing sea-chest, A7= insufficient experience, A8= inadequate training

$$P(C) = (1 \times 3.86 \times 10^{-1} \times 3.17 \times 10^{-1} \times 2.48 \times 10^{-1}) +$$

$$(1 \times 3.86 \times 10^{-1} \times 3.17 \times 10^{-1} \times 7.52 \times 10^{-1}) +$$

$$(1 \times 3.86 \times 10^{-1} \times 6.83 \times 10^{-1} \times 2.48 \times 10^{-1}) +$$

$$(1 \times 6.14 \times 10^{-1} \times 3.17 \times 10^{-1} \times 2.48 \times 10^{-1}) +$$

$$(1 \times 6.14 \times 10^{-1} \times 6.83 \times 10^{-1} \times 2.48 \times 10^{-1}) +$$

$$(1 \times 6.14 \times 10^{-1} \times 3.17 \times 10^{-1} \times 7.52 \times 10^{-1}) +$$

$$(1 \times 3.86 \times 10^{-1} \times 6.83 \times 10^{-1} \times 7.52 \times 10^{-1})$$

$$= 0.0303 + 0.0920 + 0.0654 + 0.0483 + 0.1040 + 0.1464 + 0.1983$$

$$= 0.6847$$

Finally, we could estimate the most probable scenario occurrence probability for small trawler capsize accident as:

$$P(MPC/C) = \frac{P(A8, A7, A1, C)}{P(C)} = \frac{0.0303}{0.6847} = 0.044$$

The safety barriers serve as control measures capable of reducing accident occurrence and are broadly categorized into personal protective equipment (PPE) and engineering and administrative controls. Engineering and administrative controls are usually a preferred choice over PPE, and as such, the latter will only be employed after all avenues of the earlier controls have proved unsuccessful. For all the three events constituting the most probable accident scenario, engineering and administrative controls may be the suitable measures to control their occurrence. Before a member joins a small trawler as a crew, proper training and certification checks must be verified. Also, a procedural list for carrying out operations can be placed at vantage points on board to prevent the crew from using their discretional will in making decisions on jobs assigned to them.

Also, a checklist completion is submitted to the chief engineer by any crew assigned to work on the sea-chest (ITF, 2010; Sarvari et al., 2019). An alarm system can be incorporated to alert the shipboard crew should the vessel be sailing with the sea chest opened (ITF, 2010).

Alternatively, a numerical demonstration of the control measures can be illustrated. From the practical point of view, the experience can never be substituted and must be acquired by the fishing operator (crew member) over time. This reasoning means the probability value assigned to insufficient experience as a primary event is likely to only reduce by ensuring every voyage of fishing activity should involve at least an experienced fisher onboard. Furthermore, an increase in the number of fishers having training on the facets of safety onboard a vessel, with additional essential stability and navigation competence, is also presumed to improve the probability value for inadequate training. The training, however, may sometimes require certification authorities and regulators' approval. The risk control analysis results have been observed to corroborate the findings in FAO (2010), Howe and Johansen (2006), and Molyneux (2007). Training can be improved by scheduling drills at irregular time intervals and getting feedback after training; experience, however, can somewhat be enhanced with more realistic drills and a higher frequency of testing (Khan et al., 2006).

Table 3.7 illustrates the summary of control analysis results following assumptions based on motivations from studies conducted by (DiMattia, 2004; Khan et al. 2006; Deacon et al. 2010).

1) For training (i.e., people having the required skillsets for the operation of a system and updating the knowledge and skills periodically).

- Every fifty (50) fishermen who received basic safety and stability training improves the prior probability to a tenth of the prior probability (i.e., 1/10)
- Every hundred (100) fishermen that received training on basic safety and stability improves the prior probability to a hundredth of the prior probability (i.e., 1/100)

2) For experience (i.e., personnel being competent and knowledgeable about the current state of the art on the system's operation).
   - One experienced fisherman onboard the voyage improves the prior probability by a tenth (i.e., 1/10)
   - Two or more experienced fishermen onboard voyage improves the prior probability by a hundredth (i.e., 1/100).

For instance, when a team of 50 fishermen in a community underwent a training program and subsequent periodic refresher training, the probability of the basic event (inadequate training) reduces from 2.5E-2 to 2.5E-3. Table 5 (a-c) shows the improved probabilities based on the above assumptions and the estimated capsizing occurrence probabilities represented by the residual values after improvement.

Table 3.7a.

Table 3-7 (a) Probability estimates for small fishing trawler capsize under control measure.

Critical basic event	Prior probability	One experienced person onboard	Two or more experienced persons onboard
Insufficient experience (A7)	2.30E-02	2.30E-03	2.30E-04
Trawler capsize	0.07	0.05	0.048

Table 3.7b. Probability estimates for small fishing trawler capsize under control measure.

Critical basic event	Prior probability	Training (50) people	Training (100) people
Inadequate training (A8)	2.50E-02	2.50E-03	2.50E-04
Trawler capsize	0.07	0.048	0.046

Table 3.7c. Probability estimation for small fishing trawler capsize under control measure.

Critical basic event	New probability (combining)			
Insufficient experience (A7)	2.30E-03	2.30E-03	2.30E-04	2.30E-04
Inadequate training (A8)	2.50E-03	2.50E-04	2.50E-03	2.50E-04
Trawler capsize	0.028	0.0258	0.026	0.0238

Table 3.7(a) shows results when the human error case of insufficient experience is addressed, 3.7(b) when inadequate training is addressed, and 3.7(c) when both are addressed simultaneously. The best risk control measure approach will be to execute option (c), and the example shows the likelihood of small trawler capsize reducing from 7% to 2%.

The retention of knowledge and especially hands-on skills decays or diminishes relatively quickly, and at best, many skills can be retained for six (6) months (see Sanli and Carnahan 2018). These authors have reviewed the literature on long-term retention of skills in the context of multi-day training in their study and identified factors related to the task and the learner, which needs to be considered in the training and performance of skills.

The most critical safety situations usually do not occur frequently, and combating these safety-critical issues requires knowledge and skill competencies that must be executed correctly outside of training (Sanli and Carnahan 2018). Addressing human factors related to maritime safety issues is very important to policymakers also, and therefore understanding the retention and decay of the needed complex knowledge and skills is key and a necessity. Ericsson and Lehmann (1996), in their review, also find that a basic mental capacity measure cannot validly predict the attainment of expert performance in a domain, and the superior performance of experts is usually domain specific.

Procedural skills that are central to our job domain are normally learned gradually and are retained throughout most of our working life, culminating into what we refer to as experience. Romano et al. (2010), after studies on one-year retention of general and sequence-specific skills in a probabilistic serial reaction time task, concluded that both young and older experts and older non-experts showed sequence-specific skill retention even after one year. Furthermore, in the handbook of expertise and expert performance (Ericsson et al., 2006. pp265-286), Proctor and Vu discuss laboratory studies of training, skill acquisition, and retention of performance, in which they probed the advantage of being able to control the conditions of training and testing. Also, retention tests can be conducted after delays of minutes through days, weeks, months, and years in order to establish the durability of the acquired skills, among others.

The Manila amendments to the STCW Convention (STCW 2010) have also emphasized the importance of refresher training for seafarers by mandating them to provide evidence of competence in the basic safety training (including survival, firefighting, first aid, and personal safety) every five years. We see some semblance of improvements in safety by reviewing the impact of the implementation of this amendment on fishing in IMO member countries. An increase in refresher training for fishers in basic safety training (in Norway) and through the Marine Institute of Memorial University (in Newfoundland, Canada) are examples. However, in the UK, for instance, commercial fishers are mandatorily required to take basic safety training, and beyond this, voluntary training to help maintain skills and knowledge up to date is also encouraged alongside refresher training. The Netherlands similarly has refresher training intended for crew members that sail on seagoing fishing vessels, and they are expected to possess STCW basic safety training certificate already. The Australian Maritime Safety Authority's Torres strait marine safety program (AMSA, 2020) has worked with stakeholders from 2006 to reduce islanders' chances of being involved in a marine incident through boating safety education programs. In addition, there is a safety grab bag scheme in place alongside an EPIRB replacement program, which makes essential life-saving equipment available to boaters.

Generally, these refresher trainings do take place usually to update delegates basic skills and knowledge obtained initially and normally targets mostly registered fishers in most countries. This training will normally span between one to three days.

The findings of this study have shown that training and refresher training is critical to any risk management for small fishing vessel operations, and the above-stated examples further buttress this.

3.4.5. Uncertainty analysis

Determination of uncertainties in accident modeling is a vital part of quantitative risk assessment (QRA). Uncertainty in QRA is broadly grouped into aleatory (or irreducible) uncertainty and epistemic uncertainty. Aleatory uncertainty examines the model structure adequacy in predicting the accident modeled. Often this uncertainty is difficult to estimate precisely; as a result, it has been termed as irreducible uncertainty. In addressing aleatory uncertainty, expert opinion (opinion of the individuals who have knowledge and experience on the subject) can be elicited on the adequacy of a model structure. The developed model can also be tested on similar accidents with known results, and the output is compared with the already known estimate. A statistical test of significance can then be performed on the two estimates; if the hypothesis test reveals no significant difference between estimates, the model structure is assumed adequate in representing the accident modeled. Otherwise, the opposite will hold. In this way, the aleatory uncertainty evaluation would have been carried out. In the present study, some revisions were made to the developed OOBN model for capsizing accident occurrence probability estimation. It was then adjudged suitable and adequate for a small trawler capsize accident. Epistemic uncertainty evaluates the accuracy prediction boundary of the model output result. Often the challenge with evaluating epistemic uncertainty is the lack of data, especially for models analyzing first-time accidents. In the present study, this challenge was overcome by generating new probabilities for root nodes by increasing the prior probabilities at a 5% rate. The values are then used in the OOBN model, several posterior probabilities estimated, and the standard error computed. In the last two columns of Table 3.3, the procedure results for a sample size of 20 are shown, giving rise to a 0.003 and 0.092 standard error and mean, respectively. Hence, in the present study framework, the epistemic uncertainty attached to small trawler capsize occurrence probability estimation is 0.092 ± 0.003.

3.5. Conclusions and recommendation for further work

This present study seeks to demonstrate the application of Object-Oriented Bayesian Network (OOBN) methodology for small fishing trawler capsize accident modeling using existing data generated from past studies and historical data. Critical emphasis is placed on the identification of risk influencing factors and their dependencies under different operational scenarios.

The proposed model was observed to capture the critical influencing factors, and their degree of influence on the capsize accident scenario, and the capsizing probability predicted based on the prior probability of the risk factors. Further sensitivity analysis identified human factors (such as inadequate training, insufficient experience, sea-chest open, and alcohol use) as the critical risk factors influencing small fishing trawlers to capsize. Based on the critical risk factors, robust and practicable risk control measures are proposed as follows: the training of more fishers in basic operational safety and stability; the use of experienced fishers on every voyage; and improving the integrity of vessels. The most practicable measure is that of training, and once fishermen receive basic safety and survival training, attention should then be shifted to refresher training, such as proposed in the Manila amendment of the STCW 2010 convention for which many member countries have seen positive improvements in safe operations for its seafarers after ratification.

The uniqueness of the current model in comparison with previously proposed probabilistic and statistical approaches lies in this model's ability to capture the failure or risk influencing parameters and update their likelihood by using new or hard evidence from accident scenarios. The Bayesian network also captured the associated uncertainty, which the statistical tool could not adequately address. The Bayesian network further captures the multidimensional causal dependencies that practically represent the real-time scenario in an uncertain ocean environment, and these merits reliably provide a dynamic tool for the capsize accident model.

The proposed methodology can be used by maritime administrations to learn about vessel capsize and associated risk factors. Further studies will focus on integrating this model into a geographical information system for more comprehensive studies on vessel capsize for different maritime environments.

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CHAPTER FOUR

4. Analyzing Operational Risk for Small Fishing Vessels Considering Crew Effectiveness

Preface

A version of this chapter is published in the Journal of Ocean Engineering, 249 (2022) 110512. I am the primary author along with the Co-authors, Vindex Domeh, Faisal Khan, Neil Bose, and Elizabeth Sanli. I developed the conceptual framework, methodology and investigation of the operational risk model for a small fishing and reviewed the literature along with implementing the model with a case study. I prepared the original draft of the manuscript and subsequently revised the manuscript based on the co-authors' and peer review feedback and comments. Co-author Faisal Khan helped in the concept development, method, formal analysis, of model, reviewing and revising the manuscript. Co-author Neil Bose helped in the methodology, formal analysis, of model, reviewing and revising the manuscript. Co-author Elizabeth Sanli helped in the formal analysis of model, reviewing, and revising the manuscript. Co-author Vindex Domeh helped in the concept development, methodology, reviewing and revising the manuscript.

Abstract

Investigations into the causes of maritime incidents/ accidents have often identified human error as one of the leading causal factors. Small vessels employed in small-scale fisheries activities, usually have little or no onboard shelter and limited navigation and safety equipment. The operator’s effectiveness at the performance of their duty task is therefore critical, and they must be well-tooled to succeed. This paper presents a novel generic human factor analysis model proposed for analyzing small fishing vessel operations. Coupled with the Bayesian network the methodology is tested with a case study focused on a small fishing boat operating in the Atlantic Canada region of Newfoundland and Nova scotia. The accident occurrence likelihood is estimated, and a sensitivity analysis is also performed on the model. The analyses findings show the accident's most critical influencing factors to be related to operator’s actions, the natural and technological environment, unsafe management of operations, and factors associated to the vessel itself.

Keywords: Human factor; Accident; Small fishing vessel; Sensitivity; Bayesian Network; Risk factors; probability.

4.1. Introduction

Throughout the world, every year, there are several occurrences of maritime incidents/ accidents that result in the loss of lives and injuries, damage to the environment and property. The fishing industry is considered one of the most dangerous occupations globally and accounts for a significant percentage of fatal maritime accidents yearly. The most predominant accidental events involving vessels have been found to include collision, capsizing, fire and explosion, grounding, foundering, and flooding. A maritime incident/accident is classified as an occurrence that directly results in vessels other than a pleasure craft (TSB, 2020). An incident will normally result in a person falling overboard, crew unable to perform a task because of physical incapacitation, risk of collision, and near misses, while accidents will usually include death, loss or damage to the vessel, and environmental pollution. Accidents can also be considered undesirable events that result in adverse consequences, such as injury, economic loss, property damage, environmental damage, or the loss of life (Harrald et al. 1998; Grabowski et al. 2010; Ugurlu et al. 2015).

The world's outlook regarding the safe operation of maritime structures has changed since the Herald of Free Enterprise and Derbyshire's fatal accidents; 193 and 200 lives were lost, respectively, and the incidents impacted the environment terribly (Wang, 2002). The safety of ships, including fishing vessels, is a major concern worldwide today for most governmental agencies and private organizations both at the national and international levels. It is common knowledge that fishing is considered one of the most dangerous occupations around the world compared to other industries. Commercial fishing is consistently ranked as one of the most hazardous occupations in the United States (Drudi, 1998; U.S Coast Guard, 1999; Zohorsky et al., 2020).

The types of vessels built for fishing are usually small in size, having different operational challenges, and their involvement in accidents mostly under-reported (Pillay and Wang, 2003). There are, however, larger fishing vessels that are used for commercial fishing, and these vessels will generally operate under International maritime orgainization (IMO) regulations for safety. The IMO member states, through the adoption of these regulations, mandate responsible governmental agencies who are then required to ensure compliance with the rules and regulations.

The records according to the Food and agricultural organization (FAO), International labor organization (ILO), and IMO indicate the majority of fishing vessels can be found in the small-scale fishing industry where the size of vessels employed are of a length overall (LOA) of 12 m and less, without sophisticated navigation and onboard advanced safety equipment (Caledonia, 2001). These vessel types have been found to be more likely to be involved in accidents, as observed from the literature. For example, The Transportation Safety Board (TSB) of Canada and the Marine Accident Investigation Board (MAIB) of the U.K. have both reported a high fatality rate amongst incidents of fishing vessels under 12 m (MAIB, 2006; TSB, 2016). "Statistical reviews conducted by the M-SAR branch of Newfoundland Region (CCG, 2000) and Transport Safety Board (TSB, 2016), analyzing incident database from 1993 to 1999 and 2000 to 2015, respectively", found 29 out 46 and 19 out 31 total fatalities for the two studies, occurring in the vessels less than 7.6 m categories. Another study (Wang et al., 2005) identified the most common causal factors associated with fishing vessel accidents, having analyzed the MAIB database to be machinery damage, flooding and sinking, grounding, collision, and fire, in the descending order of severeness. Faulty vessel design, lack of equipment, and poor stability in bad weather conditions have also been identified as significant safety issues after analyzing the data.

One way of making improvements to the safety of maritime operations is through the investigation of accident/ incidents occurrences. An investigation is therefore recognized as a simple method adopted by many organizations in their quest to improve the safety of their operations. Accident investigations generally examine all aspects to gain an understanding of the mechanisms involved, in addition to the interactions related to machinery, personnel, and the working conditions contributing to them (Kuhlman, 1977). However, there are some challenges that are associated with accident analysis in terms of the lack of or incomplete information on fishing vessel accidents, which can be due to the under-reporting of incidents and poor database management. Both accident investigation and analysis help reduce the incident rate of fishing vessel accidents. The challenges encountered during a fishing voyage in the North Atlantic Ocean and hazards confronted while operating commercial fishing vessels in harsh weather conditions have been thoroughly studied (Junger, 1997).

The influencing factors for the causation of a fishing vessel accident as identified in the several studies from the literature are also known to be probabilistic in nature, and therefore a risk analysis could best help identify its root causes. During the identification of these risk factors, two different pathways can be adopted. The first is the use of an investigative process to study the circumstances that surrounds an accident and then draw an inference on the causes. The second approach is the use of statistical analysis to capture such influences, which may be remotely further from the chain of causes of an accident (McKnight et al., 2007). The former approach has been applied extensively in the study conducted by Treat et al. (1977) to identify traffic accident causal factors, while the latter method was applied by Smith et al. (2001) to study recreational boat passengers and operators' intake of alcohol in relation to deaths.

There exist in the literature a myriad of evidence of attempts made in the past to address maritime safety challenges. The importance of safety to the international maritime community, however, cannot be overstated; the Torremolinos International Convention for the safety of fishing vessels in 1977 (IMO (1977)) must attest to this commitment. This was pivotal because it was intended to establish uniform rules and regulations concerning its design, construction, and equipment involving fishing vessels (24 m and above). This led to further developments in terms of guidelines on training and certification for small fishing vessels, and IMO member countries have adapted them to improve the safety of fishing. These guidelines have mostly been prepared by the IMO in conjunction with the ILO and FAO; prominent among them are the Code of Safety of Fishermen and Fishing Vessels (IMO (1975a)) and Vessel Design and Construction (IMO (1975b)). Also important is the Document for Guidance on Fishermen's Training and Certification (IMO (1988)) and the Voluntary Guidelines for the Design, Construction, and Equipment of Small Fishing Vessels (IMO (1980)). After realizing that their safety records were at unacceptable rates, the U.S. Congress passed a Commercial Fishing Industry Vessel Safety Act of 1988. This law resulted in the National Research Council's fishing vessel safety study (NRC, 1991). The NRC report presented a review of fishing vessel casualties and their common causes and identified them in the descending order of severity, material failure, grounding, collision, flooding, fire, sinking, capsizing, and disappearance.

The study conducted by Wang et al. (2005), have found that risk in terms of both casualty rate and the consequences was size-dependent. The NRC (1991) report also attributed the fishing industry's high casualties to a mixture of causal factors that resulted from a complex interaction involving the fishing vessels, equipment, the environment, and the fishers with external factors such as fisheries management. Human error was found as either a primary or secondary cause in many incidents, especially in those involving capsizing, collisions, groundings, and high fatality accidents.

Despite the IMO regulations and the NRC recommendations, there are still challenges associated with fishing safety, especially small fishing vessel operations. To further examine the prevailing fishing safety challenges, the formal safety assessment (FSA) techniques have been recommended by the IMO (Wang et al., 2002; Molyneux, 2007). FSA is a process of assessing maritime risks and evaluating the cost benefits of risk-reducing measures. This consists of steps that include hazards identification, assessment of the associated risks, managing the estimated risks, conducting a cost-benefit assessment of risk control options, and finally deciding on which control options to select. The FSA has been applied extensively worldwide in maritime safety research; most of these works, however, were qualitative in nature. Studies on fishing safety conducted by Köse et al. (1998) and Pillay et al. (2002) both implemented the FSA method to study the risk assessment of fishing vessels, using the fault tree analysis (FTA) to show the dependence of a loss of a fishing vessel in relation to the causal factor that contributes to the accident event. Both studies found that human error was one of the most common risk factors causing the loss of vessels and proposed several measures that could be introduced for the improvement of fishing safety. Other studies in the literature which have made use of the FSA approach are Wang et al. (2005), Zhang et al. (2013), and Görçün et al. (2015).

Human error has been identified as the most contributing factor (about 70-85%) to maritime accidents, as evidenced in the literature (NRC 1991; Wang et al., 2005; Amir et al., 2014; Talley, 1999), and in the case of the small-scale fishing industry, this poses a serious safety problem.

The terms human factors, human errors and human element are mostly used interchangeably across many industries. A definition of human error according to (Woods et al., 2010), is an action performed by human that fails to yield the intended outcome. Dekker (2002) propounds a new view of human error as merely a symptom of deeper trouble within a system and juxtaposes it against the old view which sees human error as a cause of an incident/ accident. Alternatively, human error can be defined as an 'out-of-tolerance action or deviation from the norm, whereby the limits of acceptable performance are defined by the system' (Rausand and Haugen, 2020). The situations leading to these errors may be due to sequencing problems, timing, knowledge, interface, procedures, and other sources (Rausand and Haugen, 2020; NUREG/CR-6883, 2005).

Human factors on the other hand, refers to the organizational and work factors, the environmental factors and the human and individual characteristics which can influence the behavior at work as reflected in its effect on health and safety (HSE, 1999). In a maritime context, the human element can be said to be a complex issue spanning an entire spectrum of human activities that includes crew task, management duties ashore, regulatory bodies and other task. The human element is indispensable in critical decision making during maritime operations. To build a useful risk model, the knowledge of the interrelation between human error and accident is vital. Risk assessment techniques can provide us with some knowledge about the various categories and causal events leading to maritime accidents/ incidents through reasonable quantitative estimates. However, for human error contribution to the accident, these quantitative models require some specific data captured in the assumptions made in the description of the phenomenon of interest (Harrald et al., 1998; Grabowski et al., 2010).

Proctor and Van Zandt (2008) described human factors as an interdisciplinary area of study which focuses on the optimization of human and machine system interactions. Human error has been described as a normal human function, bound to occur; however, it can be prevented (Nimmo, 2012). The author states that "the individual comes to work with skills, knowledge, and experience, they are trained for the task" (p. 3). The book emphasizes the challenge of ensuring all operators are competent. All accidents can be traced back to the human being, since a machine cannot design, operate, and maintain itself. Bennett (2001) studied air disasters and contends that errors can be induced through poor design, improper training, sub-standard maintenance, and other factor beyond the control of the flight crew. Human error is also seen as a normal function of humans, and it is accepted as an inevitable incident, although preventable. In Clemens (2002), human errors are classified as errors of commission (e.g., executing a correct step at the wrong time), errors of omission (e.g., ignoring an important step) and cognitive task errors (e.g., wrongful diagnosis and drawing a hasty conclusion). The human judgement could be bias (i.e., decisions systematically off-target) or noisy (i.e., seemingly no common agreement in addressing same problem). Hutchins (1996), having examined and discussed human cognition, defines socially distributed cognition as one that is in a setting where the problems that individuals confront and their approach to finding solutions to them are culturally structured and no individual while acting alone will be responsible for the outcome that is meaningful to the society at large. Human beings behavioral patterns follows sequential processing system and are very poor at multi-tasking (Hughes, 2002).

There are three pivotal areas in the evolution of human error studies that need considerations when analyzing the role of humans in a systems' operation, and these are the human reliability analysis (HRA), human error identification (HEI), and accident analysis (Zohorsky et al., 2020). To predict and reduce the contribution of human error to accident causations, the Human Factors Analysis and Classification System (HFACS) model, originally developed by Wiegmann and Shappell (2001) for categorizing the human-related causes of military aviation accidents, has been applied to accidents across healthcare, transportation, and other industries. The HFACS is based on the 'Swiss cheese' accident model, which was proposed in the human error studies completed by Reason (1990, 1997). These studies explored human contribution to accidents in the nuclear power industry, where his "Swiss cheese model" compared accidents as the failure of layers of defenses to the holes lining up in slices of Swiss cheese.

Other studies have also used the HFACS framework to examine accident data across the transportation, industrial, and healthcare sectors can be found in the literature (Shappell et al., 2007; Baysari et al., 2009; Lenne et al., 2012; Cohen et al., 2018; Zohorsky et al., 2020). The studies by Zohorsky et al. (2020) evaluated a modified version of HFACS for commercial fishing industry vessels by analyzing ten years of data that documents the causal factors of fatal accidents in the commercial fishing industry. After converting the accident investigation information with the modified model by independent raters and measuring for inter-rater reliability, the various human factor categories were identified for commercial fishing vessel safety improvement. Although the HFACS has seen a lot of application, almost all of the studies have been qualitative in nature (Reason, 1990; Weigmann & Shappell, 2003; Yildirum et al., 2017; Zohorsky et al., 2020), whereby the framework is adapted to categorize human causal factors for the industry of interest. Additionally, studies have also been conducted to test the reliability of the model's effectiveness (Olsen & Shorrock, 2010; Olsen, 2011; Zohorsky et al., 2020). To address the human element challenges in the maritime sector, the International Maritime Organization (IMO, 2019) have also initiated proposals to review, developed and implement new and existing requirements such as skills, education and training, the human capabilities, limitations and needs. A quantitative risk due to human error is mostly evaluated in terms of probabilities and incorporated into the models used in a probabilistic risk assessment.

Although from the literature survey several methods have been proposed to minimize the challenges with fishing vessel safety, there remains still inadequate solutions to specifically address the peculiar problems associated with small fishing vessels (LOA=12m). There is also the need to bridge the knowledge gap for the human error contribution to the small fishing vessel operations, which has its own unique characteristics due largely to the peculiar nature of their design and the operating environment. In addition, a model or framework which can comprehensively identify human error contributing causal factors must be developed for small fishing vessel accidents. Thus, to study and answer the questions of how human error accident for a small fishing vessel is likely to happen and when it happens, the object-oriented Bayesian network (OOBN) is adopted here to fragment the causative factors in a complex formulated network.

The aim of this study is to develop a novel methodology that has the capability of assessing the operational risk of small-scale fishing operations with an emphasis on the crew members' effectiveness. This aim is achieved through the following key objectives: (i) to identify the accident triggering factors and contributing factors for small fishing vessel operations. (ii) to formulate a generic human factors framework that can analyze potential accident scenarios and capable of human error modeling, and (iii) to assess operational risk and the contribution of different human factors in the accident causation.

4.2. The Methodology to develop and analyze Human Factor Model

The evolution of an accident can be analyzed both qualitatively and quantitatively, depending on the scope of study and also the availability of data. Each analyzing approach has its own pros and cons. A combination of the two methods, however, is usually the pathway that yields optimum outcome. The logical tree diagram such as fault tree analysis (FTA), is one method that is widely used in the literature for performing qualitative analysis. In a fault tree analysis, the determination of minimal cut sets and common cause failures are usually pursued. The FTA has also been implemented in the quantitative analysis of accidents using available basic probabilities. However, it may be expensive and time-consuming for implementation in a complex system. Instead, the Bayesian network (BN) approach which is probabilistic in nature is the preferred quantitative method as seen in the literature (Obeng et al, 2022; Domeh, et al., 2021; Ugurlu, et al., 2020). The BN method can present the interdependencies that exist amongst the accident causal factors and has been used for the modeling of maritime risk. In this study, a hybrid approach (FT/BN) is adopted to analyze the human factor (HF) contribution to accident occurrence during operations of small fishing vessels. Fig. 4.1 presents a complete overview of the proposed methodology.

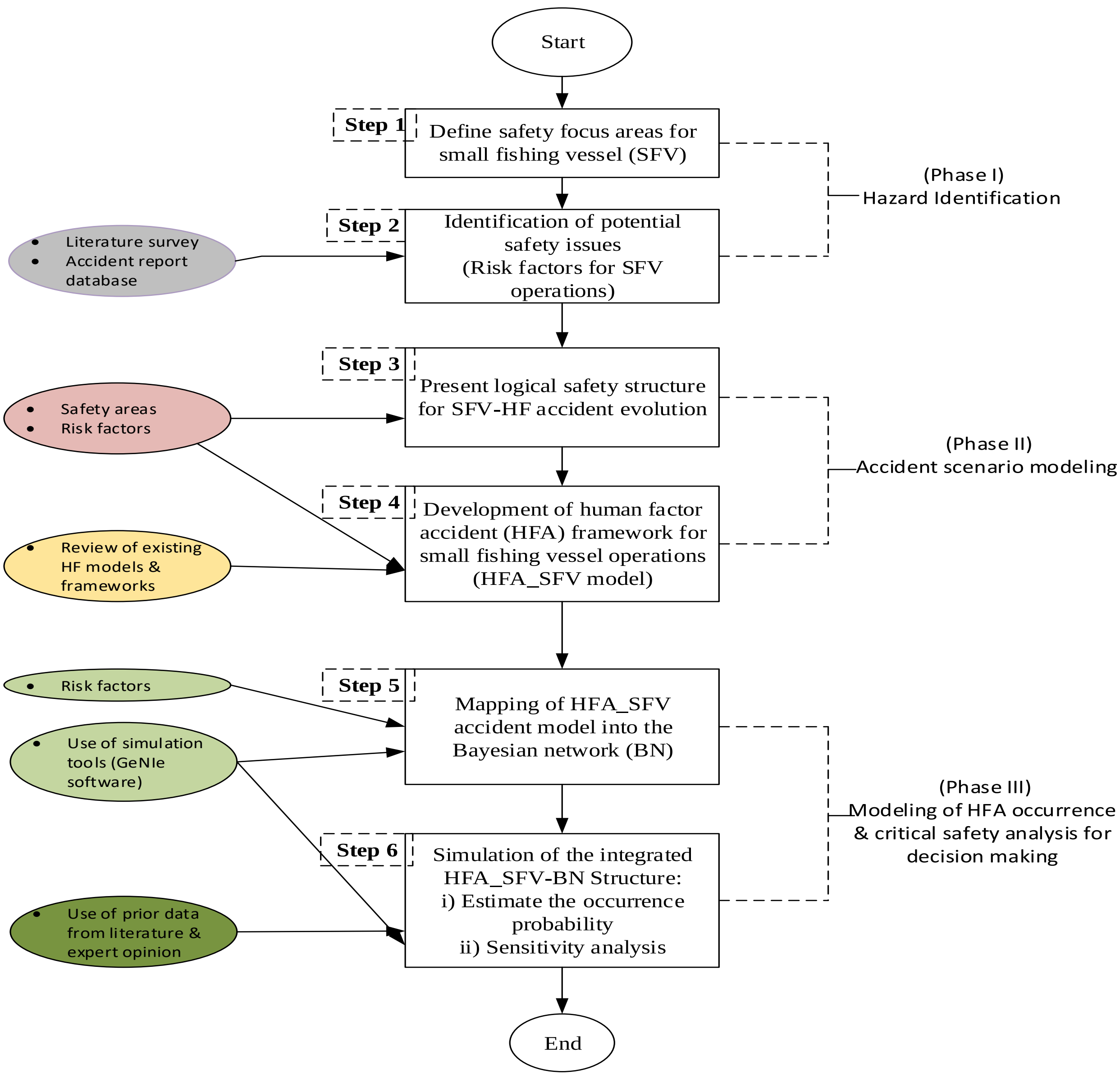

Figure 4.1. The methodology to model and analyze the operational risk of Small Fishing Vessel (SFV)

The proposed method comprises three (3) phases, namely, hazard identification, accident scenario generation, and critical safety analysis for decision-making. In total, there are six (6) task steps to perform for the various phases of the methodology.

Phase I-Hazard Identification: The first stage of the methodology, as shown in figure 4.1, seeks to identify the numerous hazards associated with the operations of small fishing vessels. It involves two steps, a definition of the safety focus area and the identification of potential safety issues. The IMO resolution included guidelines on the approach to hazard identification (MSC-MEPC.2/Circ.12/Rev 2; Pillay et al., 2002; Görçün, Ö. & Burak, S., 2015). The method used in this study was to review published literature and historical data on fishing vessel accident studies (such as NRC 1991; MAIB, 2006; EMSA, 2018; TSBC, 2020).

Phase II-Accident Scenario Generation: The modeling of the human factors and human error accident scenario for the small fishing vessel operation consists of two task steps. First, a logical diagram is produced to represent the logical evolution of accidents occurrence in small fishing vessel with a focus on the contribution of human errors. Next is to develop a generic human factor analysis (HFA) model for the small fishing vessel by learning from existing human factor analysis frameworks in the literature. Assumptions made during this phase are that the analyst presents the sequence of events leading to the main accident as close to the real situation as far his/her depth of knowledge of the system and the interdependencies amongst the various risk factors can be represented probabilistically.

***Phase III-Analysis and Decision-making*:** The third and last phase of the proposed methodology is the quantitative analysis of human factor accident (HFA) to estimate the probability of occurrence for the small fishing vessel operation and the execution of critical safety analysis for decision making. The two steps involved in this phase are, first, the mapping of the developed human factor accident model into the Bayesian network (BN), using conditional probability tables to model the dependence and interdependencies amongst the risk causal factors and their link to the top accident. The second step is the simulation of the integrated human factor accident/ BN model in order to estimate the top accident occurrence probability. Also, sensitivity analysis is further performed to identify the critical safety influencing factor to make risk management decisions. The various steps in all three phases are explained in detail going forward.

4.2.1. Definition of Safety Focus Areas for Small Fishing Vessel Operations

In this study the authors have identified the safety focus areas to be capsizing, collision, flooding, fire/explosion, foundering, hull failure and loss of control after after reviewing literature and relevant accident reports. The following reports NRC 1991, MAIB 2006 (1992-2006), EMSA 2014 (2011-2013), EMSA 2018 (July-Dec. 2017), TSB 2020 (2009-2019) have been reviewed. The trend in these reports is the analysis of reported incident/accident occurrences to develop general statistics and patterns and also the detail attention given to the analysis of accident triggering events and contributing factors. Other journal publications such as (Wang et al. (2005); Köse et al., (1997); McKnight et al. (2007); Kum and Sahin (2015); Ugurlu et al. (2015); Ung (2019); Davis et al. (2019); Ugurlu et al. 2020). Table 4.1. presents the results obtained, and this is used as an input for the next stage of the methodology.

Table 4-1 The safety focus areas and their definition for the small fishing vessel accident.

Number	**Safety Areas (Small Fishing Vessel Operations)**	**Definition**
1	***Capsizing/ Listing***	Capsizing is when the vessel has turn upside down, whiles listing refers to the vessel with a fixed angle of heel. This may occur due to a negative metacentric height or a shift of the centre of gravity transversely or as a result of external impact.

2	***Collision/ Contact***	A collision event occurs as a result of the vessel striking or it being hit by another ship, and this may involve two or more vessels. A collision can happen either whiles the vessel is moving or in anchor at the shore. A contact is an event whereby a vessel strikes or is struck by an external object, and the object could be fixed, floating, or flying.
3	***Flooding***	A flooding event happens as a result of the vessel taking water on board, either gradually or massively.
4	***Fire/ Explosion***	This event happens when there is an uncontrolled ignition of flammable fuel and other materials.
5	***Foundering***	This is the progressive intake of water on board the vessel and eventually causing it to sink.
6	***Hull Failure***	This is an event leading to the damage of the vessel hull, thereby affecting the structural strength of the vessel.
7	***Loss of Control***	An event that leads to the total or partial loss of ability to operate or maneuver the vessel

4.2.2. Identification of Potential Safety Issues (PSI)

In this step, the potential safety issues are identified by conducting a thorough review and analysis of accidental events (root causes) and the contributing factor (i.e., causal factor) for the selected safety focus areas in table 4.1. This exercise is performed by adopting the IMO three levels of incident occurrence severity classification (IMO MSC-MEPC.3/Circ.4/Rev 1); very severe (involving total loss of vessel or loss of life or major damage to the environment), severe (injuries or damage to the vessel), and near-miss (marine incident). This analysis is based on secondary data from previously published results of completed investigations. The outcome of the phase one exercise is to obtain a list of the major risk causal factors of small fishing vessel accidents/incidents, as shown in table 4.2.

Table 4-2 The identified safety issues and their definitions (as related to the human elements).

Number	Safety Issues	Definition
1	***Environment factor***	This relates to the effects of the natural climatic conditions such as rainfall, temperature, and snowfall. The impact of the sea states such as the currents, tides, waves, and winds on the operator. Equipment design, installation, adequate signage, and operating. Includes human-machine interaction (ergonomics) considerations.
2	***Vessel design & fabrication factors***	It refers to design defects and poor construction of vessels, including material selection, stability assessment, equipment installation, and functioning with adequate signages—factors that influence the ability to acquire and maintain a compliant vessel.
3	***Operator errors***	These are intentional and thinking actions executed for a situation as intended but which end in error. These are highly practiced sets of skills and knowledge-based actions that go wrong as a result of memory failure, inattention, or technique error.
4	***Maintenance***	This is related to the processes and actions of maintenance of the vessel and the installed equipment—for example, lack of maintenance of bilge water pump, which lead to sinking accident.
5	***Emergency handling***	The actions that are taken in the event of an emergency. For example, in the event of a massive water intake.
6	***Operator violations***	This is an intentional or atypical action which are against the procedural rules but may become common practice.
7	***Management/ leadership factors***	It relates to the ownership and management of the vessel, as well as the organizational system been run. The preparation and management of crew for duty through training and also ensuring the availability of qualified crew and equipment for operations.
8	***Regulatory & policy factors***	This has to do with the effect of the role of government legislation, regulation, and standards have on the fishing industry. The registration and licencing of fishing vessel, fishing permit issuance, inspection, and compliance of the fisher folks to the rules. For example, the non-compliance of a vessel or inadequate conduction of inspection.
9	***Unsafe operation***	Allowing operations to continue despite known deficiencies in crew abilities, vessel status, lack of or poorly maintained equipment (PPE's) etc., by supervisory authorities.

10	***Education, training & experience***	This refers to the required education, training, and skills that are needed by the operator to perform efficiently. Examples are inadequate training and insufficient experience.
11	***Risk assessment***	The evaluation of the limitations of operations in respect of the crew, environmental condition and the state of the vessel prior to fishing voyage. This also relates to the non-compliance or insufficient safety assessment prior to the fishing voyage. For example, embarking on a fishing voyage irrespective of bad weather warnings.
12	***Social & cultural factors***	The effect society has on the health and safety of the small-scale fishing industry, including the cultural and economic pressures.
13	***Crew practices & condition***	This has to do with the physical and physiological status of the operators or crew members and their impact on performance and decision-making. For example, crew fitness for duty, or alcohol consumption.
14	***Fatigue***	A lack of psychological or intellectual ability capable of affecting operator's discharge of duties. A temporal or long-term physical disability e.g., strength, sight, hearing etc., that negatively impacts the performance of duties.
15	***Planning & communication factors***	The plans and procedures that are located onboard the fishing vessel. For example, the planning and preparation for the fishing voyage. Communication and teamwork impact on operation, including the common language of communication amongst crew

4.2.3. Logical Safety Structure for Small Fishing Vessel (with focus on human factors)

The sketch in Fig. 4.2 can be considered to represent the first level of a logical diagram sequencing the evolution of a small fishing vessel accident. The identified hazards (i.e. triggering events) which constitutes the root cause of a fishing vessel (FV) accident are shown to be connected to their dependent accident causal factors. From the literature, the top safety concerns include capsizing, collision, flooding, foundering, hull failure, loss of control, and others. For each hazard identified, the intermediate events can be grouped under technical, environmental and human factors. In addition, since the effect of human factors is prominent (generally contributing approx. 80%) in each case, an emphasis is placed on the human element contribution. The case of capsizing accident is used for further scenario development, and examples of the major human factor contributing events are shown.

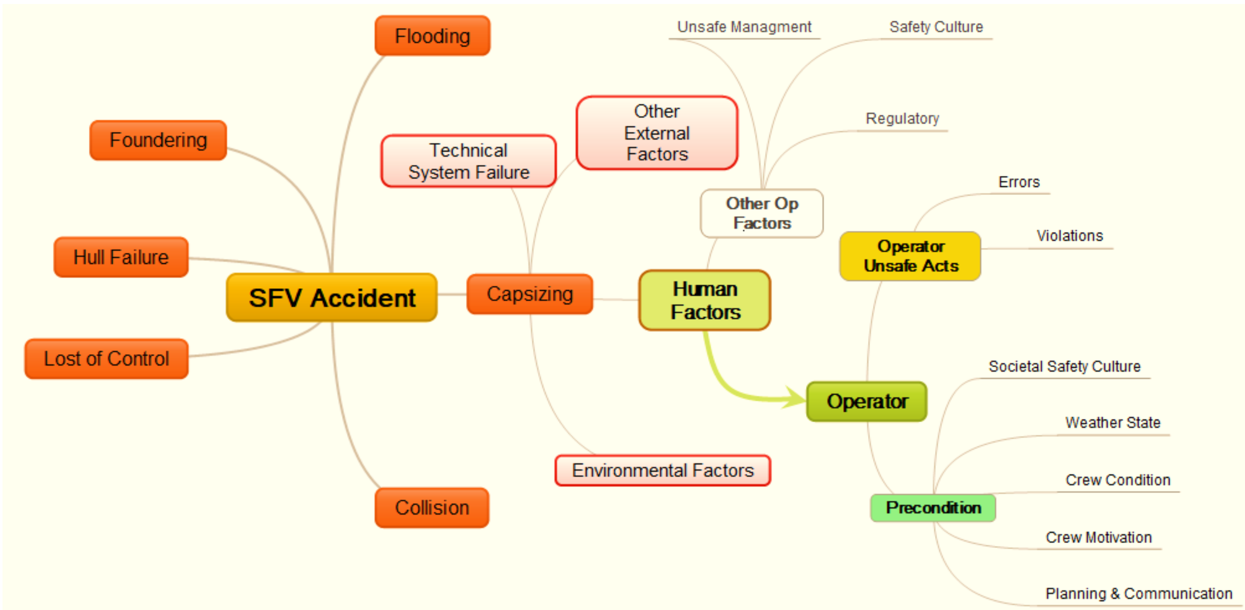

Figure 4.2 An adopted first level logical safety structure for human factor in small fishing vessel operations

4.2.4. A Human Factor Accident Framework for Small Fishing Vessel (HFA_SFV)

A generic human factors framework to analyze small fishing vessels operation known as the Human Factor Accident of Small Fishing Vessel (HFA-SFV) is proposed in this section. The accident framework has roots from Heinrich's industrial accident causation model (Heinrich, 1931), the Reason's Swiss cheese model (Reason, 1990), and the Human Factors Analysis and Classification System, HFACS (Weigmann & Shappell, 2003). The proposed human factor accident model comprises of three (3) major accident triggering factors (i.e., root causes) of human error during the operation of a small fishing vessel. This model identifies both human and systematic errors and projects the systematic categorization of errors across events, namely, people in operations, vessel/ equipment human interface, and the environmental influence on vessel operations. The accident contributing factors (ie. risk factors) are known to combine in a complex manner to influence almost all incidents/ accidents that have been observed in small fishing vessel operations. The complexities in the factors can be represented in the triangular model, as shown in fig. 4.3. The direction of arrows illustrates interdependencies amongst the three factors and their contribution towards human factor accidents for the vessel. The sub-categories of accident factors are further explained briefly below.

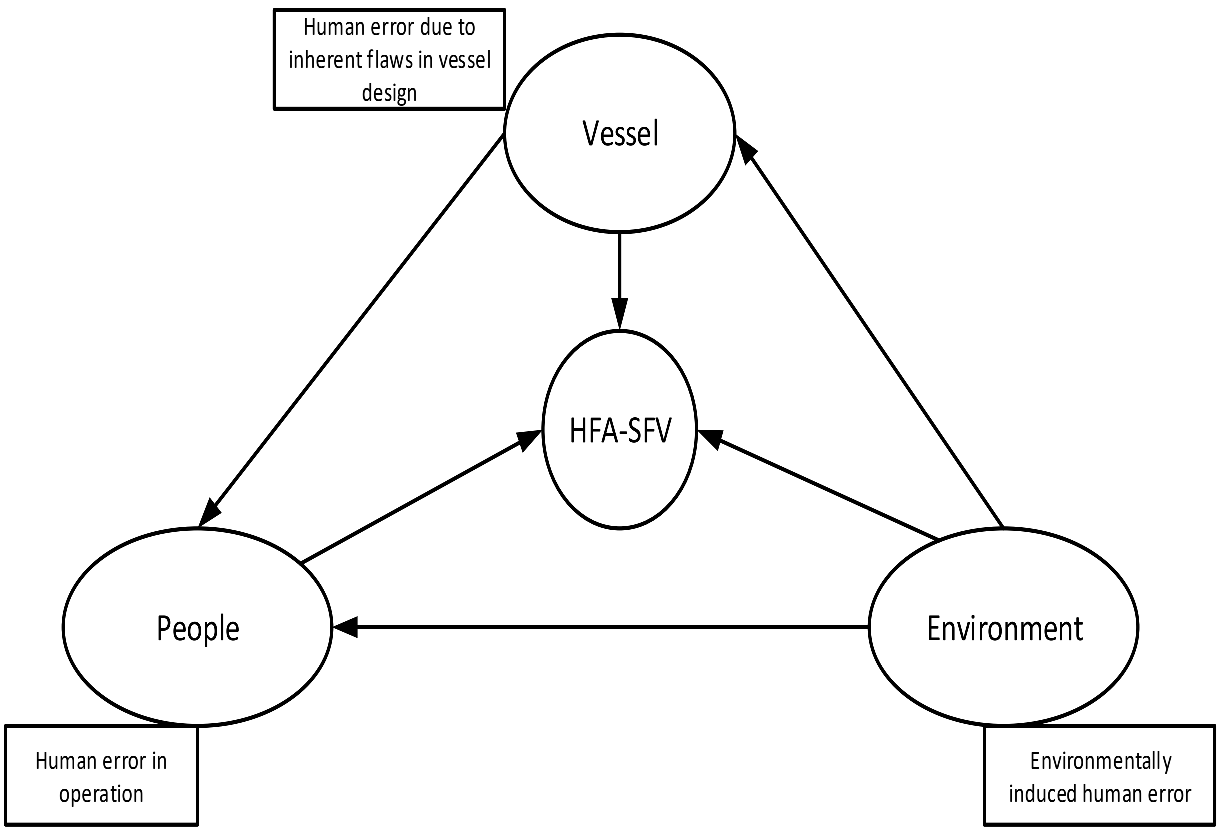

Figure 4.3 Small Fishing Vessel Operation Human Factor Accident Analysis Framework.

PEOPLE**:** This category represents the role of the human in the operations of the small fishing vessel across all sequences of events, including the operators, supervision, and management of cooperative fishing associations and governmental regulatory agencies. Crew preparedness and fitness-for-duty reflect an assessment of the crew member's ability to perform their duties safely and reliably. The model has three sub-levels under this category such as unsafe management and supervision, preconditions for an unsafe act, and unsafe action by the operator. The individuals' information processing abilities and its effects on the operational system are captured by the cognitive task errors under operator's errors and this addresses issues such as flawed logic, a faulty data processing and flawed intuitive skills.

VESSEL: This category represents the deficiencies and inadequacies in the design and fabrications found in the small fishing vessel types under consideration. It also addresses the interaction between equipment and humans in design. The inherent flaws associated with the fabrication, operation, and maintenance of this type of vessel and its components are captured in this human factor accident root cause. As an example, these vessels are not built to any standards and are not constructed based on design drawings. Another example is a scenario where the vessel is built in ways that make it difficult to access and maintain and come with inadequate stability assessment.

ENVIRONMENT**:** It comprises of the impact on the operation because of adverse physical environmental factors such as bad weather conditions in the marine environment, including rough seas, poor visibility due to fog. In addition, it addresses the physical comfort and the occupational health features of the working environment, such as lighting, noise, and climate. Also in this category is the impact of the technological environment. Table 4.3 illustrates the HFA-SFV categories and subcategories and causal factors for the proposed human factor analysis framework.

The table was prepared based on the literature and accident reports used in the current study with emphasis on the human factors contributing to the accidents.

Typically, an analysis procedure will start with the operator actions which are located under PEOPLE at the time of the accident. If unsafe acts of the operator are found to have contributed to the accident, then an examination of the categories of errors and violations will be performed to determine if they were factors in the accident. Next, would be to consider the subcategories, including judgment error, performance error, and violations. After this stage, we would proceed through the tiers of preconditions for unsafe acts, unsafe management and supervision, the VESSEL and ENVIRONMENT categories. At each tier, we assess any potential causal factors and then proceed through each category and subcategory, fully evaluating the contributing causal factors.

4.2.5. The Bayesian Network (BN) Method

A major step in the performance of a safety analysis of engineering system is to quanntify the occurrence probability of a selected accident scenario. For the current study, the authors use the Bayesian network method for the numerical simulation of the proposed model. The BN method is a probabilistic graphical approach encoded over a directed acyclic graph for which the nodes or vertices represent variables. Several authors have investigated into the techniques that are used to analyze accident scenarios (Sklet, 2014; Zheng & Liu, 2009; Nivolianitou, et al., 2004). Most of these studies compared fault tree analysis, event tree analysis, barrier analysis and petri net. However, fewer studies have made use of the BN method. A key limitation of the FTA is the nonsuitability of the approach to handle dynamic systems. However, this can be overcome by using a BN for the analysis. Additionally, capabilities of a BN been able to update known probabilities given the certain state of other parameters (ie. evidence) by propagating the known probabilities has made the method appealing to researchers. A BN can replace any FT and is more flexible to handle.

The BN approach is usually adopted due to dynamic analysis capabilities in the accident model (Adumene et al., 2021). In this way new knowledge in the form of future incidents occurrence rates data could be captured to update the model's output probability. This capability minimizes the challenges associated with the non-availability and correctness of the primary causal events data, even when data may exist. The BN method also uses a conditional probability approach, which is based on the Bayes theorem, and which has found its roots in many studies that are probabilistically based. Utilizing directional arrows (i.e., edges), the statistical relationship between the developed network variables depicts the real events. A directed edge from node 1 to node 2 implies that 1 depends on 2, and node 1 is referred to as the parent of node 2, and node 2 called a child of 1.

Sometimes however, the standard BN is rendered impractical or insufficient, which could be due to; 1) when the developed network contains so many nodes and therefore it becomes too difficult to conceptualize, and 2) when the network includes many similar repeated fragments. The challenge in both cases is how to comprehend and visualize the network representation. Hence the need to decompose the model into smaller component models. The method used for the fragmentation of the BN is known as object-oriented Bayesian networks (OOBN), (Koller and Pfeffer, 1997).

Each node has a prior probability distribution except root nodes which has the variable probability mass function (PMF). An assumption of the non-dependence of the root node is implemented, and the chain rule is then applied to develop the joint probability distribution (JPD) between the child node and the parent nodes (Bielza and Larrañaga, 2014; Obeng et al., 2022).

$$P(U) = \prod_{i=1}^{n} P\left(P_a(A_i)\right) \tag{4.1}$$

Where, U= variables ($A_1, A_2, \ldots A_n$)

$$P_{\ a}(A_i) = parents\ of\ Ai\ in\ the\ BN$$

$$P(U) = reflects\ the\ properties\ of\ the\ BN$$

Table 4-3 Accident model components and classification of event category and subcategory with their descriptions.

Major Factors of Human Errors	Sub-level of related Human Errors	Risk/ Causal factors related to the human factor
PEOPLE (unsafe operational actions by people)	**Unsafe Management & Supervision (A)**	
	Regulatory/ Policy factors (A1)	A.11. Inadequate government regulations for SFV operations
		A.12. IMO rules & regulations not fully ratified by government
		A.13. Maritime authority improperly issues licensing, not conducting inspections and enforces requirement
	Inadequate Leadership/ Supervision (A2)	A.21. Inadequate oversight and guidance
		A.22. Inadequate prescribed training and certification of crew
		A.23. Non-availability of operational equipment
	Unsafe operation (A3)	A.31. Failure to correct wrong procedures
		A.32. Continuous use of known defective/ improper equipment
		A.33. Known deficiencies in training (Inadequate training).
		A.34. Nonperformance of proper operational risk assessment.
	Leadership/ Supervisory violations (A4)	A.41. Failure to implement and enforce standard operating procedures by government agency
		A.42. Fisher people association's leadership disregard for existing rules and regulations
	Precursors for Unsafe Acts (B)	
	Crew Practices & Condition	
	Crew Fitness for Duty (B1)	B.11. Physically fatigued.
		B.12. Mental fatigue
		B.13. Crew self-medicating

	B.14. Alcohol and drug abuse
	B.15. Impairment due to health or from intoxication of medication.
Planning and Communication (B2)	B.21. Effective communication among crew
	B.22. Inadequate planning (route selection)
	B.23. Interpretation failure
	B.24. Failure to back-up
	B.25. Breakdown in communication procedures
Fatigue (B3)	B.31. Insufficient rest prior to duty
	B.32. Working long shifts without breaks.
	B.33. Stress
	B.34. Insufficient reaction time
Crew Motivation	
Greed (B4)	B.41. Crew greediness informs bad decisions
	B.42. Misplaced motivation
Morale of Crew (B5)	B.51. Positive morale among the crew
	B.52. The incentive for the crew (bonus payment), benefits, profit sharing.
Training & Competence (B6)	B.61. Inadequate training
	B.62. Lack of skill and proper qualification of the crew.
	B.63. Insufficient experience.
	B.64. Lack of education
	B.65. Unintelligence or poor aptitude
Social/ Cultural factors (B7)	B.71. Beliefs which affects the fishing activities in a particular community

		B.72. Accepts and practice safety culture
		B.73. Society's risk perception about SFV operations
	Unsafe Acts (C)	
	Errors	
	Wrong Judgement (C1)	C.11. Improper lookout
		C.12. Follow improper procedure
		C.13. Over confidence
		C.14. Improper route plan
		C.15. Interpretation failure
	Incorrect Task (C2)	C.21. Inattention failure
		C.22. Lack of knowledge
		C.23. Poor technique
	Violations	
	Violations (C3)	C.31. Failure to proceed at a safe speed
		C.32. Ignoring the use of PPE's or lack of maintenance
		C.33. Carrying load above the limit
		C.34. An operating vessel without proper licensing
ENVIRONMENT (Precondition for operator error due to environmental factors)		
	Physical environment (D1)	D.11. Adverse/ harsh weather (waves, winds, snowstorm, extreme temperatures)
		D.12. Shoaling at boundaries to ocean
		D.13. Poor visibility

		D.14. Presence of obstruction (submerged objects, obstacles)
	Technological environment (D2)	D.21. Poorly designed equipment
		D.22. Lack/ inadequate PPE's
		D.23. Faulty/ Poorly maintained PPE's
		D.24. Lack of warning and danger signs indicator on equipment
VESSEL (Precondition for operator error due to vessel)		
	Vessel Design and Fabrication (E1)	E.11. Faulty design
		E.12. Improper fabrication
		E.13. Difficult to maintain vessel
		E.14. Poor stability
	Inspection and certification (E2)	E.21. Improper permit for fishing quota
		E.22. No proper license acquisition by master
		E.23. Vessel not passing periodic inspection
	Socio-Economic Influence (E3)	E.31. Fisher people’s ability to acquire and maintain a sea-worthy vessel for fishing
		E.32. Poor maintenance of the vessel
		E.33. Social and economic pressure

4.3. Application of the Methodology and Human Factor Model

In this section, a step-by-step application of the proposed methodology as outlined in Fig. 4.1 under section 2 is implemented. The HFA_SFV model proposed for the small fishing industry operations is analyzed quantitatively using the Bayesian network (BN). This is done using the human error subcategorization as shown in table 4.3. The analysis is performed on a case-study based on a proposed generic small fishing vessel whose characteristic features are described in the section below.

4.3.1. Characteristics and features of the model small fishing vessel.

A small fishing vessel is one that primarily operates in coastal (inshore), fresh waters (lakes and rivers), and brackish waters. This vessel type is mostly adopted for the small-scale fisheries (i.e., artisanal, traditional, or subsistence). It is less sophisticated in technology and mostly owned by individuals or a family. The model small fishing vessel considered for the study has a length overall of 7.5 m; an open boat construction built with wood/ fiberglass/ aluminum and powered by a 4-stroke outboard motor of capacity 25-60 Hp (19-45kW). It is equipped with a magnetic compass, a handheld searchlight on the console, and mounted navigation lights on top of the wheelhouse. The vessel is also fitted with a trap hauler, which is driven by a gasoline engine and has safety appliances such as PFDs, lifejackets for each crew, flares, handheld aerosol horn, a mobile phone placed in a covered bucket, and a dry chemical fire extinguisher. The sketches in Fig. 4.4 and 4.5 present the plan and side views of the model vessel, respectively.

This vessel was built with no lines plan or engineering drawings and built to no standards. For this reason, there was no stability assessment, and the vessel has unknown stability limits. In the absence of a freeing port, drain plugs are fitted on the main deck and have an automatic electric bilge pump installed on the main deck with an accompanying battery on board. The fishing vessel's operational areas are in the inshore waters of Newfoundland (NL), Nova Scotia (NS), and British Columbia (BC). The size of our model fishing vessel makes it fall under TSB Canada's applicable regulation (for vessel 6m-9m), which requires safe operations, installation of safety and lifesaving equipment onboard, keeping records of maintenance and modification, and written operational procedures. Detailed design features and drawings of the case vessel are captured under appendix D in supplemental material.

4.3.2. Analysis of Human Error Probability Estimation

This section describes how the authors have developed the Bayesian network (BN) and Object-oriented Bayesian networks (OOBN's) for the accident model and represented the dependency and interdependency amongst the causal factors and the top main event (human factor accident).

4.3.3. Accident Model Development in BN and OOBN.

A mapping of the developed human factor accident model into a Bayesian network (BN) is undertaken. The acquisition of new knowledge in the form of future incidents occurrence rates data could be captured to update the small fishing vessel accident occurrence probability. This capability also helps address the challenges associated with the availability and correctness of the primary causal events data, even when data may exist.

At this stage, the human factor accident event categories and subcategories are represented by nodes, to construct a BN. To simplifying the complex accident network for proper comprehension, the BN is modified to form OOBNs, shown here in (fig.4). The submodel tool in the simulation software is further used to reduce the network into the major triggering events (Fig.5). The OOBN captures the human factor accident root causes (ie. Operator, vessel factors, and environmental factors) and their subcategories by connecting them to the dependent hazardous event of human factor accident (HFA). The BN/ OOBN is analyzed using available data on the basic events.

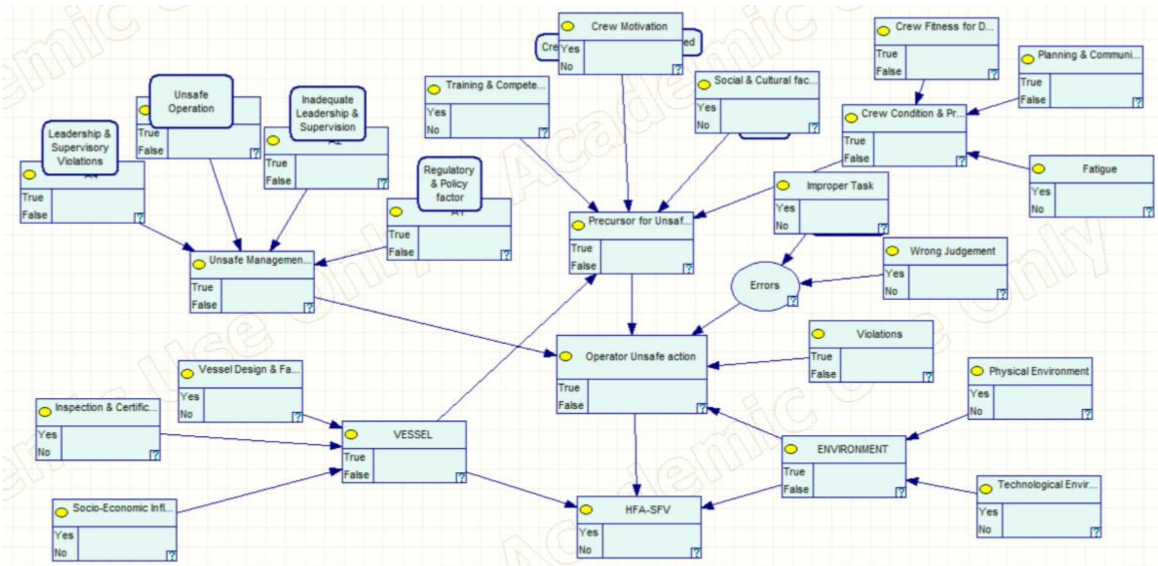

Figure 4.4 Mapping of human factor accident framework into BN for small fishing vessel operation accident CFs.

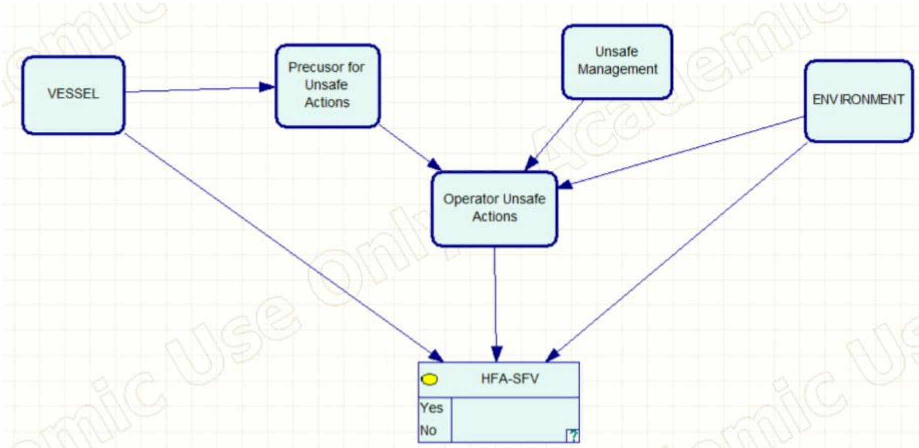

Figure 4.5 Simplest OOBN model for human factor accident framework for small fishing vessel operation.

Figure 4.5 shows the major triggering factors of the accident scenario and how they are interrelated. The accident root causes are the operator's unsafe actions, the preconditions for these operator actions, and unsafe management, combined with the vessel and adverse environmental factors. The remaining sub-groups of the OOBN are found in the supplementary material. The subcategories of causal factors and their basic events in the developed OOBN all have two states (failure and success) which are represented with a true/ false or yes/no in the software cells.

The interdependencies which exist amongst the risk causal factors of human error accident is presented through conditional probability tables (CPT's). The CPT's are constructed based on the function in equation (4.2).

$$y = 2^n \qquad (4.2)$$

Where 'y' is the number of rows for a particular CPT entry, and 'n' is the number of subcategories/ events. This equation assists the analyst in computing the number of probability entries for the nodes. The probabilities for the CPT's in this task have been obtained based on literature and historical data. The values assigned are subjective and based largely on two assumptions. (i) The "80-20" rule, (ie. transportation accident-related studies have mostly attributed 80% causes to human error), and (ii) The human error data from other domains can be applied to maritime risk analysis. In this situation, the analysis will reflect a real case scenario instead of using a simple logic OR/ AND gate. Sample CPT's that were implemented for top accident event HFA-SFV are shown in table 4.4.

Table 4-4 Conditional probability table values for main human factor accident capturing the interdependencies amongst risk factors.

Accidental factors			HFA_SFV	
Operator Unsafe Actions	***Environmental Factors***	***Vessel Factors***	TRUE	FALSE
T	T	T	0.80	0.20
T	T	F	0.46	0.54
T	F	T	0.86	0.14
T	F	F	0.077	0.92
F	T	T	0.090	0.91
F	T	F	0.087	0.91
F	F	T	0.46	0.54
F	F	F	0.087	0.91

4.3.4. Data Source

Executing the model requires the use of prior probabilities for the identified basic human error event. The probabilities could be acquired through a primary source (i.e., frequency of events occurrence from field data or expert elicitation) and from a secondary source (i.e., literature or historical data). The use of literature data was the option adopted in this study due to the non-availability of probabilities from a primary source. Much of the probability data comes from the generic human failure probabilities published in technology and safety of marine systems (Wang and Pillay, 2003). Additional data used for the prior probabilities of the risk influencing factors were extracted from the literature (Wang et al. (2005); Ugurlu et al. (2015); Ung (2018); Ung (2019)). Table 4.6 shows the basic human factor events (risk factors) and their prior probabilities. To operationalize the proposed model, these prior probabilities are used as inputs for the software (GeNIe) simulation and solved to analyze forward and updating solutions.

Table 4-5 Identified basic human error risk factors for small fishing vessel operations and their prior probabilities.

Unsafe Management & Leadership		
Event	***Symbol***	***Prior probability***
Regulatory / policy factors (intermediate)		
Inadequate government regulations for SFV operations	***A.11***	3.00E-03
IMO rules & regulations not fully ratified by the government	***A.12***	2.00E-02
Maritime authority improperly issues licensing, not conducting inspections, and enforces the requirement	***A.13***	3.00E-02
Inadequate leadership (intermediate)		
Inadequate oversight and guidance	***A.21***	2.00E-03
Inadequate prescribed training and certification of crew	***A.22***	1.00E-02
Non-availability of operational equipment	***A.23***	3.00E-03
Unsafe operation (intermediate)		
Failure to correct wrong procedures	***A.31***	3.00E-02
Continuous use of known defective/ improper equipment	***A.32***	3.00E-02
Known deficiencies in training (Inadequate training).	***A.33***	1.00E-01
Non-performance of proper operational risk assessment.	***A.34***	3.00E-03
Leadership/ supervisor violations (intermediate)		
Failure to implement and enforce standard operating procedures by a government agency	***A.41***	3.00E-02
Fisherpeople association's leadership disregard for existing rules and regulations	***A.42***	3.00E-03
Crew Practices & Condition		
Crew fitness for duty (intermediate)		
Physically fatigued	***B.11***	3.00E-02
Mental fatigue	***B.12***	2.00E-02

Crew self-medicating	***B.13***	3.00E-03
Alcohol and drug abuse	***B.14***	3.00E-03
Impairment due to health or from the intoxication of medication	***B.15***	2.00E-03
Planning & communication (intermediate)		
Effective communication among crew	***B.21***	1.00E-02
Inadequate planning (route selection)	***B.22***	2.00E-02
Interpretation failure	***B.23***	1.30E-02
Failure to back-up	***B.24***	1.00E-02
Breakdown in communication procedures	***B.25***	3.00E-02
Fatigue (intermediate)		
Insufficient rest prior to duty	***B.31***	1.00E-02
Working long shift without a break	***B.32***	2.00E-02
Stress	***B.33***	1.00E-03
Insufficient reaction time	***B.34***	1.00E-02
Crew Motivation		
Greed (intermediate)		
Crew greediness informs bad decisions	***B.41***	2.00E-02
Misplaced motivation	***B.42***	1.00E-03
Morale of crew (intermediate)		
Positive morale among the crew	***B.51***	1.00E-02
The incentive for the crew (bonus payment), benefits, profit sharing	***B.52***	1.00E-03
Training & Competence		
Inadequate training	***B.61***	2.50E-01
Lack of skill and proper qualification of crew	***B.62***	1.00E-01
Insufficient experience.	***B.63***	2.30E-01
Lack of education	***B.64***	1.50E-01
Unintelligence or poor aptitude	***B.65***	1.00E-02
Socio-cultural Factors		
Social & Cultural factors (Intermediate)		
Beliefs that affect the fishing activities in a particular community	***B.71***	1.00E-03

Accepts and practice safety culture	***B.72***	1.20E-02
Society's risk perception about SFV operations	***B.73***	1.00E-02
Operator Unsafe Actions		
Errors (intermediate)		
Wrong judgment (intermediate)		
Improper lookout	***C.11***	1.00E-02
Follow improper procedure	***C.12***	3.00E-02
Over confidence	***C.13***	1.00E-01
Improper route plan	***C.14***	1.10E-02
Interpretation’s failure	***C.15***	1.33E-02
Incorrect task (intermediate)		
Inattention failure	***C.21***	1.00E-01
Lack of knowledge	***C.22***	1.00E-02
Poor technique	***C.23***	1.00E-02
Violations (intermediate)		
Failure to proceed at a safe speed	***C.31***	1.00E-02
Ignoring the use of PPE's or lack of maintenance	***C.32***	1.00E-01
Carrying load above the limit	***C.33***	3.00E-02
Operating vessels without proper licensing.	***C.34***	1.00E-02
Environmental Factors		
Environment (intermediate)		
Physical Environment (intermediate)		
Adverse/ harsh weather	***D.11***	1.00E-01
Shoaling at boundaries to ocean	***D.12***	1.00E-02
Poor visibility	***D.13***	3.00E-03
Present of obstruction (submerged objects, obstacles)	***D.14***	2.00E-02
Technological Environment (intermediate)		
Poorly designed equipment	***D.21***	1.00E-01
Lack/ inadequate PPE's	***D.22***	1.00E-02
Faulty/ Poorly maintained PPE's	***D.23***	1.00E-01
Lack of warning and danger signs indicator on equipment	***D.24***	1.00E-02

Vessel Factors		
Vessel design & fabrication (intermediate)		
Faulty design	***E.11***	1.00E-01
Improper fabrication	***E.12***	3.00E-02
Difficult to maintain vessel	***E.13***	2.00E-02
Poor stability	***E.14***	1.00E-01
Inspection & certification (intermediate)		
Improper permit for fishing quota	***E.21***	1.00E-02
No proper license acquisition by master	***E.22***	1.00E-02
Vessel not passing periodic inspection	***E.23***	2.00E-03
Socio-economic influence (intermediate)		
Fisherpeople's ability to acquire and maintain a sea-worthy vessel for fishing	***E.31***	1.00E-03
Poor maintenance of the vessel	***E.32***	1.00E-02
Social and economic pressure.	***E.33***	2.00E-02

4.4. Results and Discussion

In this research, we have developed a generic human factor accident framework for small fishing vessel operations and have built a probabilistic model using the Bayesian network with the ability to capture key accident causal factor and their dependencies. The interrelationship and interdependencies amongst the risk causal factors are also captured by the dynamic BN model. This section presents and discusses further, the results obtained after the performance of a forward and updating (backward) analysis. The results of the parametric learning of the BN structure are presented in Fig. 4.6 and Fig. 4.7. The BN parameter learning uses the prior probabilities obtained from available data and experts' opinions, as shown in Table 4.5, as input data, along with conditional probability assessed using subject expert knowledge. The outcome of the forward analysis for the HFA_SFA-BN model shows a 0.16 occurrence probability of human factor accident for an operation of a small fishing vessel. This value is a reasonable estimate since human error is a major contributor to maritime accidents, and studies in the literature validate this (Amir et al., 2014; Talley, 1999). Most of the past accident analysis studies focused on commercial fishing vessels (Ugurlu, et al., 2020; Davis et al., 2019; Jin, 2014; Jensen et al., 2014; Havold, 2010; Wang et al., 2005; Jin, et al., 2001). In Jin, et al. (2001), the study found capsizing as well as fire and explosion to be the two most damaging commercial fishing vessel accidents. Harsh weather conditions and improper loading were the leading cause of capsizing. Fire and explosion happen due to improperly stowed combustible materials, poor maintenance culture, the lack of training and experience. Furthermore, evidence was applied to some selected major accidental (triggering) events and contributing factors through a diagnostics analysis in other to determine the critical influencing factors for human factor accidents of a small fishing vessel. This analysis also helps measure the sensitivity of the human factor accident model to changes in the probability of causal events.

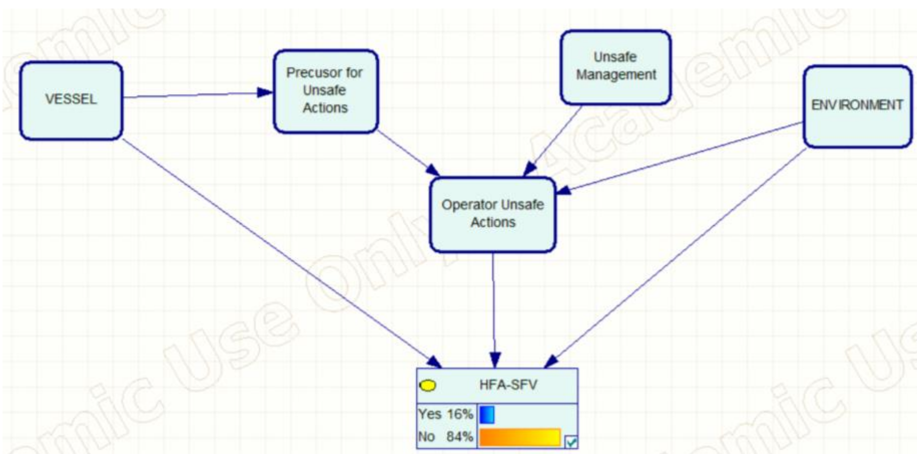

Figure 4.6 OOBN forward analysis results for Human Factor Accident for Small Fishing Vessel.

The results in Fig. 4.7 also shows the percentage contributions of the major contributing factors to the obtained human error probability; these are operator unsafe action (17%), unsafe management (11%), operator errors in knowledge and performance (10%), vessel design and fabrication problems (11%), and preconditions for unsafe acts such as socio-cultural factors (9%) and crew fatigue (7%). The trend observed in the results of the current analysis also reflect studies in the past on commercial fishing industry (NRC, 1991; Harrald et al., 1998; Grabowski et al., 2010).

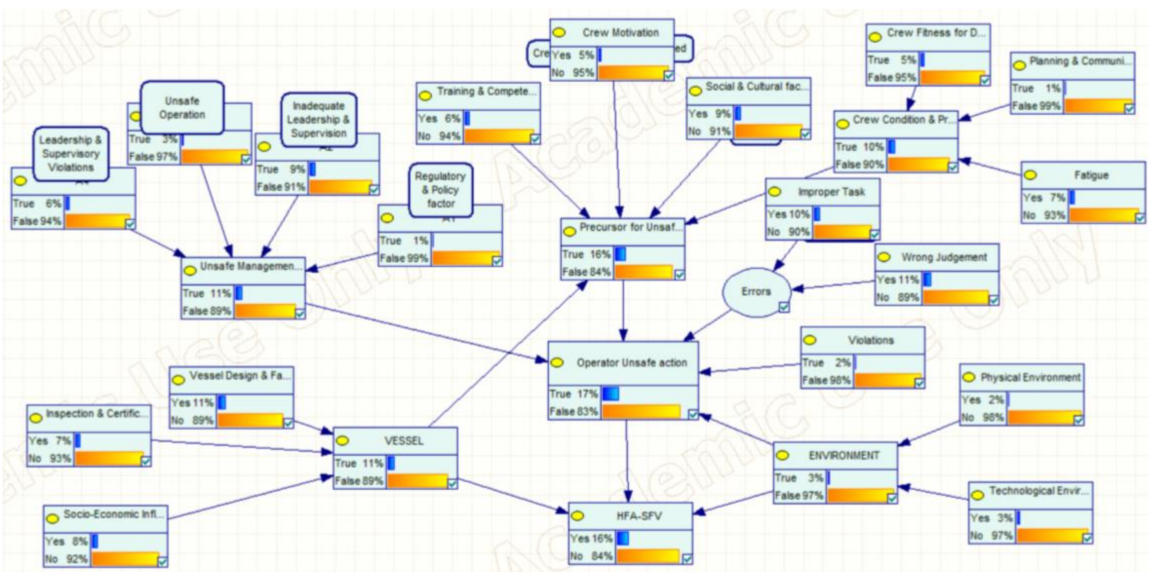

Figure 4.7 Bayesian network (BN) forward analysis results for Human Factor Accident for Small Fishing Vessel.

Figures 4.8 through 4.10 illustrate the impact of the three key root causes of human factor accidents in operating a small fishing vessel. This assessment is performed by placing evidence on the operator's unsafe actions, the environment, and the vessel factors, respectively. Our observation of the results shows that the accident occurrence rate increases for the three scenarios by 35%, 20%, and 7%, respectively. These percentages imply the proposed model, when analyzed with available data, indicates a high influence of operator’s action, followed by environmental condition and lastly, the vessel factors. These findings serve as first step to validate the applicability of the proposed model for human error analysis in small fishing vessel operations.

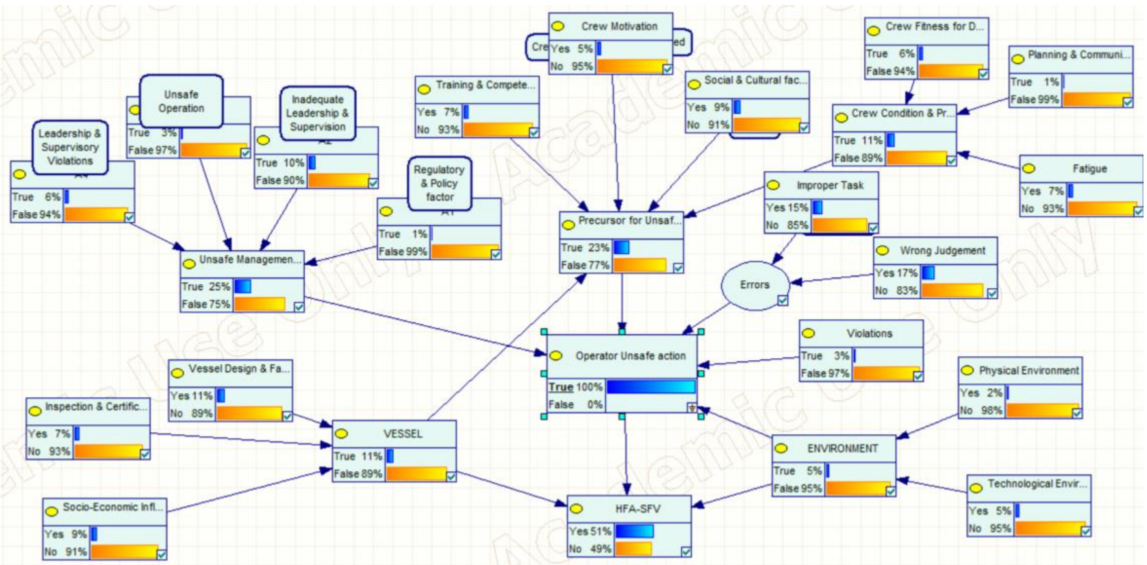

Figure 4.8 Numerical result of HFA-SFV BN when evidence is placed on the operator unsafe action.

Fishing vessel's most probable accident occurrence will happen under adverse environmental conditions (e.g., bad weather) and operator's unsafe actions (Wang et al., 2005; Ugurlu et al., 2020). Human performance errors due to improper lookout, multi-tasking, and fatigue are included in the findings. The findings of the current study on small fishing vessels operational risk also seem to agree with accident factors.

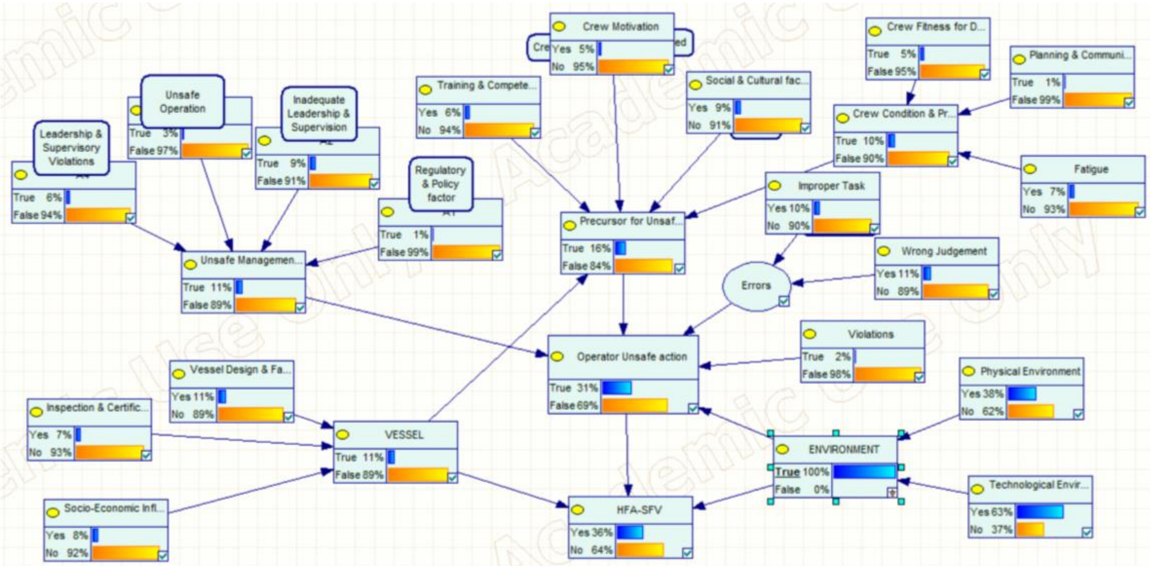

Figure 4.9 Numerical result of HFA-SFV BN when evidence is placed on the environmental factor.

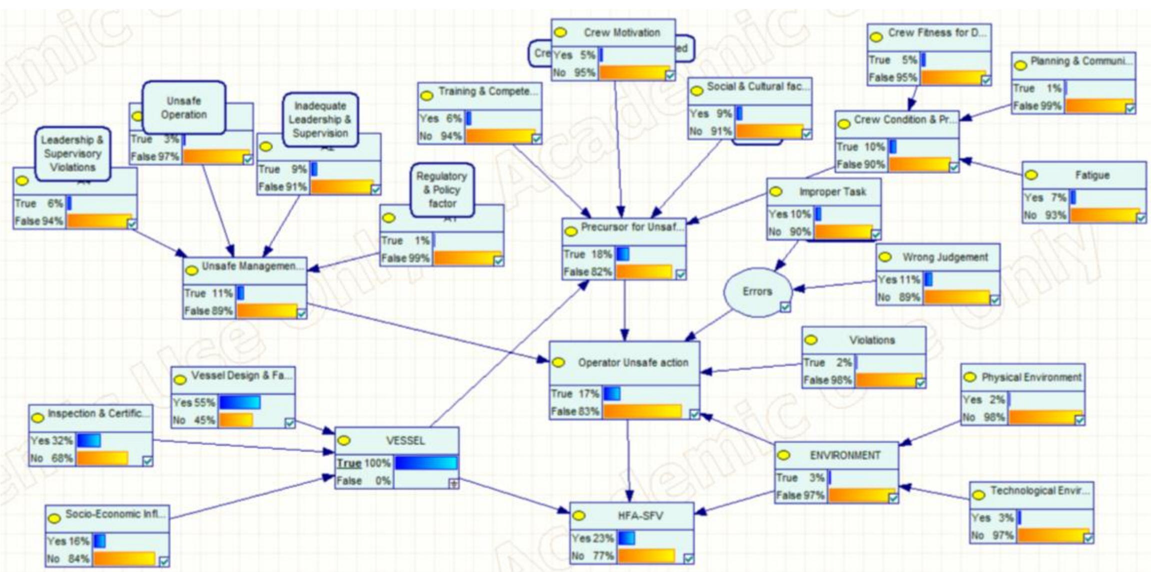

Figure 4.10 Numerical result of HFA-SFV BN when evidence is placed on the vessel.

Next, probability updating for the human factor accident causal factors was undertaken by placing evidence on the main accident event (HFA_SFV). This analysis is sometimes known as backward propagation. By putting evidence (100%) on the main event (HFA-SFV), posterior probabilities for both the major and basic risk factors are obtained. Fig. 4.11 shows the BN results of this analysis, and posterior probabilities for major accident risk factors can be found in table 4.6. Details of the results of the posterior probabilities for the basic events are shown in the supplementary material. The graph shown in Fig. 4.12 presents the percentage changes in the probability data values when evidence was placed on the leaf node. From the graph, we observe in the descending order of significance; operator's unsafe acts (38%), errors (6%), unsafe management (6%), vessel factors (4%), environmental factors (4%) as most critical contributors of human error accident in small fishing vessel operations.

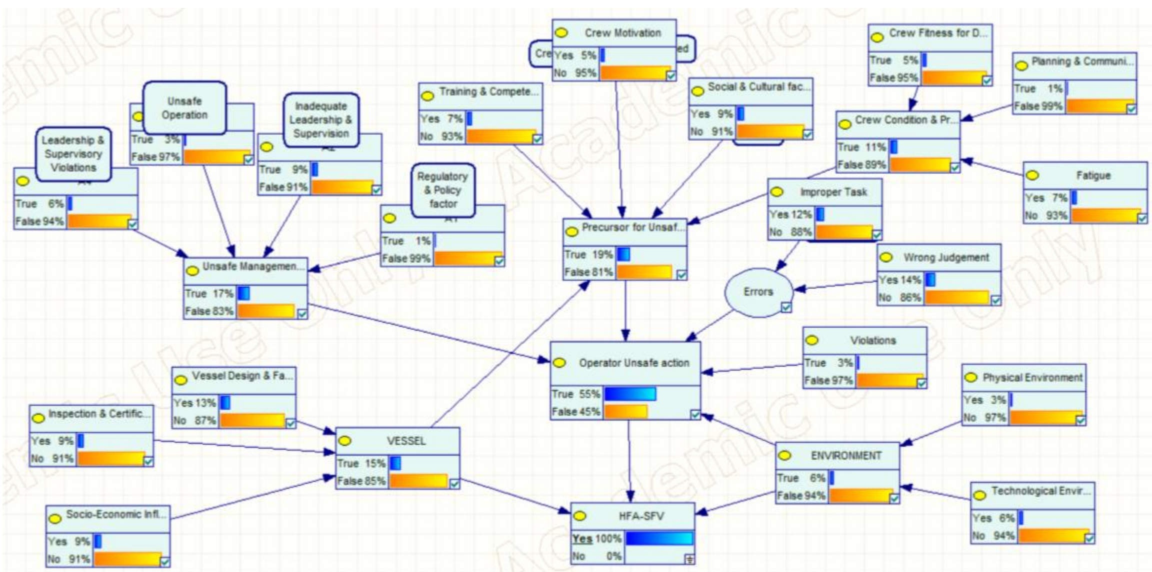

Figure 4.11 Numerical results for Backward Analysis for updating probabilities.

Table.4.7.

Table 4-6 Accidental causal events posterior probabilities during updating analysis.

No	***Major accidental/ casual event***	***Prior probability***	***Posterior probability***
1	*Environment*	0.03	0.06
2	*Physical environment*	0.02	0.03
3	*Technological environment*	0.03	0.06
4	*Vessel*	0.11	0.15
5	*Vessel design & fabrication*	0.11	0.13

6	*Inspection & certification*	0.07	0.09
7	*Socio-economic influence*	0.08	0.09
8	*Operator unsafe actions*	0.17	0.55
9	*Errors*	0.25	0.31
10	*Wrong judgement*	0.11	0.14
11	*Incorrect task*	0.1	0.12
12	*Violations*	0.02	0.03
13	*Unsafe management*	0.11	0.17
14	*Regulatory & policy factors*	0.01	0.01
15	*Inadequate leadership*	0.09	0.09
16	*Unsafe operation*	0.03	0.03
17	*Leadership/ supervisory violation*	0.06	0.06
18	*Precursor for unsafe acts*	0.16	0.19
19	*Training & competence*	0.06	0.07
20	*Crew motivation*	0.05	0.05
21	*Social & cultural factors*	0.09	0.09
22	*Crew practices & condition*	0.1	0.11
23	*Crew fitness for duty*	0.05	0.05
24	*Fatigue*	0.07	0.07
25	*Planning & communication*	0.01	0.01

Further sensitivity analysis was performed to establish the extent of influence that the accident factors have on the calculated accident risk and to identify those factors that are critical and which, therefore, attention and resources be channeled towards control. Both updating and diagnostics analyses can yield an outcome to measure the model sensitivity. Observations from both the updating and diagnostics analyses indicate that the human factor accident model’s output is very responsive to variables such as the operator's unsafe actions, the environmental factors, unsafe management, and the vessel factors. These parameters made significant changes to the model output when evidence was applied to them. The graph plot in Fig. 4.13 presents the outcome trend as obtained from the BN's diagnostics analysis. The results show operator unsafe acts (35%), environmental factors (18%), unsafe management (10%), and vessel factors (7%) as the most influencing factor of the accident occurrence. This analysis illustrates the importance of measure results which measures the sensitivity of the major causal factor to their effect on the main accident.

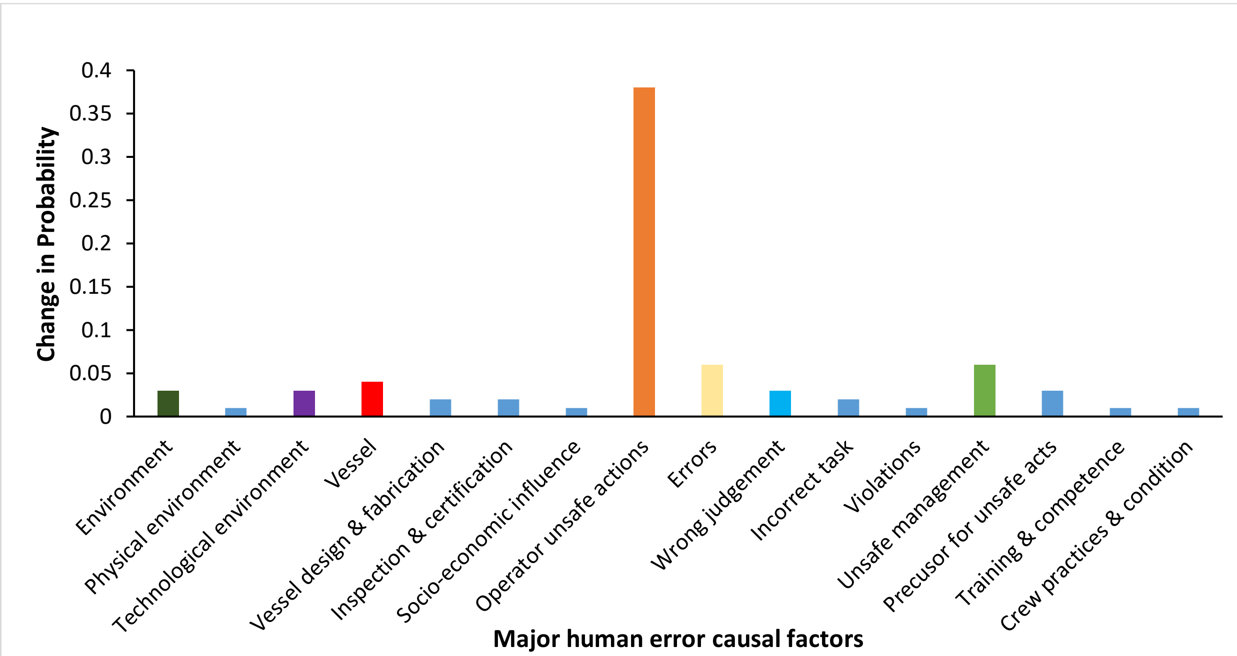

Figure 4.12 Plot of major causal factors showing their influence on human error accidents for small fishing vessel, evidence (100%) on main accident.

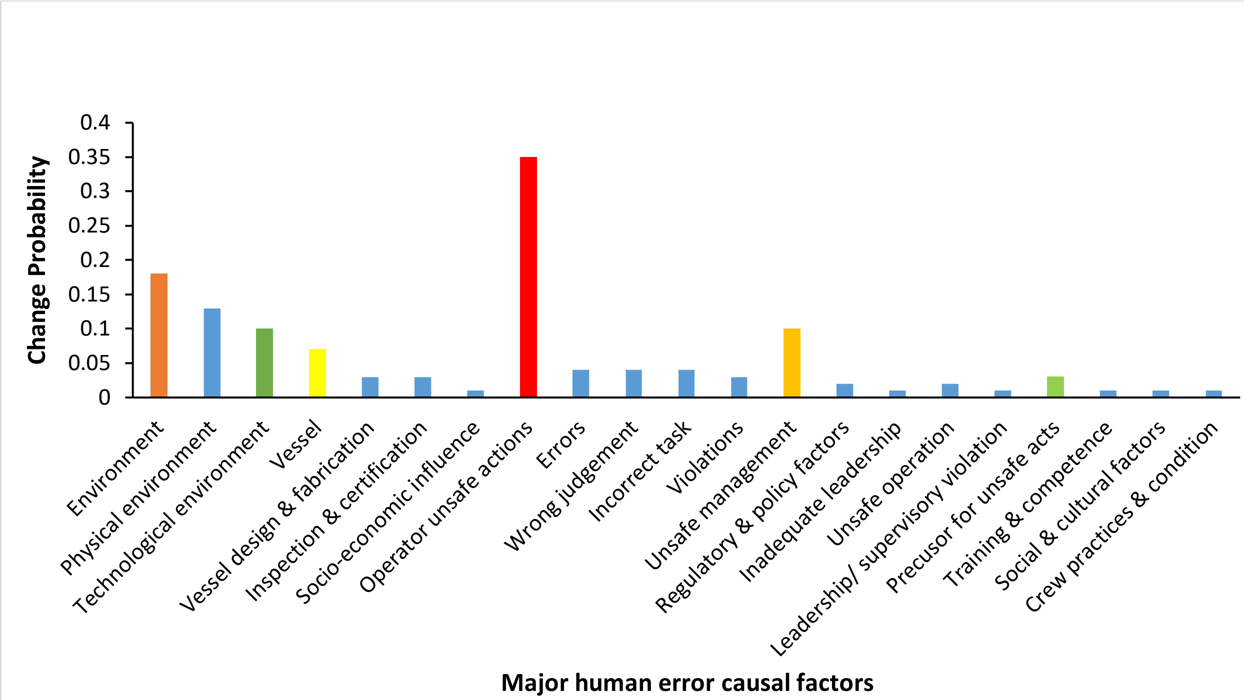

Figure 4.13 Plot of major causal factors showing their influence on human error accidents for small fishing vessel, evidence (100%) on the causal factors' accident in turns.

4.5. Conclusions

In this study, a human factor accident model for small fishing vessels has been proposed, capturing the core human error accident factors which are identified to be operator unsafe actions, the operational environment, and the fishing vessel itself. The methodology explores the important human error factors and their dependencies to predict the occurrence of human factor accidents for the operation of small fishing vessels in adverse environmental conditions. To demonstrate the capability of the proposed methodology, the model's event categories and subcategories have been analyzed dynamically using the Bayesian Network and a case study is implemented using a generic small fishing vessel model. The case analysis yielded a human error accident occurrence probability of 0.16 for a forward analysis. The model is also able to predict the most critical accident causal factors through sensitivity analysis. Major accident factors of an operator's unsafe actions, environmental factors, unsafe management, and vessel factors are identified as the most critical influencing factors of human error accidents in the small fishing industry through the performance of diagnostics analysis. Attention can therefore be focused on risk-reducing measures required to address the factors related to the operator's actions and management/ leadership since these factors are easier to mitigate and control. Recommended risk-reducing or control measures such as basic safety and stability training for operators and documented thorough regulations guidelines for small fishing vessel operation, which consider enforcement of operational requirements for the crew (i.e., compliance with alcohol and drug policy, load capacity, resting requirements, and licensing) may be adopted in this regard.

The present model has demonstrated the capacity to dynamically model human error in small fishing vessel operation. The robustness of the model can be improved by integrating safety barrier modeling and risk control measures in future research.

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CHAPTER FIVE

5. A hybrid Bayesian Network Model for Operational Risk Analysis of a Small Fishing Vessel

Preface

A version of this chapter has been revised and re-submitted for publication in the Journal of Ocean Engineering. I am the primary author along with the Co-authors, Vindex Domeh, Faisal Khan, Neil Bose, and Elizabeth Sanli. I developed the conceptual framework, methodology and investigation and reviewed the literature along with implementing the model with a case study. I prepared the original draft of the manuscript and subsequently revised the manuscript based on the co-authors' and peer review feedback and comments. Co-author Faisal Khan helped in the concept development, method, formal analysis, of model, reviewing and revising the manuscript. Co-author Neil Bose helped in the methodology, formal analysis, of model, reviewing and revising the manuscript. Co-author Elizabeth Sanli helped in the formal analysis of model, reviewing, and revising the manuscript. Co-author Vindex Domeh helped in the concept development, methodology, reviewing and revising the manuscript.

Abstract

In developing countries reliable data on accident causal factors for small fishing vessel (SFV) are not available. Studies must rely on data available through different regions and sources. This paper presents a methodological approach to integrate the data uncertainty (imprecise and incomplete data) with the Bayesian network. The integrated approach is used for operational risk analysis of small fishing vessels. The purpose of the study is to identify critical factors that contribute the most to the SFV operational risks. The data for the risk analysis was collected through direct interview of the subject matter experts drawn from the West African country (Ghana). The data collection process was reviewed and approved by the Interdisciplinary Committee on Ethics in Human Research (ICHER) of Memorial University. The integrated approach is applied to a case study and the summarized results are compared with observed data.

Keywords: Accident; Small fishing vessel; Expert opinion; Dempster-Shafer theory; Bayesian Network; Risk triggering factors; Uncertainty.

5.1. Introduction

The operation of small vessels is generally considered dangerous, and most documented accidents around the globe have been found to involve these types of vessels. It is estimated by the International Labor Organization (ILO) and the Food and Agricultural Organization (FAO) that 7% of all work-related fatalities can be attributed to the fishing industry (Mentes et al., 2016), as compared to its contribution of less than 1% it makes to the worldwide workforce. Maritime accident reporting has been receiving much attention for European and North American countries. However, evidence suggests that many similar accidents/incidents go unreported every year (FAO, 2019), especially in Southeast Asia and sub-Sahara Africa. Past studies (NRC, 1991; MAIB, 2006; EMSA, 2014; TSB, 2019) have also found fishing vessels to be predominantly involved in maritime incidents/accidents. Commercial fishing ranks consistently as one of the most hazardous occupations in the US (Drundi, 1998; USCG, 1999). Data compiled by the Bureau of labor statistics shows commercial fishing industry workers ranked second highest in occupational death in 2018 (US department of labor, 2019).

Small-scale fisheries constitute about 90% of the fishing industry worldwide (FAO, 2020). In Africa and Southeast Asia, small-scale fishing activities are performed using small boats. Also, in some of these countries with inland waterways, small vessels are used for the dual purpose of fishing and passenger transportation. It is worth noting that these types of vessels have little to no onboard shelter and limited navigation and safety equipment. Furthermore, it is evident from research studies, and accident investigation reports that human error is the primary cause of the most transportation-related accident (Harrald et al., 1998). The small vessel operator's effectiveness in performing their task is therefore critical, and they should be well-tooled to succeed.

The formal safety assessment (FSA), which is a quantitative risk assessment (QRA) methodology proposed in 2002 by the International Maritime Organization (IMO), is the adopted approach for the evaluation of risk in the maritime domain. The main philosophy behind the FSA is that the methodology can be employed as a tool to enable the decision-making process in maritime transportation. Several studies have used the FSA method to assess maritime risk (Jin et al., 2001; Wang et al., 2005; Peters, 2019; Ugurlu et al., 2020; Obeng et al., 2022a). However, significant work has also been done to understand and minimize vessel accidents. Peters (2019) studied ship capsize but focused on tolerable risk margins applicable to naval vessels. Another study (Sur and Kim, 2020) centered on estimating frequency and consequence measures without recourse to a risk factors analysis. Uğurlu et al. (2020), on the other hand, carried out a probabilistic risk assessment on causal factors to a fishing vessel sinking and collision accidents. Although the use of risk analysis helps to predict the potential for accidents due to human error, the knowledge of the relationship and the linkages between human error and the accident is required to build risk models (Harrald et al., 1998).

It is common knowledge that a small fishing vessel is very challenging to operate, with less installed outfitting, especially in countries located in sub-Sahara Africa (e.g., Ghana, and Kenya) and southeast Asia such as Indonesia and Philippines (Ugurlu et al., 2020; Domeh et al.,2021; Obeng et al., 2022a). Since most of these accidents go unreported and largely undocumented, data on causal factors contributing to small fishing vessel accidents is difficult to find. The lack of complete data reflects the non-conclusive nature of many quantitative risk assessment results usually performed by an analyst to improve fisheries' safety.

The lack of complete data requires us then to sometimes defer to expert judgment techniques. The need for expert judgment in the risk analysis process was discussed by Pate-Cornell (1996), along with Harrald et al. (1992). There exist several elicitation procedures, and some overviews are found in, for example, studies conducted by O'Hagan et al. (2006), Johnson et al. (2010a), and Aspinall and Cooke (2013). One popular elicitation method is the trial roulette method (Gore, 1987), also sometimes referred to as the chips and bins method or the histogram method. For this method, experts assign "chips" to "bins" of a histogram to ascribe probability. Further, Veen et al. (2017) attribute reasons for the trial roulette method's popularity to providing experts' immediate visual feedback. This is an important component of the elicitation procedures to reduce bias and improve the quality of the elicitation (O'Hagan et al., 2006; Johnson et al., 2010a; Veen et al., 2017). Adopting structured elicitation protocols can help improve the quality of expert judgments, and this is especially important for informing critical decisions (Cooke, 1991; Keeney & von Winterfeldt, 1991; Mellers et al., 2014; Morgan & Henrion, 1990; O'Hagan et al., 2006). These protocols, according to Hemming et al. (2018), treat each step of the elicitation as a process of formal data acquisition and incorporate research from mathematics, psychology, and decision theory to help reduce the influence of biases and to enhance transparency, accuracy, and defensibility of the resulting judgments.

The fuzzy set theory technique is a common approach in the literature on hazard identification and quantitative risk assessment with uncertainties and incomplete judgment on risk contributing factors. Studies conducted (Pelaez et al., 1996; Mohammad et al., 2017; Yazdi et al., 2018; Zarei et al., 2019) have employed the fuzzy set theory to convert expert opinions collected from the field from system experts to compute prior probability data for risk assessment. A study by Liu et al. (2015) used fuzzy analytic hierarchy process (fuzzy-AHP) methodology to calculate subjective risk factor weights and presented a modified fuzzy approach to process uncertain data and solve fuzzy multi-criteria problems with conflicting and non-commensurable criteria. Interval value is another important measure to represent experts' uncertainties in risk factors. In Certa et al. (2017), interval values were used to represent experts' knowledge and perception and have proposed a Dempster-Shafer theory-based (DST-based) approach to deal with the uncertainties associated with merging the different experts' opinions. Recent studies conducted (Suo et al., 2020; Liu & Zhang, 2022; Sezer et al., 2022; Wang et al., 2022) have also employed the Dempster-Shafer (D-S) evidence theory to convert expert opinion (information) which have been collected from the field from system experts to compute prior probability data for risk assessment. The D-S theory is convenient for epistemic uncertainty modeling and a combination of evidence from experts (Sou et al., 2020; Certa et al., 2017)

Obeng et al. (2022a) applied an object-oriented Bayesian network (OOBN) model to capture the risk influencing factors for the capsizing scenario of a small fishing trawler. The methodology also estimated the epistemic uncertainty and identified some risk-reducing options using the important measure for sensitivity. The study has found the human factor to be a major contributing factor to these accidents. A study conducted by (Domeh et al., 2021) has similarly applied the OOBN for the risk assessment of ‘man overboard’, a major accident scenario aboard fishing vessels. The proposed method captured the key accident influencing factors, modeled the vulnerability path, and proposed a pre/post-accident intervention plan to help minimize the risk.

Furthermore, in Obeng et al. (2022b), a novel methodology is proposed for modeling the human contributing factors to small fishing vessel accidents with a focus on crew effectiveness. A case study analysis was done using a generic fishing vessel operating in the Atlantic Canada region of Newfoundland (NL) and Nova Scotia (NS) with secondary input probability data. The study findings showed critical influencing factors related to the operator’s actions, adverse environmental factors, unsafe management, and the vessel factors in the descending order of significance.

Thus, to study and answer the questions of how the operational risk of small fishing vessels can be quantitatively estimated and what risk management strategies should be applied to reduce the risk and ensure the safe operation of the vessel, an integrated Dempster-Shafer theory/ Bayesian network (DST-BN) methodology along with expert elicitation is adopted to analyze the risk factors of the operations of a small vessel of length overall (LOA) of 12 m or less. Using evidence theory techniques in quantitative risk assessment may provide some answers to the above question through reasonable quantitative estimates. However, quantitative models usually require specific data to properly describe the phenomenon of interest, and the current study uses expert judgment to calculate probability data for accident causal factors.

The study aims to propose a novel framework for quantitative risk analysis of small fishing vessels that can accurately identify safety-critical factors and inform appropriate risk management strategies within the operational phase of the vessel.

The aim is achieved through the following specific objectives:

1) To construct an integrated small fishing vessel Bayesian network (SFV-BN) model connecting the accident causal factors to the safety barriers and the Consequence together and presenting the inter-dependencies amongst the various parameters.
2) To generate prior probability data based on collecting information from the expert's opinion using the Dempster-Shafer evidence theory.
3) To evaluate the risk for decision-making on small fishing vessel operational safety.

5.2. The Research Methodology

This paper combines the strengths of two widely used tools for quantitative risk assessment and uncertainty analysis to predict the occurrence rate (i.e., likelihood) of small fishing vessel accidents in the country Ghana, located in sub-Sahara Africa. The Bayesian network and Dempster-Shafer evidence theory are integrated and applied to model accident scenarios and combine expert judgments for risk factor probabilities estimation. Using the Bayesian approach for risk assessment requires analysts to have prior knowledge and data on event occurrence probabilities. However, this is not always the case; in particular, for socio-technical systems where human performance data with greater detail is most difficult to find in real-world situations and, as a result, requires expert judgment techniques. Although, expert judgment is subject to uncertainty, incomplete knowledge, and understanding of the situation of interest. In this paper, prior knowledge about human factor events in small fishing accidents is taken from different experts (see questions for experts in appendix A). The expert's knowledge is aggregated using the Dempster – Shafer (D-S) evidence theory (Sentz and Ferson, 2002).

Fig. 5.1 shows the overview of the proposed dynamic and robust study framework for integrating DS theory with BN to analyze operational risk of SFV. The following steps describe the process of the method development and its application.

Step 1- Hazard Identification: After planning a risk assessment and defining its output, the next important step is the identification of hazards. Using statistical data and literature review of fishing vessel accident reports and publications, an understanding of small fishing vessel (SFV) accident can be achieved. In turn, this helps to identify SFV accident parameters and risk causal factors which will be assessed. It also helps to gather information on the frequency and likelihood data available on past undesirable events in operating SFV.

Step 2- Next is the modeling of the accident scenario for SFV operation. Based on output of step 1, accident scenarios can be developed in addition to describing the consequences of their happening. The barriers and other factors influencing accident scenarios are also identified. In this study, the accident network is obtained by combining recently published, developed generic human factor accident for SFV with the safety barriers and the accident consequence.

Step 3- Data for the risk analysis (Expert elicitation): Human factor data is hard to find for socio-technical systems, and in cases where they do exist, may be given for generic activities and tasks. Such data may lack detail or may represent a more general task. Probabilistic data collection for the study subject follows next through soliciting expert opinion on the likelihoods of accident factors. The D-S theory is employed to compute the failure probabilities by converting linguistic terms into quantitative numbers.

Step 4- Risk estimation: Output from step 3, becomes prior data for the numerical analysis. With probabilities calculated from expert opinion as input data for BN risk model, a simulation of the model can be performed to estimate the likelihood of hazards and consequence. Summarizing the results by highlighting the major contributors to the risk, and their consequences.

Step 5- Risk evaluation and validation: The results from the risk analysis is compared to acceptance criteria and a judgement about its tolerability is determined based on corroborated results. The evaluation of the uncertainty in the risk analysis results and conclusion is equally important and needs to be performed. In addition, in this step, a sensitivity analysis is undertaken to identify critical risk factors and then identify risk reducing measures (i.e., whether the risk must be reduced and how this can be done).

The remaining portion under this section briefly explains the fundamentals of the analysis tools and approaches adopted in the study. This is followed by a case study to demonstrate the implementation of the proposed methodology/framework under subsequent sections.

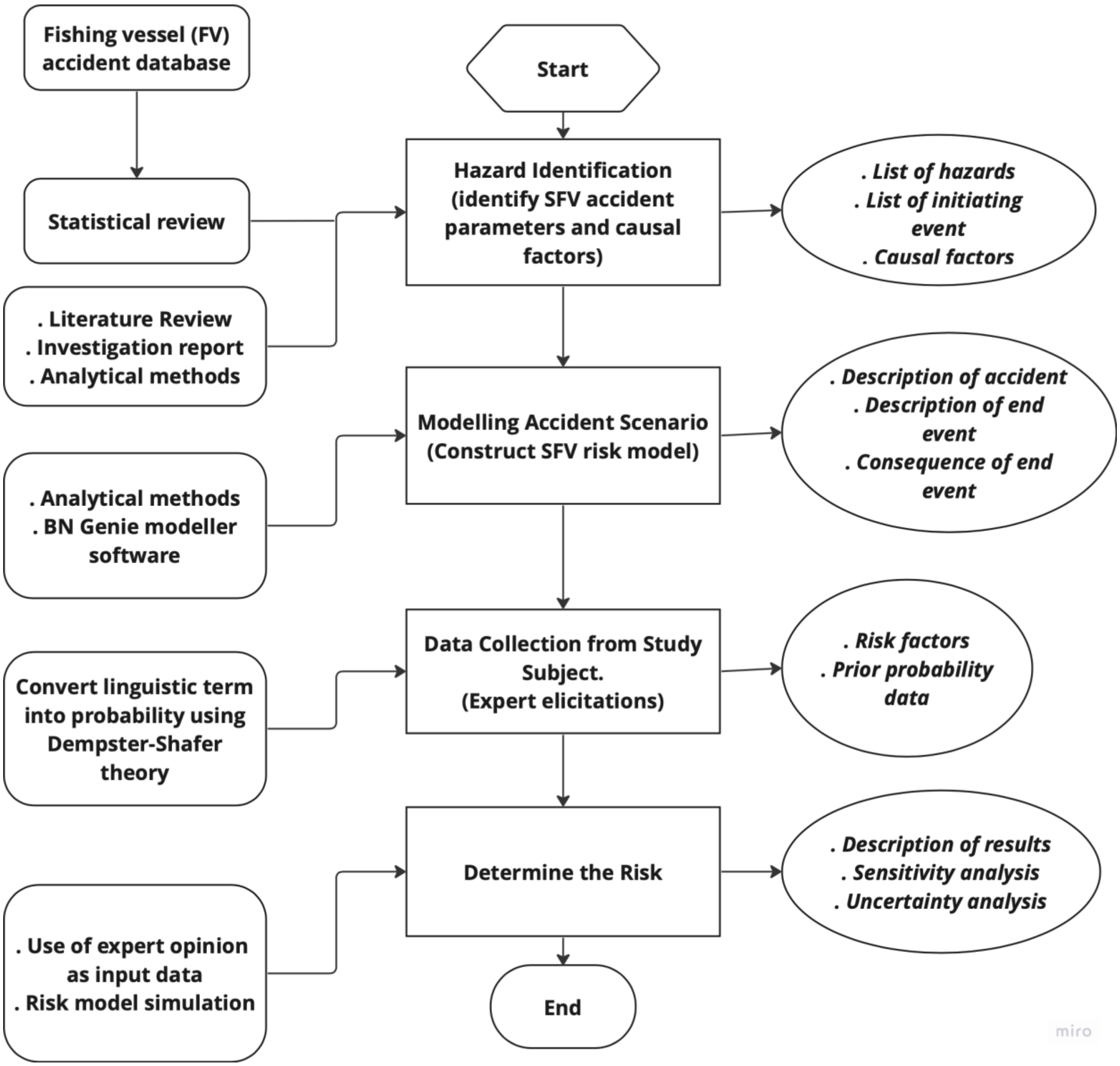

Figure 5.1 The detailed methodology to develop proposed risk model.

5.2.1. *Bayesian network fundamentals*

The Bayesian Network method is a probabilistic graphical approach that represents the interaction of parameters using a directed acyclic graph (DAG), and for which the nodes represent variables. It is also called belief nets or causal networks and is described by Neil et al. (2001) as a graph with a set of probability tables. The BN method also uses a conditional probability approach based on the Bayes theorem, widely used in probabilistic risk analysis. In BN, the DAG constitutes the qualitative part which represents a set of conditional independence assumptions that are captured through a graph-theoretic notion called d-separation (Pearl, 1989; Bobbio et al., 2001). The quantitative analysis aspect is based on the conditional independence assumption (Bobbio et al., 2001). Utilizing directional arrows (i.e., edges), the statistical relationship between the developed network variables depicts the real events. A directed edge from node 1 to node 2 implies that 1 depends on 2, node 1 is referred to as the parent of node 2, and node 2 is called a child of 1 (Obeng et al., 2022b). In addition, the BN model is probabilistic which makes it possible to include the factors that can influence the frequency of events. However, the model is unable to determine event occurrence since the model is not deterministic (Bearfield & Marsh,)

In quantitative risk analysis, the proposed model must have the capabilities to capture new information on influencing factors as they become available. Recent studies (Adumene et al., 2021; Obeng et al., 2022b) show dynamic analysis capabilities in the accident model with BN. This way, new knowledge in the form of future incidents occurrence rates data could be captured to update the model's output probability. This capability minimizes the challenges associated with the non-availability and correctness of the primary causal events data, even when data may exist.

Each node has a prior probability distribution except root nodes which has the variable probability mass function (PMF). An assumption of the non-dependence of the root node is implemented, and the chain rule is then applied to develop the joint probability distribution (JPD) between the child node and the parent nodes (Bielza and Larrañaga, 2014; Obeng et al., 2022b).

$$P(U) = \prod_{i=1}^{n} P\left(P_a(A_i)\right) \quad (5.1)$$

Where, U= variables ($A_1, A_2, \ldots A_n$)

$$P_{a}(A_i) = parents\ of\ Ai\ in\ the\ BN$$

$$P(U) = reflects\ the\ properties\ of\ the\ BN$$

5.2.2. Dempster-Shafer (D-S) evidence theory

The Dempster-Shafer theory (DST), sometimes called the evidence theory, was initially proposed by Dempster in 1967 whiles studying lower and upper limits of probability (Dempster, 1967) and later formalized by Shafer in 1976 (Shafer, 1976). The literature on D-S theory promotes it as a useful and convenient framework for modeling epistemic uncertainty and combining evidence from multiple sources. The use of uncertain and incomplete information in evidence theory for reasoning and representation is commonplace in literature, as seen in (Sentz & Ferson, 2002; Sezer et al., 2022). The D-S theory was originally proposed based on a finite non-empty set (also called a universal set) which consists of the observed situations. The set is popularly referred to as a frame of discernment, Θ can denote the universal set, and it power set also expressed as 2^{Θ} in which each element of 2^{Θ} takes a value in the range of [0,1].

There are three important functions in the D-S theory, namely, the basic probability assignment function (*bpa* or *m*), the Belief function (*Bel*), and the Plausibility function (*Pl*). The *bpa*, mostly represented by m, defines a mapping of the power set to the interval between 0 and 1, where the *bpa* of the *null set* is 0, and the summation of the *bpa*'s of all the subsets of the power set is equal to 1. Furthermore, the value of the *bpa* for a given set ***A***, written as *m(**A**)*, called the mass function, expresses the proportion of all relevant and available evidence that supports the claim that a particular element of **X** (the universal set) belongs to the set A but no subset of **A** (Klir, 1998;

Sentz & Ferson, 2002). The value of *m(**A**)* will pertain only to set A and will make no additional claims about any subsets of **A**. The *bpa*'s, which represent sets of propositions, are then assigned an upper (***plausibility***) and lower (***belief***) bound interval, which will contain the precise probability of a set of interest. Note, however, that this interval bound is non-additive, although it is continuous (Sentz & Ferson, 2002). The theory constitutes a set of propositions (*bpa*'s) and then assigns to each of them an interval of [***belief***, ***plausibility***], and the *bpa* is defined mathematically by the belief function m: $2^{\Theta} \rightarrow [0, 1]$ over a frame of discernment Θ, that satisfies the relations below; (Wang et al., 2022; Omid & Assefa, 2016)

$$\sum_{\boldsymbol{A \in \Theta}} \boldsymbol{m(A) = 1} \quad \textbf{(5.2)}$$

$$m(\emptyset) = 0. \quad (5.3)$$

$$m(\Theta) = 1 \quad (5.4)$$

Where, the number of all subsets of Θ is 2^{Θ}. If $m(A) > 0$, then A is the focal element.

The mass function $m(A)$ represents the degree of support given to proposition A. The mass $m(\Theta)$ also represents the uncertainty of the evidence for proposition A. If $m(A) = 1$, then the evidence does not provide valuable information (Wang et al., 2022).

The plausibility (Pl) function P: $2^{\Theta} \rightarrow [0,1]$ is defined by using the belief (Bel) function as

$$Pl\ (\text{A}) = 1 - Bel\ (\tilde{\text{A}}). \tag{5.5}$$

The *Bel* and *Pl* functions are the lower and upper envelopes of a class of probability assignments about A so that $Bel(\text{A}) \leq Pl(\text{A})$ (Omid & Assefa, 2016). The precise probability of an event (in the classical sense) would lie within the lower and upper bounds of Belief and Plausibility, respectively (Sentz & Ferson, 2002).

$$Bel(A) = P(A) = Pl(A). \tag{5.6}$$

The plausibility and belief functions of the D-S evidence theory help us obtain information about the uncertainty in the knowledge and understanding of experts.

5.2.3. Dempster combination rule

The D-S theory is very useful and has seen increased application in the literature due largely to the combination or synthesis rule, which can be applied to combine evidence from multiple sources. Assuming that m_1 and m_2 are two *bpa's*, their corresponding focal elements are $B_1 \ldots, Bp$ and $C_1, \ldots, Cq$. Then the joint m_{12}, according to (Sentz & Ferson, 2002; Wang et al., 2022).

$$m(A) = \frac{\sum_{BnC} m1(\text{B})\text{m}2(\text{C})}{1-K} \tag{5.7}$$

$$when\ A \neq \emptyset$$

$$m(\emptyset) = 0 \tag{5.8}$$

$$K = \sum_{BnC=\emptyset} m1(\mathrm{B})\mathrm{m2}(\mathrm{C}) \quad (5.9)$$

K is known as the conflict coefficient and measures the conflict between the two sources of evidence.

Considering the above equation, two sets of evidence are said to be in complete conflict when K=1, and the combination cannot be applicable. The denominator in the Dempster's rule, 1-*K*, is a factor that normalizes the equation, according to (Yager, 1987). The normalization effectively ignores the conflict and assigns any probability mass associated with conflict to the null set. The reader should consult (Zadeh, 1984) for more conflicting evidence in the D-S theory.

5.2.4. Bayesian Network vs. Dempster-Shafer Theory

The evidence theory seems closely related to the probability theory, and Smet (2004), observed that the generalized Bayesian theorem could be found in the evidence theory. The Bayesian probability theory has generally been the method traditionally applied to analyze epistemic or subjective uncertainty. The probabilistic analysis requires that an analyst have prior knowledge and information on the probability of all events. Suppose we have three events (A, B, C) as an example, without evidence of their occurrence likelihood.

Bayes' theorem will initially assign a prior probability equal to 0.33 for each event for the analysis. The D-S theory will, however, initially assign an interval of [0, 1], to indicate total ignorance of the occurrence of the events, and as evidence has gathered, this interval will shrink.

5.2.5. Improvement of D-S evidence theory

The Dempster's combination rule is a generalization of the Bayes' rule, and a key assumption behind the theory is the consideration of independence in the sources of information. However, the information gathered from the various sources may sometimes be highly conflicting ($K \rightarrow 1$), and in such situations, the combination rule has come under serious criticism (Zadeh, 1986; Yager, 1987; Sentz & Ferson, 2002). This can be asserted in the light of the resultant counterintuitive effect of the normalization factor in Dempster's combination rule, as demonstrated with a simple example in [Zadeh, 1984, p.84]. The study found that when there is a high to complete conflict between evidence, the D-S rule is inapplicable, and therefore a newer approach will have to be employed. A search in the literature has also revealed various Dempster's synthesis rule improvement studies such as (Yager, 1987; Deng et al., 2004; Li et al., 2002; Liang et al., 2008; Guo & Li, 2011). These proposed new approaches modify the original combination rule to improved or extended frameworks that reflect the consideration of expert's evidence credibility and the reliability of evidence.

Further studies recently (Suo et al., 2020; Liu & Zhang, 2022; Sezer et al., 2022; Wang et al., 2022) have shown the use of cross-merging between evidence and standardization method based on pignistic probability transform (PPT) for improved combination rules. In addition, to address the limitations of Dempster's synthesis rule for conflicting evidence (Chao & Peng, 2012) proposed the synthetic rule based on the credibility of the evidence. For comprehensive discussions on the derivations of these improvements and extensions of the original combination rule, the reader can refer to the literature. This paper quotes summaries of the key equations for analysis.

Experts' opinions, when acquired, usually may include incomplete information and multiple values due to their subjective nature and the different evidence collection structuring. A standardization method can be applied to different evidence structures through a pignistic probability transform (PPT) proposed by Smets and Kennes (1994).

If Θ is the frame of discernment, and *A*∈*Θ*., Then the pignistic probability function is defined as Smets and Kennes (1994)

$$BetP(B) = \sum_{A \in \emptyset} m(\mathrm{A}) \frac{|B \cap A|}{|A|} \qquad (5.10)$$

where $|A|$ is the number of atoms of Θ in *A*, and denotes the cardinality of subset *A*. In decision-making, *BetP* (B) is usually used to translate a BPA into a probability function.

Assuming two sets of evidence, *E*1 and *E*2 on Θ, with their corresponding mass functions *m*1 and *m*2, are collected from two experts. If the focal elements are *Ai* and *Bj*, then the consistency and conflict of the set of evidence (*E1)* and (*E2)* as defined by (Wang et al., 2022) are,

Consistency,

$$H\ (E1, E2) = \sum_{Ai=Bj} m1(Ai)m2(Bj) \qquad (5.11)$$

Conflict,

$$C\ (E1, E2) = \sum_{Ai \cap Bj = \emptyset} m1(Ai)m2(Bj) \qquad (5.12)$$

If C > H, E1 and E2 are said to be conflicting, and when C⩽H, E1, and E2 are deemed consistent.

The synthesis method based on evidence credibility can be expressed as

$$m(A) = \sum_{i}^{n} mi(A)Crd(mi) \quad (5.13)$$

Where Crd_i (mi) reflects the credibility of evidence from the expert, and $\sum_{i}^{n} Crdi$=1.

$$Crd(mi) = \frac{Sup(mi)}{\sum_{i}^{n} Sup(mi)} \quad (5.14)$$

Sup(*mi*) represents the degree to which the evidence *mi* is supported by other evidence.

5.2.6. Expert Elicitation

Elicitation is a commonly used tool to extract viable opinions or information from experts. O'Hagan et al. (2006) define elicitation as the process of extracting and creating a representation of an expert's beliefs. The expert knowledge may be expressed through a probabilistic representation, availing its usefulness to science and engineering research, and providing prior knowledge in statistical analysis, when we lack historical data. Expert judgment has been applied in areas as diverse as aerospace programs, military intelligence, nuclear engineering, seismic risk evaluation, weather forecasting, economic and business forecasting, and policy analysis (Cooke, 1991).

In this study, the belief (Bel) function was used to present the probabilities considering the uncertainties in the expert elicitation of event occurrence frequency for fishing vessel accidents in Ghanaian waters. The Bel function framework used three relevant representations of belief: the Bel, the plausibility (Pls), and the basic probability assignment (m or bpa). Initial judgments are frequently explained through basic probability, whereas the final judgments on the likelihood of events are expressed through Pls.

5.3. Application of the Proposed Methodology

In this section, the proposed study framework is demonstrated with a generic small fishing vessel accident model published recently by the authors (Obeng et al., 2022b). The model combines the original human factor accident (HFA-SFV) framework with onboard machinery failure and adverse environmental conditions. The resulting BN model schematically describes the risk and comprises the accident contributing factors (*CF*), safety barriers (*SB*), and the Consequence (*C*) of the accident occurrence.

5.3.1. Problem Statement

African nations and those in southeast Asia, lack reliable data on accident causal factors for small fishing vessel. In this research, information is collected from a group of 6 experts with substantial (minimum of 5 years) experience in maritime safety and accident investigation, SFV ownership or operation, and on enforcement of regulations and rules in the study area (Ghana in West Africa). The information gathered assisted in the calculation of prior probability data for quantitative risk assessment. Authors previously studied the operational risk of SFV but had had to rely on data from secondary sources to analyze the developed model. In the current study we are able to generate primary data specific to the study area for analysis. The subject-matter experts were drawn from the fishing industry, academia, relevant government regulatory agencies, and the Navy. The expert judgement approach was adopted in this study as a scientific consensus tool for weighting and assigning probability values to risk contributing factors and, in addition, to rank the expert's capabilities.

Memorial University's Interdisciplinary Committee on Ethics in Human Research (ICEHR) approved the structure, questions, and data collection and handling procedures for the survey/interview portions of the study. Prior to the survey/interview taking place, all participants read and signed an informed consent. After the data collection exercise was completed, the Dempster-Shafer (D-S) evidence theory was employed to help calculate prior probabilities for risk contributing factors, including failure probabilities for the safety barriers. These probabilities are then used as input data to analyze the BN, estimate the risk of SFV accidents and validate the results.

The remaining section of the paper presents results obtained after implementing the proposed method in a step-by-step process as illustrated in Fig. 5.1.

5.3.2. Hazard Identification (HAZID)

The first question of what can go wrong in a risk analysis can be answered through a process of identifying and describing all significant related hazards, threats, and hazardous events that can be associated with our socio-technical system (Rausand & Haugen 2020). This objective can also be satisfied using a combination of creative and analytical exercises that aim to identify all relevant hazards (Kontovas & Psaraftis, 2009; Görçün & Burak 2015). This is a proactive process and captures effects of accidents and hazards that are currently present and also those that have materialized in the past (IMO, 1997). All potential hazards leading to damages to personnel, asset and the environment are identified. When available, data sets related to marine accidents are converted into quantitative values and the numbers of outputs are obtained as a list of hazards and their associated scenarios usually prioritized by risk level and a description of causes and effects. The main result of this step is a list of hazards and a description of associated scenarios published by authors (Obeng et al., 2022b). Table 5.1. lists the identified human factor hazards (i.e., accident triggering events) as adopted from the previous study.

5.3.3. Bayesian Network Modelling of Accident Scenario

The accidental scenario identification and selection is the most vital stage of any risk assessment procedure or quantitative risk assessment and management (QRA&M). The evolution of a small fishing vessel's accident is dynamic, which has been illustrated with the BN model shown in Fig. 5.2. The network comprises the accident triggering events (representing basic events), intermediate events, machinery failure, adverse environment, and the top event, a small fishing vessel (SFV) accident. The accident network was translated into a risk model by connecting the hazard network to the safety barriers and the consequence networks. Fig. 5.2 shows a BN of the risk model for a small fishing vessel accident. In this study, the level of causal events for which data is gathered for the model's analysis was stopped at the level of an accident triggering events (TRE) to simplify the analysis. Therefore, the triggering events are the analysis's basic events (root nodes). Table. 5.1, contains a list of the identified accident triggering events for small fishing vessels (Obeng et al., 2022b) and combined with the safety barriers contained in Table. 5.2, these parameters were the basics for the expert's elicitation process.

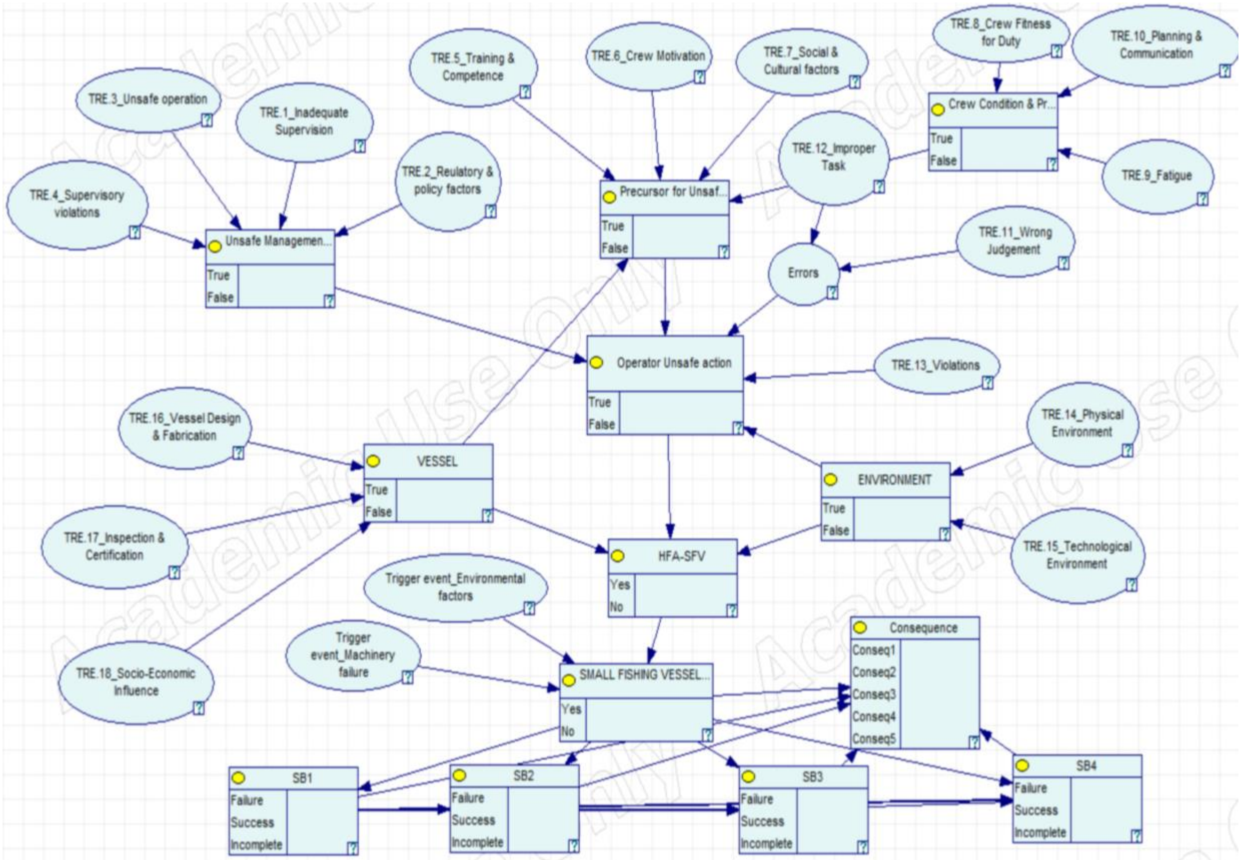

Figure 5.2 Bayesian network (BN) of risk model for small fishing vessel accident scenario.

In order to use Bayesian Networks tools with the evidence theory, we adopted the conditional probability tables and prior probabilities. The interdependencies among the risk factors are presented through this conditional probability tables (CPTs). The CPTs for the intermediate and leaf nodes depend on the parent nodes pertaining to each. The tables contain the conditional probabilities which explains the failure propagation mechanism through the functional sequence of operations. The probabilities for the CPTs in this task have been obtained based on (Obeng et al., 2022b), a sequel to the current study and an example illustrating an event connected to three (3) root nodes.

The subjective assigned values largely relied on two assumptions. (i) The "80-20" rule (i.e., transportation accident-related studies have mostly attributed 80% causes to human error), and (ii) human error data from other domains can be applied to maritime risk analysis.

Using the logic OR/ AND gate sometimes simplifies the problem; however, a transformational conditional mass table could result in the case of evidence theory. This is done to integrate the basic belief assignment and describe the propagation mechanism of failures (Simon et al., 2007). The conditional probability for (yes) and (no) modalities can be used directly, and efforts should be made on the (yes, no) modality. Note that the modality (yes, no) characterizes our ignorance about the state of the event of component. See (Simon et al., 2007) for further reading on this subject.

Table 5-1 Identified accidental/triggering events causing small fishing vessel accidents.

TAG	Triggering Events (TRE)
TRE.1	Inadequate supervision/ leadership
TRE.2	Regulatory & policy factors
TRE.3	Unsafe operation
TRE.4	Leadership & supervisory violations
TRE.5	Training & competence
TRE.6	Crew motivation
TRE.7	Social & cultural factors
TRE.8	Crew fitness for duty
TRE.9	Fatigue
TRE.10	Planning & communication
TRE.11	Judgment error (wrong judgment)
TRE.12	Tasking error (improper task)
TRE.13	Crew violations
TRE.14	Physical (natural) environmental

TRE.15	Technological (ergonomically) environment
TRE.16	Vessel design & fabrication
TRE.17	Inspection & certification
TRE.18	Socio-economic influence.

5.3.4. Safety Barrier

The safety barrier, also sometimes called the safety-critical function or system, may be a piece of protective equipment or certain features introduced into the system to protect the human being, the environment, and other assets against harm, should hazardous events lead to undesirable incidents (Rausand & Haugen, 2020). For this study, the proposed safety barriers used are adopted from the study of Hollnagel, (2004). The barriers are classified based on their nature and have four categories, namely: physical/material, functional, symbolic, and immaterial barriers. During the operation of a small fishing vessel, the layers of safety barriers (SB) and their definitions are adequately captured as below and presented in table 5.3. The correlation of the safety barriers in the current study is mutually applied (i.e., *SB1 to SB2, SB1 to SB3, SB1 to SB4, SB2 to SB3, et al)*.

Barrier one- (SB1) - *Monitoring and detection system (e.g., bilge level alarm)*

Barrier two- (SB2) - *Operator intervention (i.e., ensuring water tightness, use of damage control kits, pumping system, etc.*

Barrier three- (SB3) - *Onboard safety equipment (Built-in floatation, PFD, flares, distress signal, EPIRB.*

Barrier four- (SB4) - *(Maritime search and rescue (M-SAR)*

Table 5-2. Proposed safety barriers for operating a small fishing vessel.

TAG	Safety Barrier (SB)
SB1	Monitoring and detection system failure
SB2	Operator intervention failure
SB3	Onboard safety equipment failure
SB4	M-ASR failure

5.3.5. Consequence (accident impact)

According to the formal safety assessment (FSA), the risk is a combination of the frequency of occurrence of an accident type with the severity of its consequences, whereby some possible consequences may be loss of lives, environmental pollution, or damage to ship/cargo or financial loss (Pillay & Wang, 2003). In the current study, the impact of the Consequence was captured in the risk model of small fishing vessel accidents, which the BN presents. The consequence node has five levels of impact.

C_1*-Near miss*

C_2*-Minor injury/minor damage to the fishing craft.*

C_3*Life-threatening injury (e.g., hypothermia)/major damage to vessel/loss of catch*

C_4*-Loss of vessel/environmental pollution.*

C_5*-Death.*

The above-listed consequence impact levels can further be summarised under the IMO classification of accident consequences into three levels (less severe, severe, and very severe). With the estimation of the small fishing vessel accident probability coupled with the quantification of the Consequence, we may be able to calculate and sketch the FN (i.e., frequency (F)-fatality (N)) curves and Potential Loss of Life (PLL). In the current study, however, subjective assumptions are made for probabilities during the consequence modeling due to the lack of data on the economic cost of such accidents. Table 5.3. Presents the classification of the severity of Consequences for small fishing vessel operational risk.

Table 5-3 Small fishing vessel accident consequences with their classifications

Consequence classification	Consequence
Less severe	C_1, C_2
Severe	C_3
Very severe	C_4, C_5

5.3.6. Data

The availability and reliability of system failure and human functional event data are crucial during a risk assessment exercise. Furthermore, in risk assessment, a theoretical framework is less useful unless there is relevant data to support its usage. Unfortunately, most accident databases do not have data recorded in a manner compatible with existing theoretical frameworks, making it difficult to adopt the results of most human factor research in a risk analysis. To analyze the accident model, prior probability for risk factors obtained from experts' opinions is employed. The failure probability for the safety barriers is equally calculated from expert judgment.

In general, probability data for machinery failure and environmental factors can be estimated based on historical data and modeling for risk assessment. It is important to note that the accuracy of probability estimates for machinery failure and environmental factors will depend on the quality and relevance of the data used. Studies have found extreme weather conditions mostly affect to small fishing vessels. Accordingly heavy weather can weaken the hull structure of the vessel and cause deck fittings to come loose or lead to an accident (Wang, J. et. al., 2005).

The prior probabilities of the non-human factors (i.e., machinery failure and environmental factors) used for the current analysis are adopted from literature data from (Mentes et al., 2016). Fishing vessel accidents statistics in Turkey showed causes as extreme weather (23%), mechanical failure (15%), navigation error (4%), rudder failure (2%), amongst other causal factors. Therefore, the approximations for prior probability the two non-human factor events mentioned above.

The conditional probability tables (CPTs) used for this analysis were adopted from our recent study (Obeng et al., 2022). The CPT's are constructed based on the function in equation (15).

$y = 2^n$ (5.15)

Where 'y' is the number of rows for a particular CPT entry, and 'n' is the number of subcategories/ events. This equation assists the analyst in computing the number of probability entries for the nodes. The probabilities for the CPT's in this task have been obtained based on literature and historical data. The values assigned are subjective and based largely on two assumptions. (i) The "80-20" rule, (ie. transportation accident-related studies have mostly attributed 80% causes to human error), and (ii) The human error data from other domains can be applied to maritime risk analysis. In this situation, the analysis will reflect a real case scenario instead of using a simple logic OR/ AND gate. Sample CPT's that were implemented for intermediate accidental event HFA-SFV is shown in table 5.4 as an example.

Table 5-4 Conditional probability table values for the human factors capturing the interdependencies amongst risk factors.

Accidental factors			HFA_SFV	
Operator Unsafe Actions	***Environmental Factors***	***Vessel Factors***	TRUE	FALSE

T	T	T	0.80	0.20
T	T	F	0.46	0.54
T	F	T	0.86	0.14
T	F	F	0.077	0.92
F	T	T	0.090	0.91
F	T	F	0.087	0.91
F	F	T	0.46	0.54
F	F	F	0.087	0.91

As discussed in Section 2.2, the prior knowledge of each accident triggering event and safety barrier is gathered from different expert sources in terms of *bpa*, which are then combined using DST combination rule or with the improved synthesis rule when conflict coefficient (**K >= 0.7**). Fig. 5.3 is a schematic illustration of the numeric conversion of the expert evidence. As an example, an expert reported that the probability of triggering event of 'inadequate supervision' to happen, is 30%, and the probability for not happening is 50%. This can be written mathematically, as m_1 ({Yes}) = 0.30, m_1 ({No}) = 0.50 and m_1 ({Incomplete knowledge}) = 0.2. We can also convert the probabilities of a second expert as m_2 ({Yes}) = 0.3, m_2 ({No}) = 0.6 and m_2 ({Incomplete knowledge}) = 0.1, and a third expert as m_3 ({Yes}) = 0.3, m_3 ({No}) = 0.5 and m_3 ({Incomplete knowledge}) = 0.2.

The three sets of expert judgments are combined initially using the DST combination rule as depicted in Eq. (5.7). In the process, the value of K is evaluated to decide on the next step. The combination process is illustrated in Table 5.5. Using a similar process, we have calculated the prior probabilities of each event and all the safety barriers. The resulting probability values are summarized in Table 5.6.

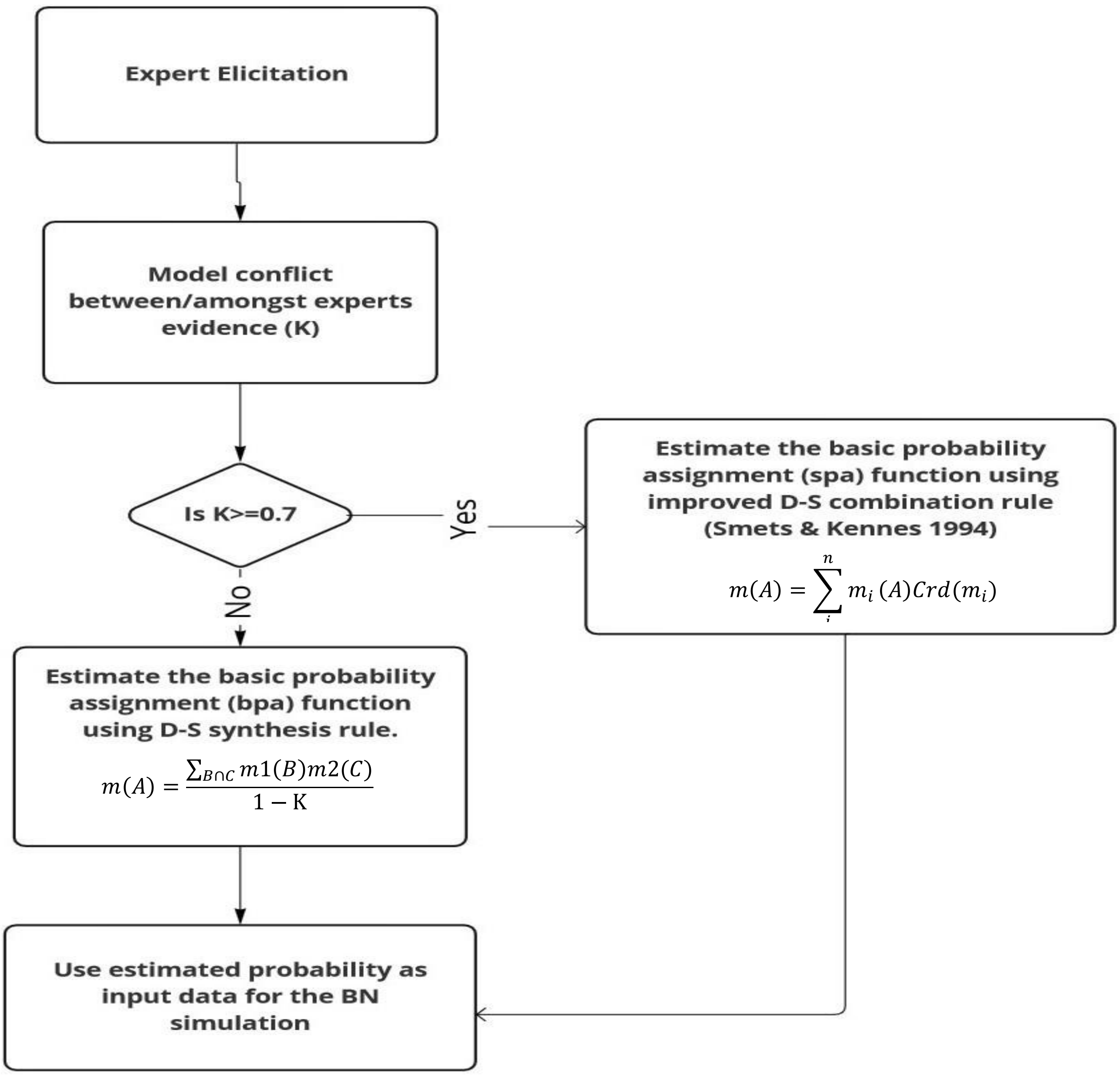

Figure 5.3 Flow chart showing schematic process of the numeric conversion of linguistic terms.

5.4. Results and Discussion

In this section, we present the results of the elicitation of expert judgment and the calculated prior probabilities for the accident triggering events in Table 5.1 and the safety barriers in Table. 5.2. Data with subjective probability values for the consequences were used to analyze the proposed BN risk model for small fishing vessels. A discussion of obtained results was also presented.

Table 5.7 presents the estimates for the events and safety barrier probabilities. The listed values under the last three columns represent calculation results for probabilities of an event happening (Yes), the event not happening (No), and incompleteness in knowledge (Yes, No), which are obtained from the expert's knowledge combination based on DS theory. These probabilities were used as inputs for the BN model, and both forward and backward analyses were performed.

Table 5-5 (a) An illustration of DST combination of expert opinion using the triggering event of inadequate supervision.

	m_2		yes		no		yes, no
m_1			0.3		0.6		0.1
yes	0.3	(Yes)=	0.09	(∅)=	0.18	(Yes)=	0.03
no	0.5	(∅)=	0.15	(No)=	0.3	(No) =	0.05
yes, no	0.2	(Yes)=	0.06	(No)=	0.12	(Yes, No) =	0.02
	K		0.33				
	$\sum m_1(Pa)m_2(pb)$		0.18		0.47		0.02
	m_{1-2} (DST)		0.268656716		0.701492537		0.029850746

(b)

	m_3		yes		no		yes, no
m_{1-2}			0.3		0.5		0.2
yes	0.2687	(Yes)=	0.08061	(∅)=	0.13435	(Yes)=	0.05374
no	0.7015	(∅)=	0.21045	(No)=	0.35075	(No) =	0.1403
yes, no	0.0299	(Yes)=	0.00897	(No)=	0.01495	(Yes, No) =	0.00598
	K	0.3448					
	$\sum m_1(Pa)m_2(pb)$	0.14332		0.506		0.00598	
	m_{1-2} (DST)	***0.2187***		***0.7723***		***0.0091***	

The current proposed framework requires we initially estimate the conflict (k) value. Table 5.6. which shows the conflict coefficients between two experts for accident triggering event of inadequate supervision, as an illustration, represents why the original D-S evidence theory is preferential. After computing the same for all event *bpa* from the experts, a similar pattern was observed, with very low K values. We conclude there is minimal conflict between the three experts, and therefore more appropriate to use the traditional D-S evidence fusion rule instead of the modified D-S evidence theory. The result from the aggregation is shown in table 5.7, and values under last three columns are used as prior probabilities for numerical analysis.

Table 5-6 Conflict coefficient between experts for triggering event of inadequate supervision.

Pairwise of experts	*Conflict coefficient*
K (p_1, p_2)	0.330
K (p_1, p_3)	0.300
K (p_2, p_3)	0.330
K (p_{1-2}, p_3)	0.345

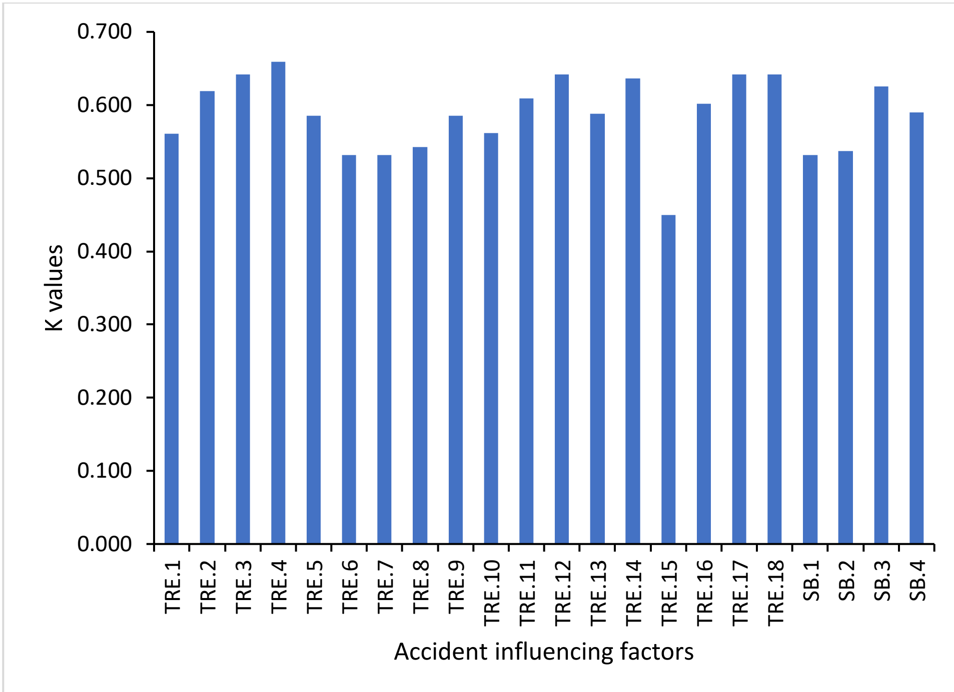

Figure 5.4 Graph of conflict coefficient (K) estimated values across SFV accident triggering factors for the experts.

Fig. 5.4 also shows a graph presenting the estimated conflict coefficient (K) values amongst the sets of three pieces of evidence using the probability theory across the accident triggering events. Again, as can be observed from the trend in the graph, the K values show less conflict among the three experts (less than the 0.7 thresholds). Based on these results for the k's, as seen in table 5.6, the computation of the prior probabilities by the original DST combination rule was enough for the current study.

Table 5-7 Combination results from expert knowledge using DST.

		Expert #1			Expert #2			Expert #3			Experts Knowledge Combination			
Tag	***Triggering Factors***	***Yes***	***No***	***Yes, No***	***Yes***	***No***	***Yes, No***	***Yes***	***No***	***Yes, No***	***K***	***Yes***	***No***	***Yes, No***
TRE.1	**Inadequate supervision/ leadership**	0.30	0.5	0.20	0.30	0.60	0.10	0.30	0.50	0.20	0.561	0.2187	0.7722	0.0091
TRE.2	**Regulatory & policy factors**	0.30	0.5	0.20	0.50	0.30	0.20	0.20	0.70	0.10	0.619	0.2651	0.7244	0.0105
TRE.3	**Unsafe operation**	0.40	0.5	0.10	0.60	0.20	0.20	0.50	0.40	0.10	0.642	0.6648	0.3296	0.0056
TRE.4	**Leadership & supervisory violations**	0.50	0.4	0.10	0.50	0.30	0.20	0.30	0.60	0.10	0.659	0.4868	0.5073	0.0059
TRE.5	**Training & competence**	0.50	0.4	0.10	0.50	0.30	0.20	0.50	0.30	0.20	0.585	0.6988	0.2916	0.0096
TRE.6	**Crew motivation**	0.30	0.5	0.20	0.20	0.60	0.20	0.30	0.60	0.10	0.532	0.1624	0.8291	0.0085
TRE.7	**Social & cultural factors**	0.30	0.5	0.20	0.20	0.60	0.20	0.30	0.60	0.10	0.532	0.1624	0.8291	0.0085
TRE.8	**Crew fitness for duty**	0.40	0.3	0.30	0.30	0.50	0.20	0.30	0.50	0.20	0.543	0.3567	0.6171	0.0263
TRE.9	**Fatigue**	0.30	0.5	0.20	0.30	0.50	0.20	0.40	0.50	0.10	0.585	0.2916	0.6988	0.0096
TRE.10	**Planning & communication**	0.40	0.3	0.30	0.50	0.30	0.20	0.50	0.40	0.10	0.562	0.6575	0.3288	0.0137
TRE.11	**Judgement error (wrong judgement)**	0.40	0.5	0.10	0.50	0.30	0.20	0.50	0.30	0.20	0.609	0.6164	0.3734	0.0102

TRE.12	**Tasking error (improper task)**	0.40	0.5	0.10	0.40	0.40	0.20	0.50	0.40	0.10	0.642	0.4972	0.4972	0.0056
TRE.13	**Crew violations**	0.30	0.5	0.20	0.40	0.40	0.20	0.50	0.30	0.20	0.588	0.4903	0.4903	0.0194
TRE.14	**Physical (natural) environmental**	0.40	0.5	0.10	0.40	0.40	0.20	0.40	0.50	0.10	0.636	0.4066	0.5879	0.0055
TRE.15	**Technological (ergonomically) environment**	0.20	0.3	0.50	0.20	0.60	0.20	0.30	0.60	0.10	0.450	0.1855	0.7964	0.0182
TRE.16	**Vessel design & fabrication**	0.40	0.5	0.10	0.30	0.50	0.20	0.40	0.40	0.20	0.602	0.3668	0.6231	0.0101
TRE.17	**Inspection & certification**	0.50	0.4	0.10	0.40	0.40	0.20	0.40	0.50	0.10	0.642	0.4972	0.4972	0.0056
TRE.18	**Socio-economic influence.**	0.40	0.5	0.10	0.20	0.60	0.20	0.50	0.40	0.10	0.642	0.3296	0.6648	0.0056
SB.1	**Monitoring and detection system failure**	0.20	0.6	0.20	0.30	0.50	0.20	0.30	0.60	0.10	0.532	0.1624	0.8291	0.0085
SB.2	**Operator intervention failure**	0.30	0.5	0.20	0.30	0.50	0.20	0.20	0.70	0.10	0.537	0.1533	0.8380	0.0086
SB.3	**Onboard safety equipment failure**	0.50	0.4	0.10	0.50	0.40	0.10	0.50	0.30	0.20	0.625	0.6667	0.3280	0.0053
SB.4	**Maritime search and rescue (M-SAR) failure**	0.40	0.4	0.20	0.60	0.30	0.10	0.50	0.30	0.20	0.590	0.7073	0.2829	0.0098

5.4.1. *Estimation of SFV risk and accident occurrence probability*

The small fishing vessel accident model has shown its capability to predict operational risk (Obeng et al., 2022). Forward and backward analyses with computed prior data are performed, and the results are shown in Fig. 5.5 and Fig. 5.6, respectively.

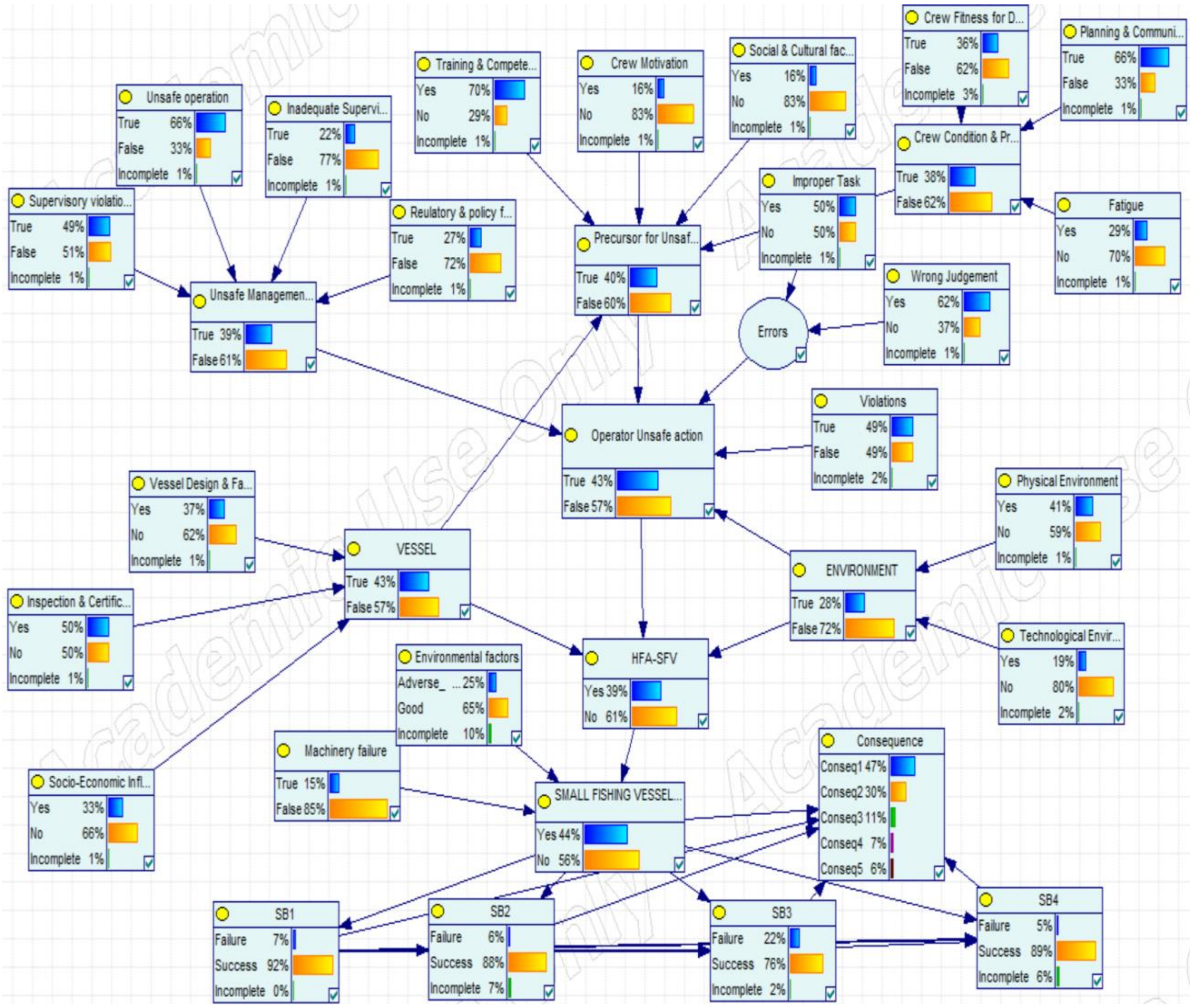

Figure 5.5 Bayesian network (BN) forward analysis results for Small Fishing Vessel operational risk model

Using the results obtained from expert data as inputs for the BN, the likelihood of an accident occurring for a small fishing vessel operating in Ghanaian waters (i.e., study area) was estimated to be approximately 44% (0.44) chance per fishing voyage. Although there are no grounded published estimates for the frequency of incidents/accidents by authorities, there is ample evidence from past studies conducted by the Food and Agricultural Organization (FAO) of the United Nations (UN) that have reported corroborating findings.

In general, from the literature, similar trends in the results have been reported for the commercial fishing industry (NRC, 1991; Harrald et al., 1998; Grabowski et al., 2010). The very high probability means there is an urgent need to have measures to reduce the risk. Also, as can be observed from Fig. 5.5, human error contribution was calculated by the BN analysis as 39% (0.39), accounting proportionately to almost half the chance to cause occurrence the main SFV accident event. However, the effective human factor probability contribution to the leaf (accident) node is 60% which reflect the generally accepted fact that suggests the most contribution to accidents is human error. An outcome that is also validated in the findings from the literature for major contributors to a maritime accident (Amir et al., 2014; Talley, 1999).

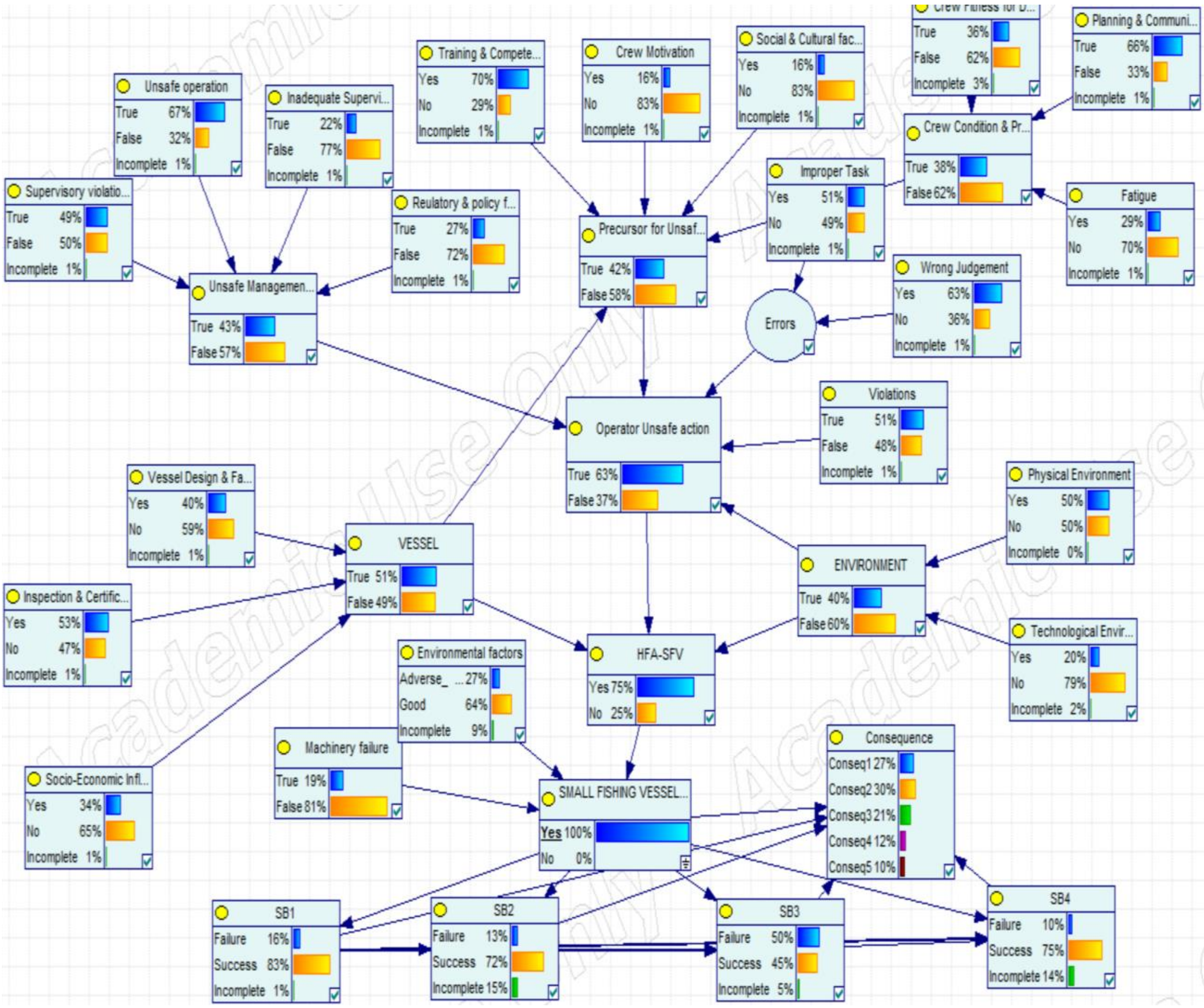

Figure 5.6 Numerical results for Backward Analysis by placing evidence leaf node (SFV) for updating probabilities.

The next stage was to do an update by placing evidence (100%) on the leaf node. The model generates posterior probabilities for the accident triggering event through this exercise. These new probabilities, along with the prior probability data, were used to determine the critical contributing triggering factors, which will need attention to reduce the hazard occurrence rate. The actions taken based on such an analysis invariably can assist in managing the projected risk of accident occurrence.

The posterior value of 75% (0.75) obtained for human error in fig. 5.6 indicates a significant chance of a small fishing accident being caused by a human factor. We have little to no control over the environmental factor except to avoid adverse conditions. The reliability of the onboard machinery (i.e., outboard motor or diesel engine) is continually improved through the collection and analysis of failure data during their operating life cycle. The only aspect of our risk contributors we control is the people's actions. As identified in an earlier study by the authors (Obeng et al., 2022), the most critical human factors were found in descending order of significance; the operators' unsafe acts, judgment and task errors, and unsafe management.

In addition, further diagnostic analyses were performed on the BN model to simulate certain scenarios of interest, for which Fig. 5.7 and Fig. 5.8 present outputs of the simulations. The results in Fig. 5.7 show a common scenario whereby adverse environmental conditions are present. To this end, the environmental nodes in the risk model are instantiated by putting evidence (100%), and the software algorithm runs to solve.

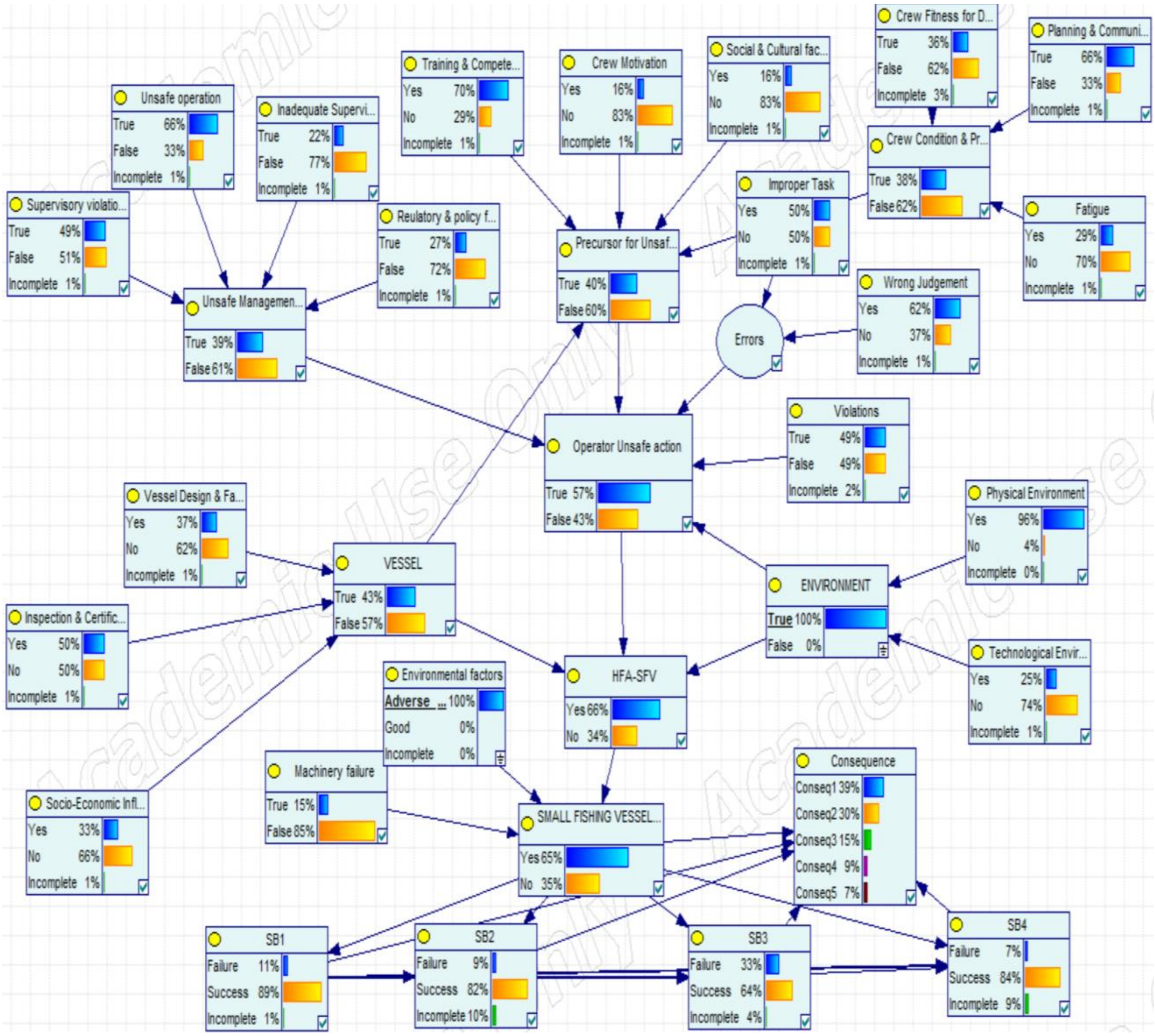

Figure 5.7 Numerical result for an adverse environmental condition scenario.

As seen from the results in Fig. 5.7, the model predicts an equally high occurrence likelihood of SFV accidents with just the presence of bad environmental situations like bad weather, for example, and in some typical cases, shallow waters with tree stumps. The accident probability is predicted to be around 65% (0.65), with the environmental impact influencing the operator performance also showing a probability of 66% (0.66). This result is validated in past studies (NRC, 1991; Wang et al., 2005; MAIB, 2006), which have shown similar pattern of results.

The general observation in the analysis results shown through Figs. 5.5-5.7 indicates a common trend for the consequence node (i.e., a high number of near misses and less severe impact, and also severe low impact and loss of lives), which was the expectation of the proposed risk model since, in reality, the data seems to point us to that direction when the safety interventions or barriers works according to plan. Fig. 8 shows the results of another key scenario of the accident evolution, where there is evidence of the top hazard of vessel accident and the initial practical interventions failed to stop the propagation of the accident.

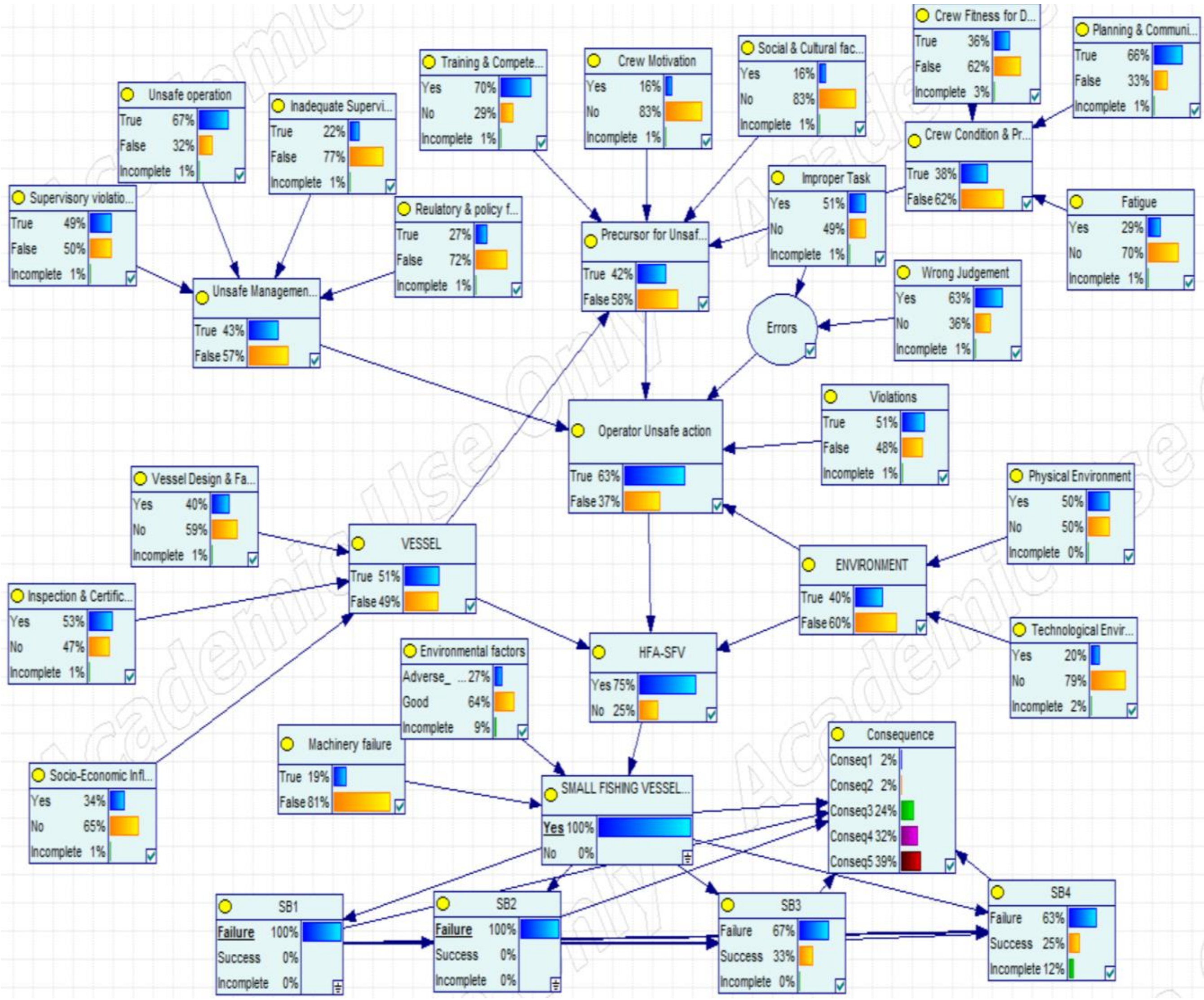

Figure 5.8 Numerical result for the Barrier failure scenario when the accident has initiated.

To this end, the leaf node is instantiated with (100% evidence), placing evidence on the first and second stages of intervention, and the software algorithm is run to solve. This scenario translates to a real-life operational situation in which an accident happens without the crew detecting the initiation of the hazard. Secondary efforts by the crew to intervene (for example, fixing damage to the hull caused by a collision) also fail to prevent flooding. As a result of the failure of the first and second safety barriers put in place, we can observe from Fig. 5.8 that the consequence node of the risk model predicts the worst-case impact after the onset of the initial accident (i.e., 39%-death; 32%-total loss and pollution; 24%life-threatening injuries and loss of catch). This result validates the proposed model's capability to capture the real propagation of accidents and their impacts closely. When the risk interventions introduced in a system of operations fail to prevent the escalation and propagation of an unwanted incident, the consequence may likely be catastrophic, as discussed in these results.

5.4.2. Uncertainty Analysis

The risk in many regards implies uncertainty; therefore, having an idea about the level of uncertainty in a quantitative risk assessment (QRA) is vital. Uncertainty in QRA is broadly grouped into aleatory (or irreducible) uncertainty and epistemic uncertainty. Aleatory uncertainty examines the model structure adequacy in predicting the accident modeled. Often this uncertainty is difficult to estimate precisely; as a result, it has been termed irreducible uncertainty. Epistemic uncertainty evaluates the accuracy prediction boundary of the model output result. Often the challenge with evaluating epistemic uncertainty is the lack of data, especially for models analyzing first-time accidents. Although the uncertainty in a risk assessment may change over time as knowledge and information develop, a quantitative analysis of uncertainty provides the decision-maker with more information about the results' reliability.

The work of (Montewka et al., 2014) discusses methodological requirements for a risk perspective appropriate for risk management in maritime transportation. This proposed perspective considers the risk as a set encompassing the following: a set of plausible scenarios leading to an accident, the likelihood of unwanted events within the scenarios, the consequences of the events, and a description of uncertainty. All these elements are assumed conditional upon the available knowledge (K) about the analyzed system and understanding (N) of the system behavior.

In the present study, the authors have statistically analyzed a set of data generated based on the knowledge gap in the expert elicitation of the *bpa's*, for the quantitative analyses of uncertainty in which the uncertainty is assumed to have a Gaussian distribution. The Gaussian distribution assumed the 95% confidence interval (95% CI) is $\mu \pm 1.96\sigma$, where μ is the mean and σ is the standard error of the mean. As stated, the analysis was conducted to further examine the gap in the knowledge of the probability data gathered from the study experts, designated as incomplete knowledge in table 5.7. The analysis yielded an uncertainty measurement of (0.01 ± 0.009).

The interpretation of this uncertainty analysis result is that the estimated value is 0.01, and the range of uncertainty around this estimate is ±0.009. This means that there is a 95% chance that the true value falls within this range. In other words, the uncertainty in the estimate is relatively small compared to the estimated value. It is important however, to consider the context of the study and the potential implications of this uncertainty in the results. To make use of the computed uncertainty in conjunction with event probabilities, we could use it to construct confidence intervals around the estimated event probabilities. As an example, suppose that the event probability estimated by the experts in the study is 0.5. Given the uncertainty measurement of (0.01±0.009), we can construct a 95% confidence interval for the true event probability as 0.5 ± 1.96(0.009) = [0.483, 0.517]. This means that there is a 95% chance that the true event probability falls within this interval. The details of the uncertainty analyses, which represent more data and parametric uncertainties, are presented in tables 5.8 & 5.9.

Table 5-8 Computational results for the uncertainties in expert judgment on the risk factors for small fishing vessel operations.

Triggering Factors	Combination probability of an event	Belief (Bel)	Plausibility (Pl)	Disbelief (D=1-Pl)	Uncertainty (knowledge incompleteness)
Inadequate supervision/ leadership	**0.2187**	0.0960	0.6610	0.3390	0.0091
Regulatory & policy factors	**0.2651**	0.1010	0.7240	0.2760	0.0105
Unsafe operation	**0.6648**	0.2380	0.8820	0.1180	0.0056
Leadership & supervisory violations	**0.4868**	0.1660	0.8270	0.1730	0.0059
Training & competence	**0.6988**	0.2900	0.8790	0.1210	0.0096
Crew motivation	**0.1624**	0.0760	0.6120	0.3880	0.0085
Social & cultural factors	**0.1624**	0.0760	0.6120	0.3880	0.0085
Crew fitness for duty	**0.3567**	0.1630	0.7180	0.2820	0.0263
Fatigue	**0.2916**	0.1210	0.7100	0.2900	0.0096
Planning & communication	**0.6575**	0.2880	0.8560	0.1440	0.0137
Judgement error (wrong judgement)	**0.6164**	0.2410	0.8540	0.1460	0.0102
Tasking error (improper task)	**0.4972**	0.1780	0.8220	0.1780	0.0056
Crew violations	**0.4903**	0.2020	0.7980	0.2020	0.0194
Physical (natural) environmental	**0.4066**	0.1480	0.7860	0.2140	0.0055
Technological (ergonomically) environment	**0.1855**	0.1020	0.5620	0.4380	0.0182
Vessel design & fabrication	**0.3668**	0.1460	0.7520	0.2480	0.0101
Inspection & certification	**0.4972**	0.1780	0.8220	0.1780	0.0056
Socio-economic influence.	**0.3296**	0.1180	0.7620	0.2380	0.0056
Monitoring and detection system failure	**0.1624**	0.0760	0.6120	0.3880	0.0085
Operator intervention failure	**0.1533**	0.0710	0.6120	0.3880	0.0086
Onboard safety equipment failure	**0.6667**	0.2500	0.8770	0.1230	0.0053
Maritime search and rescue (M-SAR) failure	**0.7073**	0.2900	0.8840	0.1160	0.0098

Table 5-9 Statistical calculation of uncertainty in expert judgment.

Median	0.0089
Variance (Var)	0.00003
Mean (µ)	0.0100
Standard deviation (SD)	0.02181
Co-variance (COV)	2.1832
Standard Error (σ)	0.00465

5.4.3. Sensitivity Analysis

In most cases, for a probabilistic risk assessment, it will be important to run a sensitivity analysis to show how the uncertainties influence our output results in the input data. The sensitivity results can help us evaluate the validity of our proposed model and to identify critical parameters related to the operational risk of a small fishing vessel. The impact of the changes in the data on the modeling results (Ugurlu et al., 2020; Obeng et al., 2022) can be observed through various approaches such as accuracy analysis and sensitivity analysis. The technique used for the sensitivity analysis in this study was the importance index (I_i) Which uses a global variance approach to rank root nodes according to the degree of impact on the vessel accident occurrence probability (Qian and Mahdi, 2020; Obeng et al., 2022).

To this end, diagnostics analyses of the model were performed by instantiating (100% evidence) the triggering events in turns and then observing the changes in the leaf node (SFV_ accident) probability values. Fig. 5.9 presents the sensitivity analysis results, which, as observed from the graph, shows that the risk model's output is very responsive to variables such as machinery failure, environmental factors, vessel factors, and unsafe operator actions. These parameters significantly changed the model output when evidence was applied to them.

The results show machinery failure, environmental factors, vessel factors, and unsafe operator actions as the most influencing factor of the accident occurrence. This analysis illustrates the importance index results, which measures the sensitivity of the major causal factor to their effect on the main accident.

This result means that to introduce a risk management strategy that is operational for a small fishing vessel, our scenario is reduced to a situation where we are operating a boat of fixed design with human operators that are changeable (and can be controlled). Lastly, operating conditions which keeps changing however cannot be controlled.

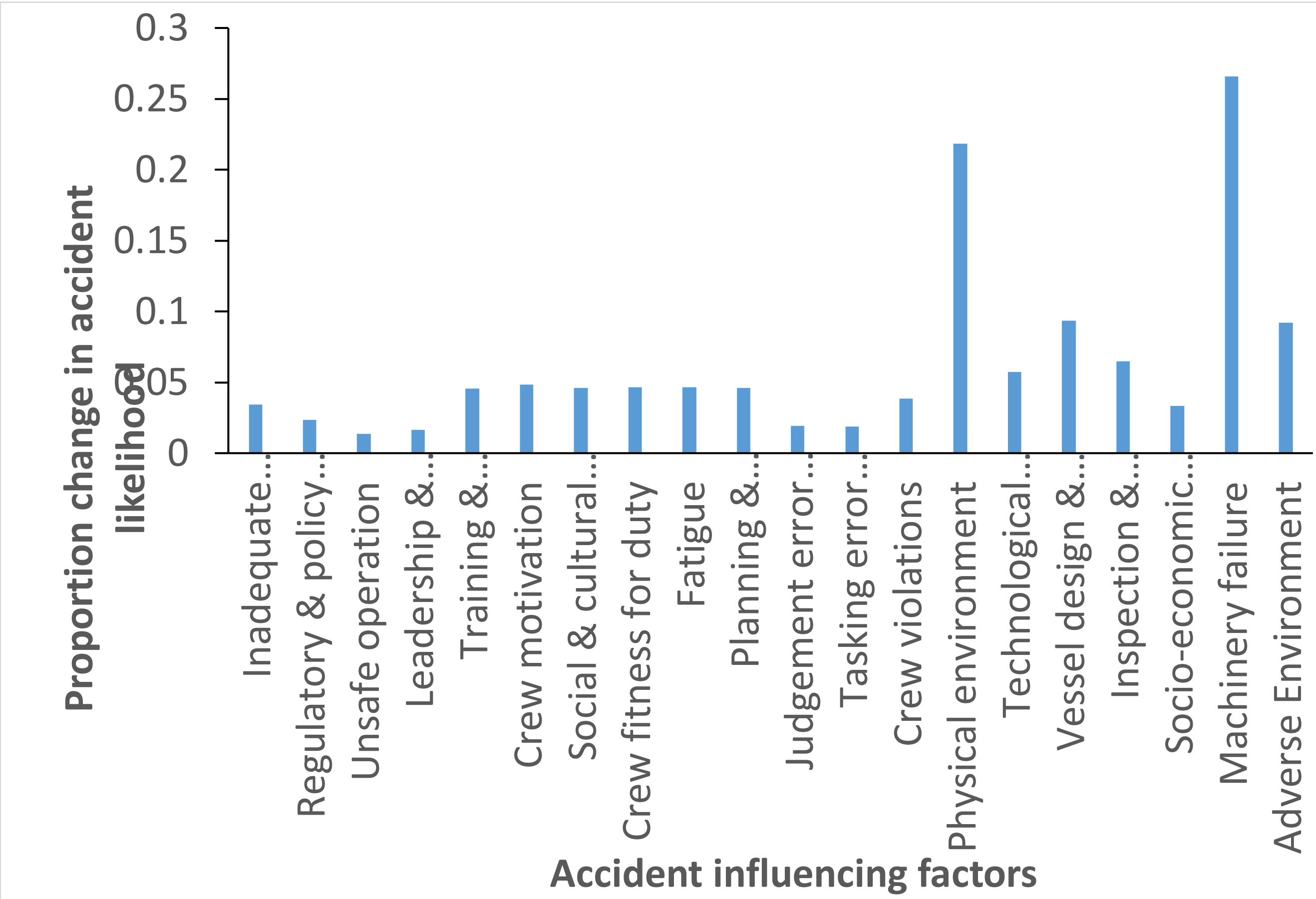

Figure 5.9 Results of sensitivity analysis showing the changes in the accident occurrence likelihood with evidence on events.

5.5. Conclusions and further works.

In this study, a hybrid approach integrating two powerful analysis tools was attempted to solve the problem of incomplete and non-existence of prior probability data for identified triggering events that cause accidents in small fishing vessels. The methodology uses evidence theory to analyze expert information to quantify the expert's judgment. The quantitative results, introduced as inputs for the Bayesian network has generated findings which could form the basis for decision-makers to recommend safety improvement measures for the operation of small fishing vessels. The following are key findings of the current study.

- The current model demonstrates the capability for quantitative human factor assessment in small fishing operations.
- Implementing methodology using a generic small fishing vessel model with calculated prior probability data from experts within the domain of the West African country of Ghana, yielded a 44% (0.44) likelihood of accident occurrence per fishing trip (with an uncertainty of 0.01 ± 0.009). This is an alarmingly high result, but as yet this has not been corroborated owing to the lack of existing records on such undesirable incidents.
- Further evaluation showed human factors to be a significant contributor to the main accident event, contributing (60%).
- The proposed risk model, along with expert opinion data, also help predict the most critical accident triggering factors through a sensitivity analysis.
- The overall results showed machinery failure, environmental factors, vessel factors, and unsafe operator actions as the most influencing factors of accident occurrence.
- The model offers a dynamic risk assessment tool for small fishing accidents considering data uncertainty.

Reducing the occurrence likelihood and/or the severity of the possible consequences of hazards can achieve risk reduction. Three main methods are found in the literature for risk reduction:

management, engineering, and operational (Kuo, 1998, Wang & Foinikis, 2001; Pilay &Wang, 2003). Now, with fixed boat designs and knowing how vessels operate under dynamic environmental conditions beyond our control, the human contributing factors become the focus of attention for possible risk-reducing measures to manage the risk. A detailed analysis of risk-reducing and control measures is beyond the scope of the current study.

In the future, further studies can explore possible risk control and mitigation measures along with their cost-benefit analysis, which could be a useful tool for decision and policymakers to improve fisheries' safety in the West African region.

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CHAPTER SIX

6. An Operational Risk Management Approach for Small Fishing Vessel

Preface

A version of this chapter has undergone internal review and has been submitted to Journal of Reliability Engineering and System Safety for publication. I am the primary author along with the Co-authors, Vindex Domeh, Faisal Khan, Neil Bose, and Elizabeth Sanli. I developed the conceptual framework, methodology and investigation and reviewed the literature along with implementing the model with a case study. I prepared the original draft of the manuscript and subsequently revised the manuscript based on the co-authors' and peer review feedback and comments. Co-author Faisal Khan helped in the concept development, method, formal analysis, of model, reviewing and revising the manuscript. Co-author Neil Bose helped in the methodology, formal analysis, of model, reviewing and revising the manuscript. Co-author Elizabeth Sanli helped in the formal analysis of model, reviewing, and revising the manuscript. Co-author Vindex Domeh helped in the concept development, methodology, reviewing and revising the manuscript.

Abstract

Small fishing vessel operations are prone to accidents causing loss of life and assets. Small fishing vessel safety can be ensured through simplified yet robust risk management strategies. The risk management strategies currently in use rely on local operational conditions and available resources as well identifying, assessing, and prioritizing risks in visualizable forms. Potential risks for a small fishing vessel operating in a harsh environment may include equipment failure, human error, weather-related risks, and administrative failure. This paper presents an approach to integrate evolving accident scenarios with risk control options—it models uncertainties in risk management strategies using the Bayesian network. The application of the integrated approach is demonstrated in the operational risk management of small fishing vessels operating in the West African region through a case study.

Keywords: Accident; Small fishing vessel; Risk management; Bayesian Network; Risk control factors; Uncertainty.

6.1. Introduction

Fishing is considered a dangerous activity. Commercial fishing ranks consistently as one of the most hazardous and dangerous occupations in the US (Drundi, 1998; USCG, 1999). According to data compiled by Bureau of labor statistics, commercial fishing industry workers rank as the second highest occupational death risk in 2018 (US department of labor, 2019). The fishing industry as estimated by the International Labor Organization (ILO) and the Food and Agricultural Organization (FAO) contributes to 7% all work-related fatalities (Mentes et al., 2016), although it makes up less than 1% the worldwide work force. Maritime accident reporting receives much attention in the developed world as compared to developing countries (Dominguez-Pery, et al., 2021).

Historically, it has always been difficult to safely operate small fishing boats for varied reason, including the heavy reliance on manual labor and the unique characteristics for every boat in terms of their physical appearance and handling characteristics accounts for this difficulty (Dasgupta, 2021). Adverse weather and sea conditions, and variable loading condition which adversely affect the stability of fishing boats. These changing loading conditions of a vessel stems from fish catching and storage, fuel consumption and the retrieval and storage of the fishing gear (TSB, 2018).

Furthermore, the literature also shows that danger is present throughout the various phases of a fishing operation, starting with and including, pre-trip loading; transiting to and from fishing grounds; fishing itself; and unloading catch and fishing gear. Sometimes, these identified dangers have led to accidents including, flooding, foundering, capsizing, collision, fire, material failure (NRC, 1991). Other occupational accidents also do occur on a fishing vessel, and may include falling overboard, and getting entangled in fishing gear to cause a fall into the water. However, these may be peculiar to commercial fishing vessels, which have large deck areas and therefore crew movement (Luca & Lincoln, 2007).

Quantitative risk assessment (QRAs) can provide an objective, and quantifiable analysis of the potential risk exposure to crew, vessel, and environmental impact (Brandsæter, 2002; Skogdalen & Vinnem, 2011; Mousavi, et al., 2017). It even becomes a very powerful tool when combined with the right guidance, as a detailed analysis can guide one through the unknown to allow for an informed decision-making process both at the individual and societal level. The QRA data can be presented in a manner that also allows us to identify sources that cause the greatest risk as well as the locations that present the greatest risk to personnel. This data can then be compared to existing benchmarks or, if applicable, governmental criteria. In addition, performance of sensitivity studies that quantify the level of risk reduction that can be achieved with potential risk mitigation strategies to support decision making and provide justification for investments (Harreld, et al., 1998; Pilay and Wang, 2003).

Formal safety assessment (FSA), is a quantitative risk assessment (QRA) methodology proposed in 2002 by the International Maritime Organization (IMO), has been the preferred approached for the evaluation of risk in the maritime domain (Pilay and Wang, 2003; MSC-MEPC.2-Circ.12-Rev.2, IMO 2018). The philosophy behind the FSA, is that, the methodology can be employed as a tool to enable decision making processes in maritime transportation, and also assisting in the prediction of potential hazards prior to serious accidents occurring.The FSA guidelines are used as a rational and systematic process for assessing the risks associated with shipping activities and also to evaluate the costs and benefits of risks reducing options for shipping (Loughran, et al., 2002; MSC-MEPC.2/Circ.12, LONDON, UK; 2013). The Formal Safety Analysis can be executed in five steps as follows: 1) Identification of hazards, 2) Assessment of the risks, 3) Risk control options or risk ranking, 4) Cost benefit assessment of the risk management, and 5) Recommendations for decision-making between options available (Wang, et al., 2005; MSC-MEPC.2-Circ.12-Rev.2, IMO 2018).

Risk can be defined in several ways, however in the context of the FSA guidelines, risk can be referred to as the combination of the frequency and the severity of the consequence. The frequency is obtained from the documented number of occurrences of an undesirable event expressed as events per unit of time. Whereas the consequences represent the unwanted events that can adversely affect subjects of interest such as humans, assets, and the environment. Distinguishing amongst key risk related disciplines like risk analysis, risk assessment and risk management, is important and has been explained by (IMO, 2013). Risk analysis is the systematic use of available information to identify hazards and to estimate the risk to individuals or populations, property or the environment; Risk assessment is to review the acceptability of risk that has been analyzed and evaluated based on the comparison with standards or criteria that define the risk tolerability; Risk management is the application of risk assessment with the intention to inform the decision making process with the appropriate risk reduction measures and their possible implementation. Risk management can also be described as a continuous process of identifying and analyzing potential hazards of a system/process/operation; and to identify and propose risk control measures to eliminate or reduce the impact on people, environment, and/or other assets (Terje Aven, 2016).

Several studies have used the FSA method to assess maritime risk, see (Jin et al., 2001; Wang et al., 2005; Peters, 2019; Ugurlu et al., 2020; Obeng et al., 2022a). Risk assessment studies on SFV have being undertaken in the recent past (Obeng et al., 2022a; Domeh et al, 2021; Ugurlu et al., 2020). Analyzing the operational risk of SFVs, based on a case study in the Atlantic Canada region of NL and NS, human factor accident model for SFV was proposed (Obeng et al., 2022b). A simulation of the proposed model with secondary data from the case region showed the method to be robust and viable in predicting accident occurrence scenarios for the operation of these vessels.

Another recent study (Obeng et al., n.b), has identified the critical risk factors after analyzing the method (SFV_HFA) with expert data for the case in Ghana of West Africa, and found these to be machinery failure, adverse environmental factor, vessel factors, and operator unsafe actions. In concluding, the authors suggested three approaches that are prevalent in the literature for control and reducing the risk in the context of engineering (i.e., engineering, management, and operational strategies). Additionally, note is made of the fact that, since under normal circumstance, SFVs have fixed designs and analysts have no control over the varying environmental factors, the focus of risk reduction and control measures will usually be on the human factors.

Controlling and reducing the risk (i.e., uncertainty), requires that we first identify the critical risk influencing factors and the accident critical events. In most cases, this process is undertaken through performing a sensitivity analysis on the model and data. In Obeng et al. (2022a), SFV capsize was studied to develop and analyze the risk assessment methodology for small vessels, which adopted a systematic approach following the IMO's formal safety assessment (FSA) approach using the fault tree (FT) analysis and Bayesian network (BN) analysis tools. The results from sensitivity analysis showed that critical risk influencing factors to be predominantly human-related faults and actions, (i.e., inadequate training, insufficient experience, and sea-chest non-closure). In concluding the studies, proposals for safety barriers were recommended, which are in turn further categorized into personal protective equipment (i.e., PPE), engineering and administrative controls. Also key in the study conclusion was the preference for engineering and administrative controls over PPE, which becomes the last resort when the other two controls are not applicable, or they are unsuccessful.

Human factor accident models for SFVs, have been developed using first principles (i.e., history of incidents and suggested causes) and implemented to analyze the operational risk of fishing vessel while using data obtained from literature for Newfoundland and Nova Scotia (Obeng et al., 2022b). Also, for this study, critical risk factors were identified based on sensitivity analysis as, unsafe operator actions, environmental factors, management factors and vessel factors. Risk reducing and mitigation measures targeting operator and organizational factors are recommended (e.g., training of crew in basic safety and stability, develop rules regulating SFV operation, enforcement or compliance, licensing, and inspection, setting load limits for SFV, etc.).

In the latest edition of their book, Rausand and Haugen (2020) identify, three main principles that underline risk reduction approaches; i) prevent an initiating event from occurring, ii) reduce the probability of an initiating event, and iii) reduce the consequence of the initiating event when it occurs. The decision-maker will ultimately choose to implement risk reduction measure proposed by an analyst. The selection is normally based on key criteria measuring effects on control measure by scope, reliability and availability, robustness of controls, and duration they remain effective. Other factors seek to measure the effect controls have on the risk, and any adverse effects of the control measure and the cost implications for implementing the measure.

Sometimes safety barriers can be viewed as a risk control option for the engineering system/operation under study. A safety barrier is defined in the literature as a physical and/or non-physical measure that is applied to a system to prevent, control, or mitigate an undesired event or accident (Sklet, 2006b; Rausand and Haugen, 2020).

The aim of the present study is to develop a logical and novel approach for identifying, analyzing, and evaluating risk reduction and control for small fishing vessel (SFV) operations. The study aim is achieved through the following specific objectives:

1. To review and identify various control and mitigation measures for maritime risk.
2. To develop a framework to analyze risk control measures applicable at different phases of the accident evolution in SFV operations.
3. To evaluate effectiveness of risk control measures on the overall safety of SFV operation and their cost implications.

Implementing a probabilistic modeling approach will best help achieve these objectives since a single statistical estimate of the current probability of an accident will be inadequate to truly express the risk. The probabilistic risk assessment (PRA) was initially developed for the nuclear industry for analyzing and predicting the risk of accident due to the hazards associated with their operations (Kwag and Gupta, 2017; Misra and Weber, 1990). At the start of the analysis, a pre-defined risk acceptance level of risk needs to be established. If this limit of accepted risk is exceeded during the assessment, then other approaches such as brainstorming by stakeholders, the elicitation of expert judgement and sometime, a written guidelines may be adopted to introduce risk reducing measures that can bring the risk to acceptable levels. The next phase is the consideration of appropriate measures that can help to control and or minimize the risk which can be done through subjective judgement and supported by techniques such as cost-benefit analysis, risk effectiveness and decision analysis.

The impact of any implemented control strategy can then be monitored and measured over time and revised or adjusted if deemed necessary. By continuously updating control measure, risk management has been classified as a cyclical or dynamic process (ISO, 2009; Haapasaari et al., 2015). The practice of safety culture, a reference to an organizational atmosphere in which safety is understood and accepted as a number one priority is an important control measure (Reason, 1998; Clarke, 2000; Cox and Cheyne, 2000).

6.2. The Research Methodology

In this study, Bayesian networks (BN) were used to model the complexities and synthesized information from varied sources to perform an integrated analysis. The GeNIe Modeler software also based on the BNs was used in this regard to perform the modeling and simulation tasks. The BN method is discussed extensively by the authors (Obeng et al., 2022a; Obeng et al., 2022b). BN methodology has also previously been applied in studies on causal factors of fishing vessel accidents (Kose et.al., 1998; Ugurlu et al., 2020; Domeh et al., 2021; Obeng et al., 2022). However, utilizing the BN method to analyze the effect of risk control options on the frequency and consequence of fishing vessels is missing in the literature.

Traditionally, managing accident occurrence frequency and the impact of accidents in the fishing industry will include solutions that are framed to address the socio-technical nature of the problem. Undertaking a risk management project will usually include the following stages,

1. Data and information gathering
2. Analysis of the data and information for use as input for risk assessment (RA)
3. Develop risk models and simulate with input data to run the model and generate results.
4. Risk profiling of the current system (baseline risk) and evaluating the proposed risk reducing measures. Additionally, the performance of quantitative risk assessment requires use of tools such as fault tree (FT), event tree (ET), Bayesian network (BN), bowtie, etc., to analyze a system or process (Kanes et al., 2017; Yazdi and Kabir, 2017; Khakzad et al., 2012).

The factors influencing fishing safety are to be captured when developing safety policy for fishery management. Considerations are given to key factors such as economic and social environment, safety regulations and compliance, high cost of investment in safety equipment, risk perception of fishers, and adoption of safety checklist (TSB, Watchlist 2020). Fig. 6.1 shows the steps involved in the proposed methodology for analyzing the risk reduction and control measures used to manage accidents for a small fishing vessel's operation.

The current study methodology starts with the collection of information from the literature and reports on existing risk reduction and mitigating measures (RRM) and safety barriers (SB) of the operation/system. Next in the methodology, the identified risk reduction and mitigating measures are then grouped by their function and also by performance, thereby understanding their influence on the accident evolution phases. The next step is identification of risk control measures in place for our baseline case (i.e., minimum safeguard/maximum safeguard cases). Finally, an evaluation plan to measure the effect of control strategy, including associated cost can be developed.

The systematic stages of the proposed methodology are explained in the following sections, which further elaborate on the four (4) main steps that captures the dynamic interactions amongst key parameters for risk management.

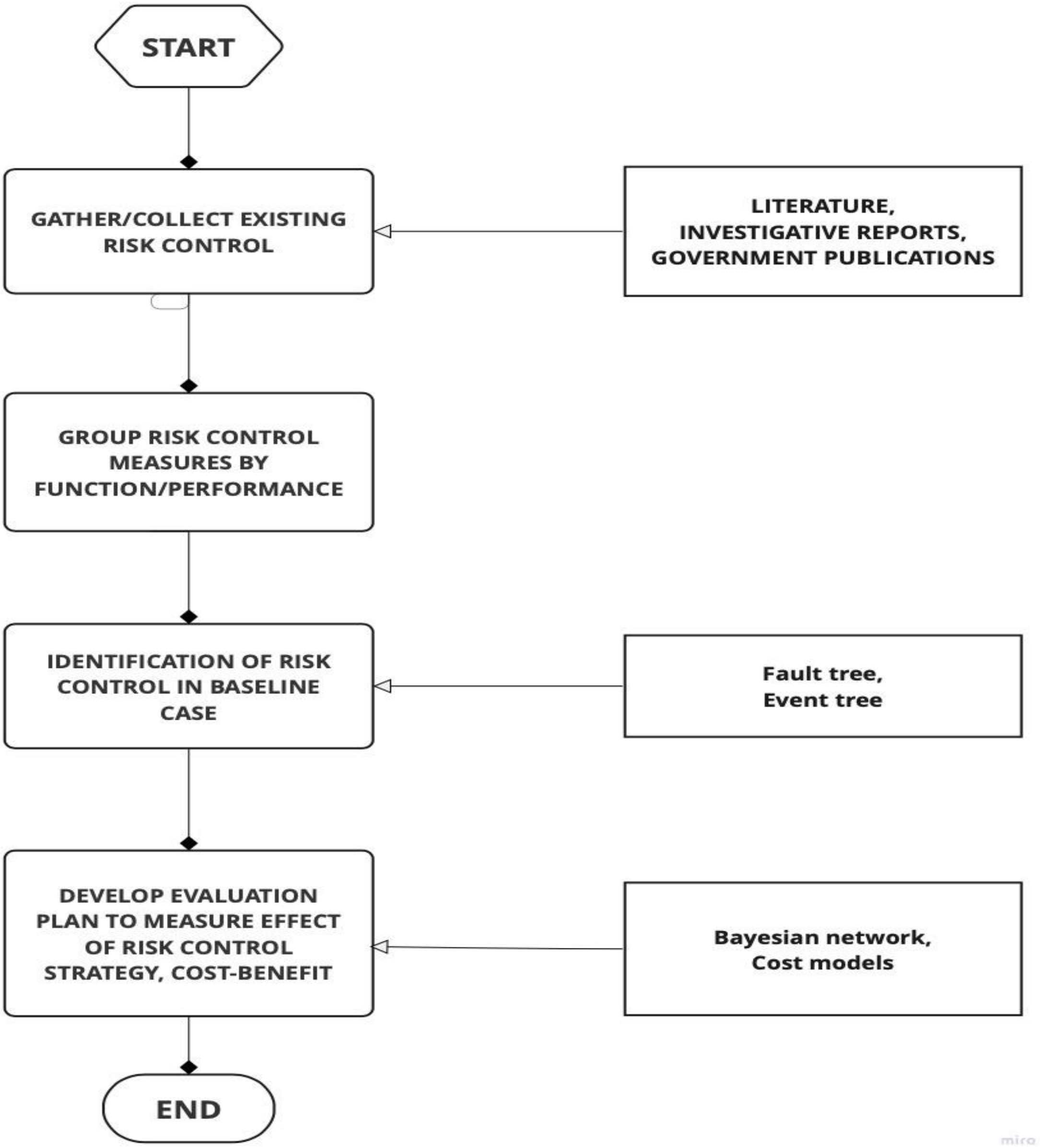

Figure 6.1 The proposed research methodology.

Step 1- The proposed methodology begins with the gathering of data and information on existing risk control measures through a review of literature, accident investigation reports, governmental agency publication on fishery safety, and from subject-matter experts. Risk control in this study has been defined as measures put in place to reduce and prevent harm due to risk of a hazardous incident. As a standard practice, a risk analyst must check the adequacy of existing controls during the risk assessment process before introducing any additional control measure. This first step is a necessary one since it helps us define the input parameters for the model. Table 6.1 shows an example of the outcome of performing this task.

The control measures are generally simplified into five (5) tier system or hierarchy namely, elimination, substitution, engineering, administrative or management, and personal protective equipment (PPE). A typical control measure will consist of a single or mixture of these options. In general, when ranking in the order of importance and effectiveness, elimination should be the best control measure choice, however, it is practically impossible in most real-world situation (i.e., meaning for example no work to be done). The closest we can get in practice is to eliminate those risk may be deemed unnecessary. The classification of risk control and their definitions are presented in table 6.2 (NRC, 1991; MAIB, 2006; Rausand and Haugen, 2020; Obeng et al., 2022a).

Step 2- Grouping risk control/reduction measures identified in step one, by their function and performance. This is done through the creation of functional decomposition of the measures, based on their implementation objectives and then converted to a form that is consistent with our defined modeling parameters. In this regard, the intended effects of the risk reduction measures on the system under study was identified during this phase, based on the causal chain concept proposed for assessing maritime risk by Harrald, (1995), Fig. 6.2 shows risk control addressing the different phases of the fishing vessel accident evolution. Table 6.2 contains list of the grouping and classification of risk reduction measures.

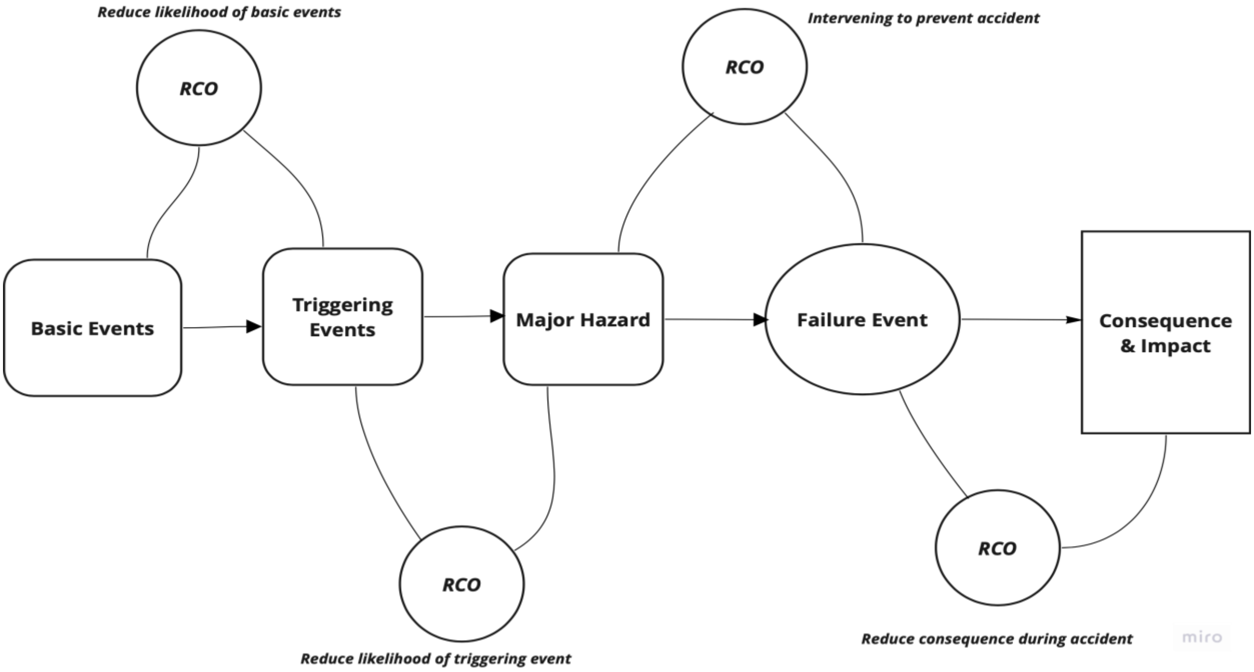

Figure 6.2. A schematic of the conceptual risk model illustrating controls at the different phases of fishing vessel accident evolution.

From the Fig. 6.2, as illustrated by the sequence of the accident occurrence, initiation of the accident follows from the onset of basic failure events which propagates into intermediate events and ending into a main accident failure (failure event).

Table 6-1 Examples of risk controls and mitigation measure in implementation.

Literature			**Expert opinion**	**Proposed risk control**
MAIB, 2006	NRC, 1991	Obeng et al., 2022	Summary	
1. Conduct risk assessment	1.Improvement of vessel fitness for service	1. Training in basic safety and stability	1. Need for regulation, certification, licensing, inspection, enforcement for operating SFV	1. Introduce standards in the design of vessels
2. Develop and implement code of practice	2. Standardized minimum vessel designs, structure, and stability	2. Develop rules and regulation	2. Recommends standardized designs for SFV industry	2. Stability requirement and testing

3. Survey and inspection	3. Onboard safety equipment requirement	3. Enforcement and compliance of regulations, licensing, and inspection	3.Fishery personnel training and certification	3. Load line limits and prudent seamanship
4. Stability	4. Improvement of human-machine interaction	4. Setting requirement for load limits	4. Safety culture and documenting of incidents	4. Improve structural design and integrity
5. Safe working environment	5. Improvement of vessel safety performance and accountability		5. Develop Search and rescue process for SFV	5. Install outfitting such as pumps and level alarms to prevent flooding and sinking
6. Use of lifesaving equipment/appliances	6. Development of load lines for vessel		6. Regular and planned maintenance	6. Development of safety regulations and standard operating procedures
7. Safety culture	7. Vessel licensing, inspection, certification and compliance		7. Introducing load lines to prevent overloading	7. Practice of safety culture by fisherpeople
8. Training	8. Establish risk communication and safety awareness programs		8. Ensuring timely accessibility to weather warning to fishermen.	8. Vessel licensing, certification, inspection and enforcing compliance
9. Marine insurance	9. Publication and distribution of safety pamphlets		9. Use of PPE to reduce the harm of a hazard	9. Promotion of education and training
	10. Requirement of emergency preparedness			10. Establish a safety awareness program and distribute safety publication materials
	11. Development and enforcement of standard operating procedures			11. Mandatory onboard safety equipment (e.g., float free EPIRBs, Personal locator beacons on each PSD) and

				requirement to always wear them
	12. Promotion of education and training			12. Search and rescue process, and emergency preparedness
	13.Requirement of education and training with certification			

Table 6-2 Control measure classification and their definition adopted for the research studies. Adopted from health and safety authority, HSA (2023) and work safe BC, (2023).

Tag	**Risk Control Measure classification**	**Definition**
1	Elimination	Control measure that can remove a hazard by abandoning an activity or carrying it out in a different way. Normally applied when the risk is too high to ignore.
2	Substitution	Control measure that can be applied to reduce risk by using a safer alternative. However, this can sometimes lead to an introduction of another hazard, which needs to be checked first.
3	Engineering/ technical	Measures that control through modifying design, and it is often employed to keep hazards away from causing harm.
4	Administrative/ management	These are safer systems of work, monitoring and supervision, planning and communication, rules and enforcement, training, and education, employed to reduce incidents and accidents
5	Personal protective equipment, PPE	PPEs are seen as the last resort to safety but also important. They are needed to be always worn properly during operations. They help to reduce residual risk of harm in a system.

Step 3- The baseline case risk control measures are synonymous to safety barriers that are already in place in the system. These measures can be identified using documentation on the operating system, regulations, and laws. Best practices and procedures known to the industry can also be relied upon. With this background information a minimum safe-guard case can be establish for the risk analysis (Harald et al., 1998). The identified baseline controls for the small fishing vessel control and specifically the system of interest is monitoring and detection system, operator intervention, onboard safety equipment, and maritime search and rescue (Obeng et al., 2022b; Obeng et al., n.b). Additionally, a determination of how we could represent the effect of each kind of risk reduction measure in our analysis model must be established.

Step 4- The last step in the method is the development of an evaluation plan to measure the effect of risk control strategies. To this end a comprehensive probabilistic model was developed to allow potential risk interventions to be evaluated. The proposed model, had to incorporate the effect of major contributors to the risk. Using the Bayesian reasoning approach, a BN model was constructed to analyze the effect on the accident top event when the risk control options are introduced and the associated financial cost-benefit of their impact.

The probability of the accident depends on organizational and vessel attributes of a fishing vessel and the situational or waterway attributes that also describe its environment. The vessel characteristics included its size, age, materials, and hull type. Crew characteristics (e.g., experience, training, and knowledge of stability), coupled with situational factors including location and type of nearby vessels, wind speed and direction, visibility, and obstacle are considered. A set of vessel and waterway attributes defines a chance for incident (CFI), which was then used in the Baye's theorem. The accident model used for the current study, was based on the notion of conditional probability. The Bayesian network (BN) configuration can be presented either qualitatively or quantitatively (Sidum et al., 2020).

Given a set of random operating variables, U= $\{X1, \ldots\ldots, n\}$, the chain rule and the joint probability distribution P(U) of the variables based on conditional independence can be mathematically modeled using Eq. (6.1), (Simsekler & Qazi, 2022; Obeng et al., 2022a).

$$P(U) = \prod_{i}^{n} P\big(Xi \big| Pa(Xi)\big) \qquad (6.1)$$

where P(U) is the joint probability distribution of the variables, and Pa(Xi) is the parent of variable Xi.

The probability Xi, can be estimated by the following equation.

$$P(Xi) = \sum_{U \setminus Xi} P(U) \qquad (6.2)$$

Where the summation is taken for all the variables excluding Xi.

Additionally, when evidence of incident/accident becomes available, the BN structure updates the prior probability of events using Bayes' theorem to produce the consequence probability known as the posterior. This process is illustrated mathematically by equation (6.3).

$$P(U|E) = \frac{P(U,E)}{P(E)} \qquad (6.3)$$

where, P(U|E) = conditional probability (probability of event U happening given that event E has happened; P (U, E) = joint probability (probability of events A and E happening together); and P(E) = total probability (probability of all possible outcomes of event E).

For the current study, the levels of conditional probability in the accident model were as follows:

• P(CFI): the probability that a particular set of vessel and waterway attributes occur in the system,

• P(incident/CFI): the probability that a triggering incident occurs given the chance, and

• P (accident/incident, waterway): the probability that an accident occurs given that a triggering incident has occurred.

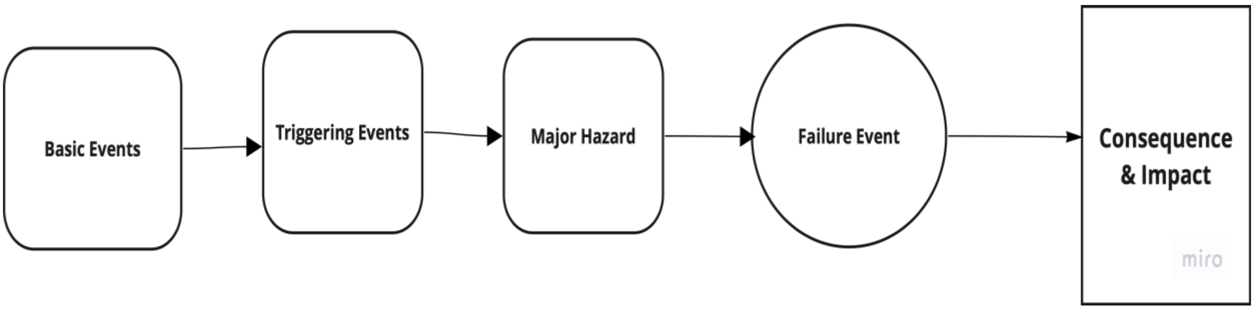

Figure 6.6.3. Illustration of the schematic framework of fishing operation risk assessment.

Figure 6.3 shows the schematic diagram of how conditional probability approach is applied to a generic fishing vessel, and illustrates the accident caused by vessel failures, environmental and human factors. The causal factors escalate from a group of basic events which develop into accident triggering factors that can lead to major incidents. At that stage if we mitigate then a near-miss event occurs otherwise we end up with a major failure event (i.e., accident). The flow of the sequence of events leading to the accidental event is depicted by the direction of the arrow heads in fig. 6.2. In the illustration a case scenario is presented for a small fishing vessel (SFV), with given vessel attributes, which has gone out on the waterways fishing for almost six (6) hours. In such an instant there is a chance that the SFV will experience one kind of failure. Once the failure has occurred, there is a likelihood that the vessel cannot be saved and cannot perform a self-correcting action and so this results in an accident happening. This accident occurrence probability depends, for example, on the waterway attributes of the CFI, wind speed, and current. The probability of an accident can be found by summing the product of the conditional probabilities over all types of accidents and triggering incidents and all combinations of vessel and waterway attributes. Thus, to perform an assessment of the risk of an accident with this model, one must estimate each of the terms in the probability model.

The best risk control option (RCO) for the estimated risks of the generic small fishing vessel can be identified by estimating the cost and evaluating benefit of each RCO with respect to all the stakeholders' concern in the industry. Each RCO can then be represented by a Cost per Unit Risk Reduction (CURR). The CURR is given by Pillay and Wang (2003):

$$CURR = \frac{Cost - Benefit}{Risk\ reduction} \tag{6.4}$$

where the risk reduction is given in terms of the number of injuries. For simple application of this equation, it can be considered that 50 minor injuries equal 10 serious injuries equal 1 life. Property damage/loss and the pollution of the environment can also be converted to the equivalent number of injuries. Each of the RCO's needs to be evaluated in accordance with the costs for its implementation and maintenance through the fishing vessel's lifetime, as well as the benefits received for the same period.

Studies conducted in the past such as (IMO (1997), MCA (1998), MSC (1998b), Wang (2001)) recommends that, the RCO evaluation to be carried out at two levels. Evaluating primarily for the overall situation and then for each of the affected stakeholders. The cost and benefit for each RCO must be calculated in terms of its Net Present Value (NPV). The risk reduction is the difference between the risk level of the given event in the base case and the risk level of the given event following the adoption of the RCO. A negative CURR will suggests that implementation would be financially beneficial (cost-effective). All that is left now, is to rank the RCOs using their CURR values and to recommend the most appropriate RCO for an accident category. The risk control options (RCOs), presented in table 6.3 for this study has been defined to capture a group of mitigating and reducing measures that addresses the engineering (technical), administrative (management), and operational (PPE) characteristics of the evaluated risk.

6.3. Application of the Methodology: Case study

This section demonstrates the implementation of the proposed methodology to determine possible best-case scenario RCOs selection for a generic small fishing vessel. As generally observed from the literature, fishery safety challenges are as result of complex interaction amongst key factors such as: vessels (e.g., design, fabrication, outfitting); fishers (e.g., crew competency and behavior); organizational factors (e.g., fisheries management, and economics), and environment (e.g., weather and sea conditions). Also, the consequence of fishery accident could result in damage or total loss of vessel, injuries, and loss of life. We can however prevent an accident through various actions such as, behavioral change of fishermen, vessel design modifications and through engineering and technical solutions. Most individual control strategies may target singular or multiple risk factors; however, a comprehensive control program must encompass all the factors as a total system. Sometimes safety options that may appear to be attractive and affordable when viewed as a stand-alone may offer only partial solutions. The option may also move resources away from other options and can sometimes yield unintended side effects (NRC, 1991; Bannerman, 2008).

To perform cost-benefit analysis for proposed risk management strategies involves comparing the costs of implementing the strategies with the benefits one can gain from reduced risks and an improved safety. Below are outlined steps used to perform the cost-benefit analysis:

1. Identifying the costs associated with implementing the risk management strategies. Which in this case included costs for equipment, training, inspections, maintenance, and other related expenses.
2. Quantifying the benefits gained from reduced risks and improved safety. Consideration is given to reduced costs associated with accidents, injuries, and equipment failures, as well as the improvement of crew morale and retention.
3. Estimating the timeline for implementing the risk management strategies and their associated costs and benefits over time.
4. Calculating the net present value (NPV) of the costs and benefits over the implementation timeline.
5. Comparing the NPV of the costs with the NPV of the benefits to determine whether the risk management strategies are cost-effective. Strategies are considered cost-effective if the NPV of the benefits is greater than the NPV of the costs.
6. Conducting sensitivity analysis to assess the impact of the different assumptions and scenarios on the cost-benefit analysis, which help identify areas where additional risk management strategies may be required.

As data needed to quantify each RCO is difficult to obtain, hypothetical RCOs were considered to demonstrate the applicability of the proposed methodology for this research. To this end we have made assumption for the cost and benefit in financial terms for the RCOs. Focusing on commercial fishing, Wang, and Pillay (2003), estimated cost of RCO options ranged between $15000-$35000 with an accompanied benefit range between $20000-$45000 approximately determined for generic fishing vessel. The present study however focuses on small fishing vessels and will therefore be conservatively assume lower cost and benefits. The outcome of the CURR depends highly on the view of each stakeholder and therefore may dictates the results. To achieve meaningful improvement, each control alternative needs to be evaluated in the context of a specific problem, which will underscore the importance of understanding benefits and associated cost. Studies have also shown that treating safety as a total concept is also a way to distinguish between theoretically desirable goals and reasonable and achievable objectives in formulating a program of corrective action (NRC 1991).

In Fig. 6.4, the BN for the proposed risk control model for small fishing operation is presented. The network nodes represent the three broad components namely, accident causal factors, the risk control option that are introduced in the system to reduce accident occurrence and minimize impacts, and RCOs impact nodes. The analysis data for accident causal factors are adapted from Obeng et al., (2022) and Obeng et al., (n.b). For detailed description and definition of the risk factors, the reader may also refer to the mentioned publications. Table 6.3 presents a list of identified risk control options that were introduced to the system based on best practices and workable examples that have been previously implemented for closely related applications. Risk control option one (RCO1) consists of control measures that are technical in nature, and which tend to address engineering challenges within the system and operations. Control option two (RCO2), on the other hand comprise of the administrative (i.e., organizational or management) solutions and actions that can address human related failure and human error reduction. The final control option for the current study (RCO3) consist of a last line of action that should be resorted to either by the fishing crew (PPE) or by administrators (M-SAR). See (Polyzois, 2017; Ζενιός, 2016; Olanrewaju, 2013).

Table 6-3 A proposed list of specified risk control measures for the current study and associated sub-actions. The control options are based on the examination of the available measures from the existing literature and experts' opinion gathered.

Risk control option	***Control measure***
RCO1	-Introducing standards in the design of vessels -Stability requirement and testing -Load line limits and prudent seamanship -Improve structural design and integrity -Install outfitting such as pumps and level alarms to prevent flooding and sinking
RCO2	-Development of safety regulations and standard operating procedures -Practice of safety culture by fisher people. -Vessel licensing, certification, inspection and enforcing compliance -Promotion of education and training -Establish a safety awareness program and distribute safety publication materials
RCO3	-Mandatory onboard safety equipment and requirement to always wear them -Search and rescue process, and emergency preparedness

Table 6-4 Model parameters (risk factors and control measures) for SFV risk management analysis and their probabilities.

No	Parameter	Probability
1	Unsafe management/supervision	0.3900
2	Precursor for unsafe acts	0.4000
3	Errors	0.7400
4	Violations	0.4903
5	Physical (natural) environmental	0.4066
6	Technological (ergonomically) environment	0.1855
7	Vessel design & fabrication	0.3668
8	Inspection & certification	0.4972
9	Socio-economic influence.	0.3296
10	RCO1	0.2020
11	RCO2	0.1406
12	RCO3	0.1018

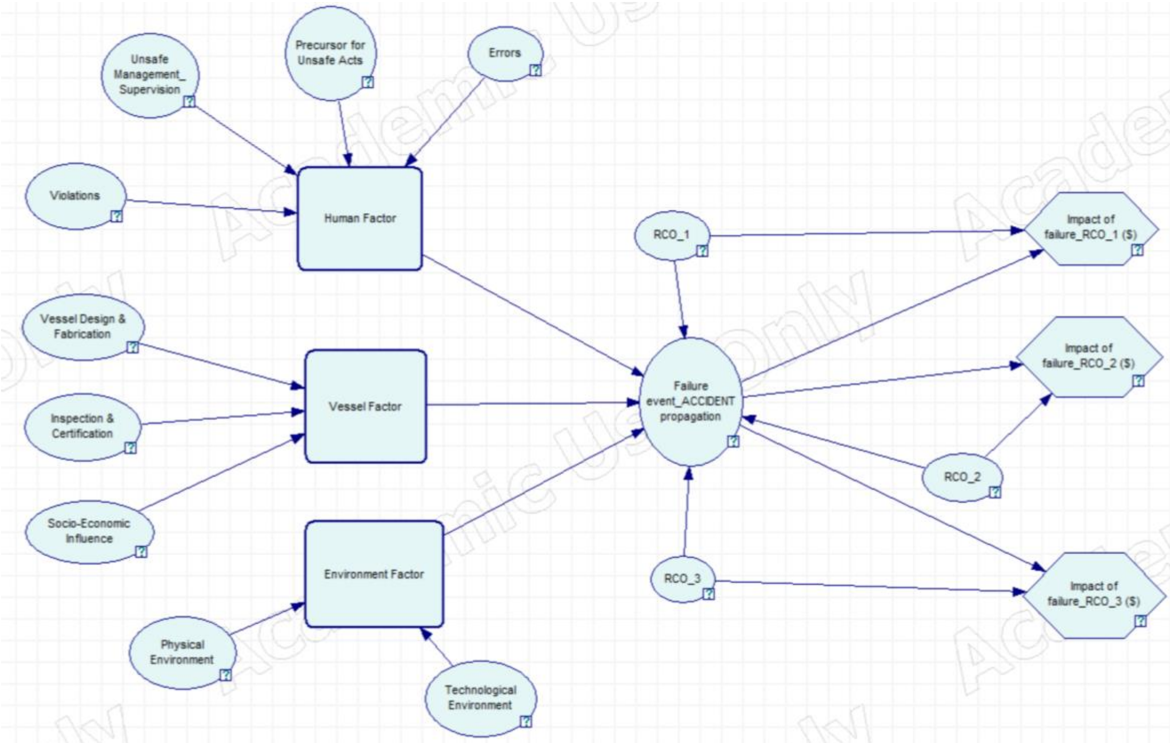

Figure 6.4. Bayesian network model of the risk management of fishing vessel operations.

6.4. Results and Discussions

The core objective of developing the BN model for an integrated accident-RCO relationship was to closely predict cost and benefits of different risk control measure options as risk management strategies for a socio-technical system like a small-scale fishery. By performing cost-benefit analysis for the proposed strategies, stakeholders in small fishing vessel operations can make informed decisions about which risk management strategies to implement and how to allocate resources to effectively manage risks while also being cost-effective. The BN was built through the connection of basic and intermediate events by arcs that represent the dependency and interdependency among accident contributing factors. The key parameters and their probabilities are given in Table 6.4, serving as input parameters, and are used to simulate the BN model. The parametric learning of resulting BN model uses the prior probabilities and conditional probabilities for contributing factors as input data to predict accident rate and RCOs effectiveness and cost-benefit. Fig. 6.5 presents the numerical simulation results for the developed BN model, that dynamically predicts the small fishing vessel accident rate and expected associated cost when the risk control measures are implemented at the model level rates.

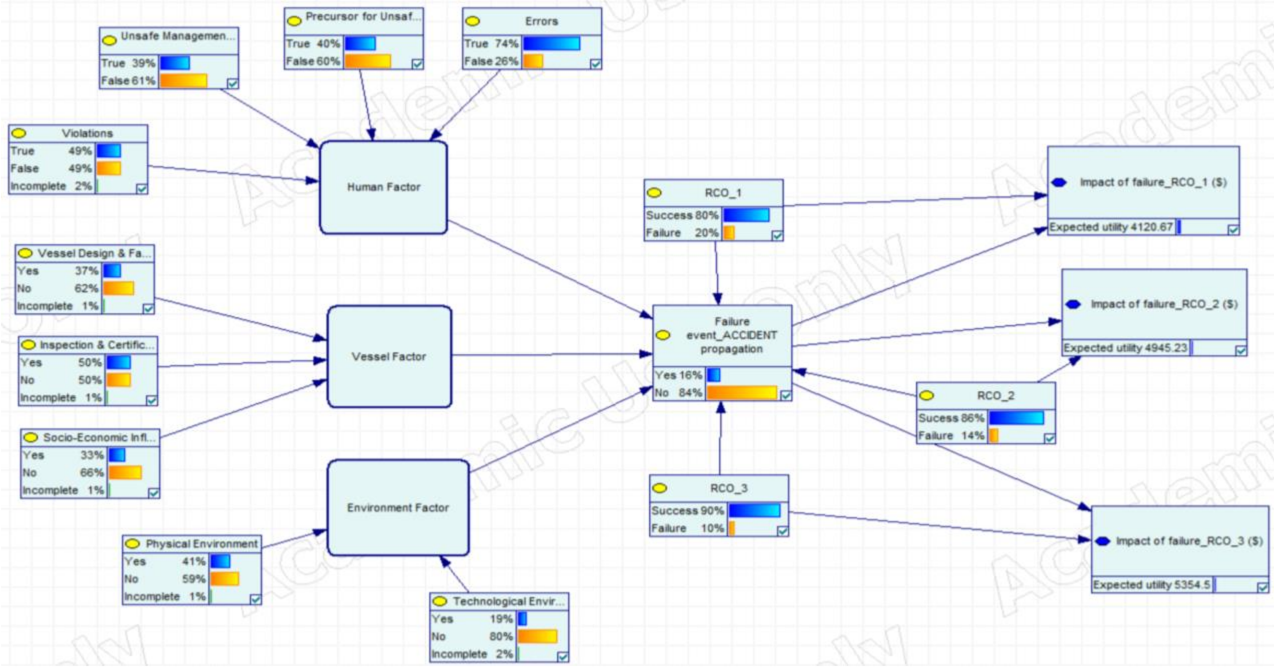

Figure 6.5 Numerical results of SFV risk management model's analysis.

Considering Fig. 6.5, we can observe that, the SFV accident occurrence probability after simulation is predict by the model as 0.16 (16 %), which closely agrees with a similar outcome from Obeng et al (n.b.). This probability was obtained while the introduced RCOs are observed to operate at rate levels of (RCO1- 80%), (RCO2- 86%), and (RCO3- 90%). A further analysis was performed by placing evidence on the three RCOs (100 %) through instantiation of the selected nodes, to measure changes in the accident occurrence probability. Additionally, from observing Fig. 6, shows a net reduction of 0.06 (i.e., 6%) in the accident occurrence rate which also gives an indication of the model's capacity to predict the level of effectiveness of the recommended RCOs. Hypothetically and subjectively, a 6% reduction rate of accident occurrence per year will be an improvement in the safety of operation for small fishing vessel.

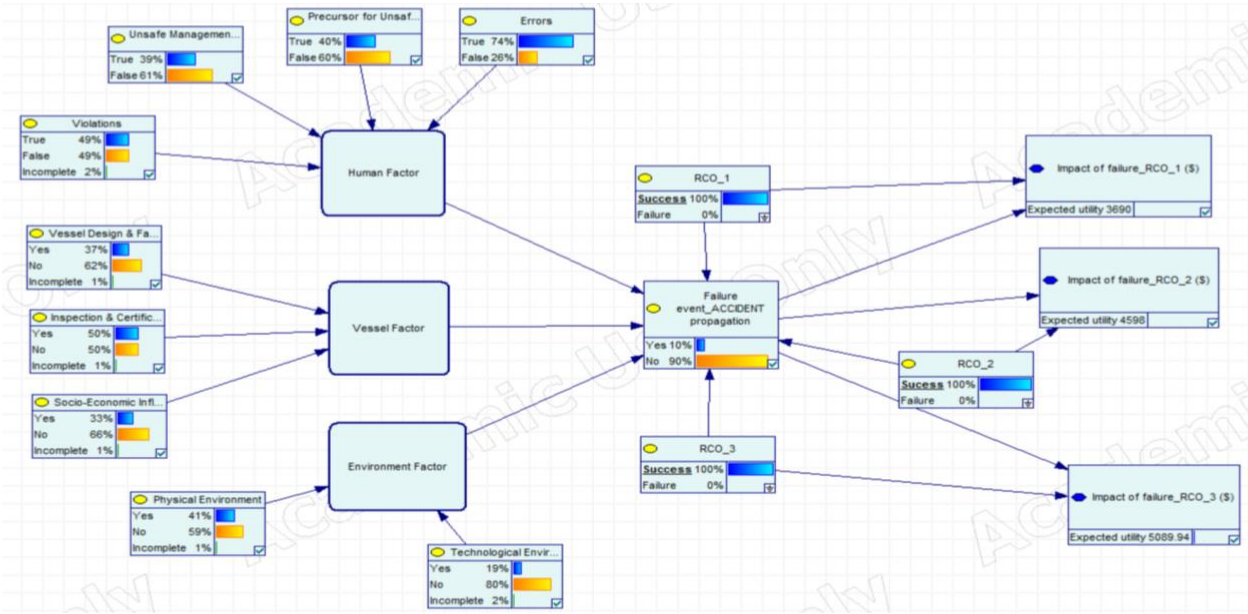

Figure 6.6 Numerical results of SFV risk management model's analysis when evidence is placed on RCO nodes.

Further results presented in Fig. 6.7 and Fig. 6.8 additionally illustrate two distinct scenarios: Results shown in Fig. 6.7 assumes that evidence of SFV accident occurrence existed, and each RCO is instantiated to 100% and then model simulated to observe the impact cost. Fig. 6.8 on the other hand shows results for a scenario whereby known evidence of accident occurrence for SFV exist, but the RCOs are either not available or exist but not implemented, and then model network simulated to determine the resulting impact cost. The result of these analyses is compared in Table 6.5 and used to evaluate the cost benefit of each RCO.

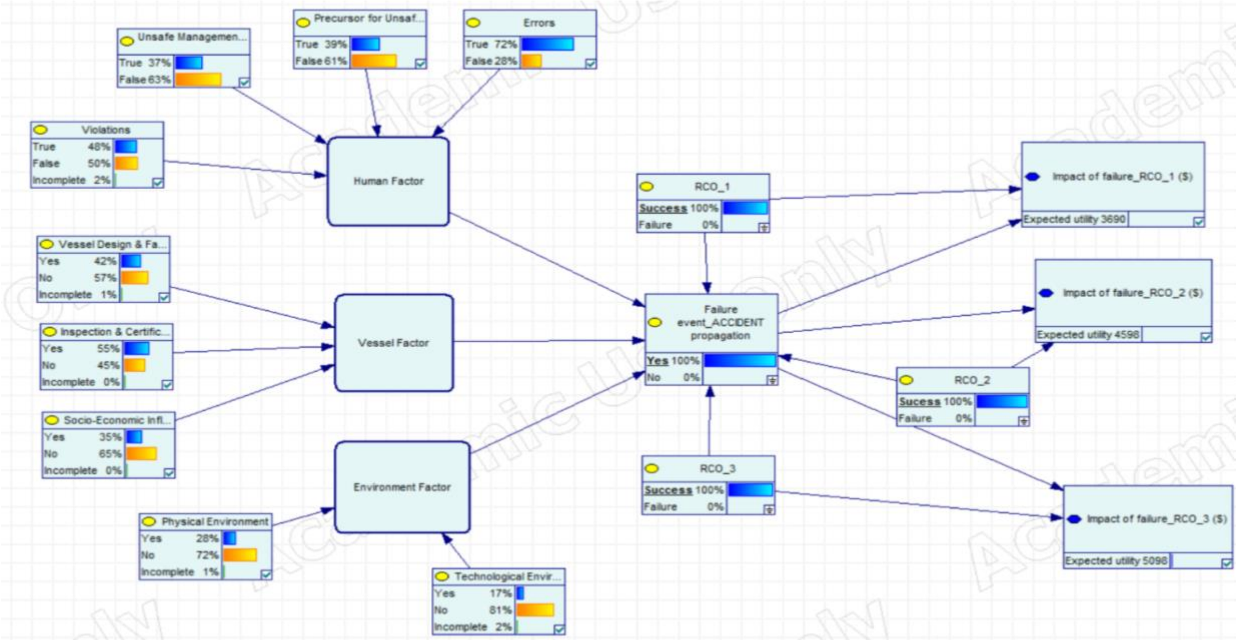

Figure 6.7 Numerical results of SFV risk management model simulation with instantiation of accident and RCO nodes.

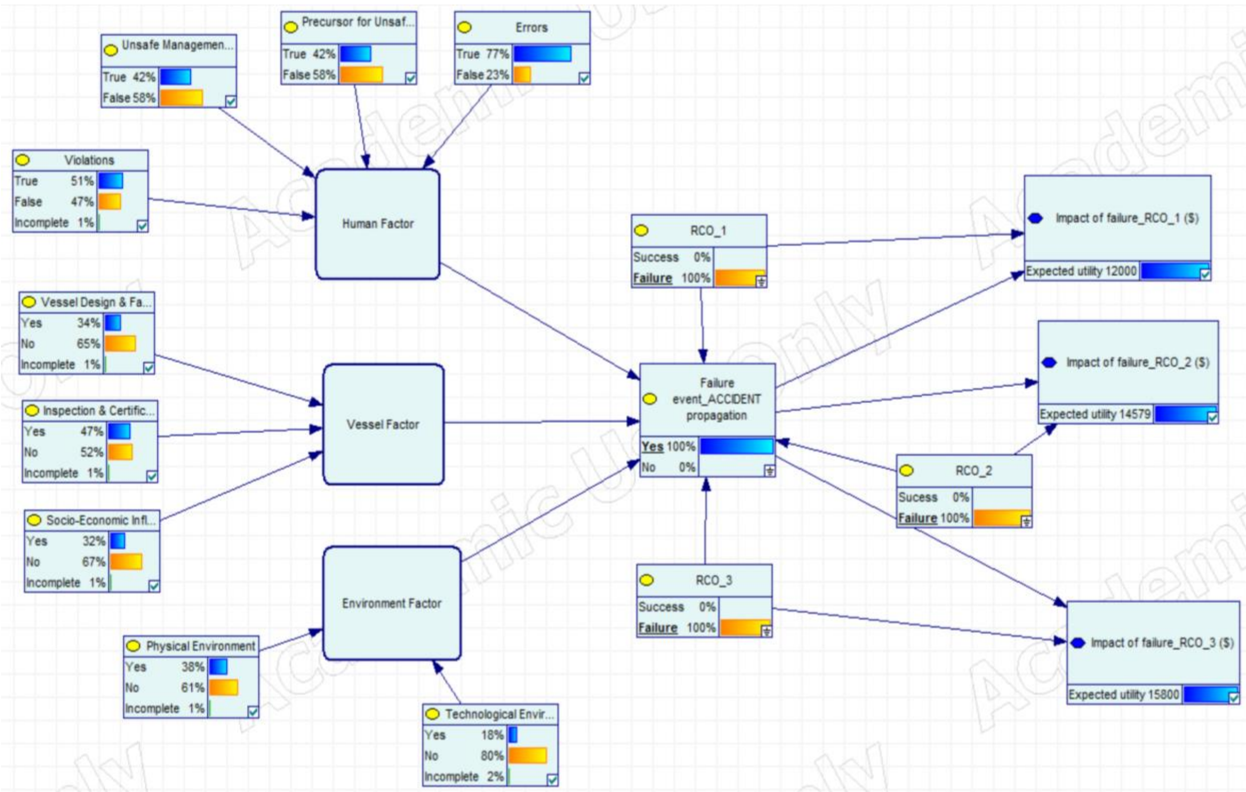

Figure 6.8 Numerical results of SFV risk management model simulation with instantiation of accident and RCO nodes.

Table 6-5 Numerical analysis result for risk controls cost and benefit evaluation.

	Risk control level				Cost-benefit estimate
Risk control option	No controls (B)	Controls fail	Working at 50% level	Working at 100% level (C)	C-B
RCO1	$8,310	$12,000	$4,120	$3,690	-($4,620)
RCO2	$9,981	$14,579	$4,945	$4,598	-($5,383)
RCO3	$10,711	$15,800	$5,354	$5,089	-($5,622)

B – benefit; C – cost.

Table 6.5 presents the results of computational analysis for risk controls costs and benefits evaluation, column 1 contain the different risk controls proposed for implementation. Column 2 shows cost to stakeholders if no controls are introduced in their operations, whereby the effective impact cost is the total of (RCO1+RCO2+RCO3). The results under column 3 meanwhile, reflects the cost to stakeholders/ operators of the specific controls introduced fails to work when needed in action. Columns 4 and 5 show results when the RCO's in the BN model are operating at the baseline and optimum levels. The last column presents the cost-benefit result, which was obtained from the difference of column 5 and column 2 data. Assuming a unity risk reduction (i.e., RR=1), we can estimate the CURR for each RCO for the study. If the result is a large negative CURR, this suggests that the strategy implementation would be financially beneficial. From the results obtained, it is determined that RCO 3 is the best option (from a cost-benefit point of view) and can be recommended for implementation. This outcome is consistent with expectations, since the nature of small fishing operation requires a combination of more oversight, use of personal protective equipment, and effective search and rescue, to be safe.

Fundamentally, to safely operate a fishing vessel demands one performs an assessment of safety issues, along with the monitoring of implemented safety programs that are in place to measure the effectiveness of those safety improvement strategies. However, any success to be gained relies on the availability of accurate historical and current data on vessels, fishers professional experience, hours and nature of exposure, and safety performance of personnel and equipment (TSB, 2012; Alli, 2008). Very limited data is regularly collected or published on these parameters. The practice of under-reporting incidents results in insufficient data on SFV accidents. This makes it difficult to quantify the risk level, determine causal relations, and assess safety improvement strategies for the industry. Meanwhile, the little available data in the literature indicate that significant safety problems exist and that major contributors are human error, vessel and equipment inadequacies, and adverse environmental conditions (Berg, 2013; Grech et al., 2008; Reason, 1995).

Assumptions of specific safety-improvement approaches to both vessel and human related causes of small fishing vessel (SFV) accidents and casualties were adapted in this research identified control measures form the literature and as constituted in table 6.3. The human behavior is factored in the way vessels were designed, fabricated, and maintained. In a study (NRC, 1991), recommendations are made that the persuasions of those at risk to voluntarily alter their behavior for increased self-protection could sometimes be the solution. Behavioral change may also be demanded through by-law or administrative rules. For an existing example, jurisdictions (such as, US and Canada) have requirements to carry personal flotation devices (PFDs). Additionally, the provision of self-activating emergency position-indicating radio beacons (EPIRBs), personal locator beacon on crew PSDs, automatic water level alarms, and automatic bilge pumps, on fishing vessels, can reduce the consequence and the impact of accidents (IMO, 2006; SAFETY, n.b).

As the evidence shows, education by itself has not proved to be an adequate preventative measure. The common way to motivate effective use of knowledge and skills from education and training is a license or certificate that attests to competency and is subject to review, suspension, or revocation. A tailor-made specialized training for interested individuals can substantially contribute to beneficial behavioral changes (see Tigchelaar et al., 2010; Pěchouček et al., 2007; NRC, 1991; McDowell Group, 1990; Boehmer, 1989). Also, note that enforcement and compliance could prove to be difficult because safety problems usually occur aboard vessels operating in isolation, away from even casual observation by law enforcement officials.

Like the critical role risk management plays in any business, stakeholders in small-scale fishery like government and fishers must be able to see the risk management process as an essential component of all small fishing vessel operations. By implementing risk management strategies, small fishing vessel operators can promote safety and mitigate the risks associated with fishing operations. For best practice (see Lind et al., 2012; Cooper et al., 2005), always develop your strategies for the high-priority risks that are identified to minimize the financial burden and to make a judicious use of resources. Additionally, by monitoring and regularly reviewing the risks, it can be ensured that the implemented mitigation strategies are effective and help identify any new risks that may arise.

Outlined below are recommended risk management strategies proposed for consideration for the operating small fishing vessel, and their adoption and usefulness is corroborated in the literature (Clothier and Walker, 2015; Sethi, 2010; Wang et al., 2004; Wang, 2002; Hudson, 2001; Rasmussen and Suedung, 2000):

- Development of a safety management system (SMS) by regulators: This is a comprehensive risk management program that identifies and manages the risks associated with fishing operations. It includes policies, procedures, and training programs that promote safety and mitigate risks.

- Conduct regular safety inspections and enforcement of regulations: Regularly inspecting vessels and equipment can help identify potential hazards and prevent accidents. The inspections must include checks of safety equipment, such as life jackets, fire extinguishers, emergency beacons, EPIRBs, and personal locator beacons.
- Conduct stability assessment: Performance of a preliminary stability assessment for SFV, using a simplified inclining experiment prior to issuing licences.
- Certify crew training and qualifications: Crew members should be encouraged to be trained in safety procedures, emergency response, and vessel stability and operation. Crew members should also have the appropriate qualifications for their roles, such as certifications in first aid and CPR.
- Access and communicate weather conditions: A small fishing vessel must be equipped with weather monitoring equipment and should have capabilities of receiving regular weather updates. If weather conditions are unsafe, fishing operations should be postponed until conditions improve, must be enforced.
- Development of emergency response plans by government agencies: Emergency response plans should be developed for different scenarios, such as man-overboard situations, vessel fires, and capsizing. Crew members should be trained on the emergency response plan and should conduct regular drills.
- There should be measures implemented to manage fatigue, since it can be a significant risk factor in fishing operations. Vessel operators can establish rest periods and limit the number of hours worked per day.
- Regular maintenance of vessels and equipment can prevent equipment failures and reduce the risk of accidents.

6.5. Conclusions

In this study, a quantitative analysis using the Bayesian network approach helps to model the risk management of small fishing vessel operation. The analysis tool integrates the accident causal factors with the risk control strategies and coupled with cost models help evaluate the cost-benefit of the control measures. The results of quantitative analysis obtained using prior probability data from earlier published primary and secondary sources, as inputs for the Bayesian network has generated findings which could form the basis for decision-makers to select safety improvement measures for the operation of small fishing vessels. The following are key findings of the current study.

- The current model demonstrates the capability for quantitative risk management in small fishing operations.
- Implementing methodology using a generic small fishing vessel model with known prior probability data from previous publications yielded a 16% (0.16) likelihood of accident occurrence per fishing trip. This result although significantly high, agrees with Obeng et al., (n.b).
- Further simulation is done by placing evidence on the three risk control options, RCOs (i.e., indicating all controls function, 100 % on nodes), to measure changes in the accident occurrence probability, and that resulted in a 6% drop in the risk level.
- The results on cost-benefit evaluation showed risk control option (RCO3) to be the measure with the most negative value and therefore considered the best control option that will be cost effective for implementation, (note: the more negative the CURR value the lower the cost of risk reduction, and the better that control option).

- The model offers a dynamic operational risk management tool for small fishing vessel accidents that takes into account data uncertainty.

By reducing the occurrence likelihood and/or the severity of the possible consequences of hazards can achieve risk reduction. To conduct a quantitative risk management analysis for a small fishing vessel, the first step is to identify and prioritize potential risks, such as weather-related risks, equipment failure, human error, and regulatory compliance. Next, gather relevant data on each identified risk, including historical environmental data, maintenance records, crew training records, accident and incident reports, and regulatory requirements. Apply quantitative methods to analyze the data and estimate the likelihood and potential impact of each risk. Afterwards, develop risk mitigation strategies based on the analysis, for example developing a maintenance schedule or providing additional crew training. Risk management should be seen as a cyclical process and therefore it should be continuously monitor and the risk management plan reviewed to ensure its effectiveness and to make necessary adjustments.

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CHAPTER SEVEN

7. Summary, Conclusions and Recommendations

7.1. Summary

The present study shows the use of quantitative risk analysis techniques in the development of a risk management approach for small fishing vessel operations. The benefits of the Bayesian network structure, and the fault tree analysis were tapped. The International Maritime Organization (IMO) has attempted to enact specific regulations with the input of member nations to govern operations of fishing activity due to high numbers of incident/ accident occurrences. The existing document address the challenging cases of fishing vessels with length-overall (LOA) above 12 m. The accepted approach for analyzing maritime risk is the formal safety analysis (FSA), however, analysts have usually found difficulty in implementing the methodology for small fishing vessels (LOA under 12 m) due to the inadequacy of applicable models and the problem of insufficient data on risk factors. A dynamic simple applicable but rigorous operational risk management approach is therefore proposed and developed to address the knowledge gaps and to aid in improving the safe operations of small fishing vessels.

This thesis presents a capsizing accident scenario developed as an example of developing a simple analysis tool for analyzing the chance of a small fishing vessel getting involved in an accident during operations. This probabilistic model presents the interdependencies of causal factors and their effects on the accidental event. A dynamic operational risk model was proposed to consider the effects of crew effectiveness for a small fishing vessel operation. This provides a useful operational risk analysis tool for safety management in small fishing vessel operations. The resulting thesis presented a novel generic human factor analysis model proposed for analyzing small fishing vessel operations. Coupled with the Bayesian network the methodology is tested with a case study focused on a small fishing boat operating in the Atlantic Canada region of Newfoundland and Nova Scotia. Also, a hybrid quantitative model for operational risk analysis of a small fishing vessel study is performed using field data. This model effectively uses expert judgement data on human factor contributions by combining multiple opinions to generate a single probability of events for quantitative analysis.

The systematic development of modeling and analysis techniques and testing models using both primary and secondary data sources are further consolidated to propose a robust and dynamic operational risk management approach for small fishing vessel. The results on cost-benefit evaluation help the decision-maker to select the best risk control option based on the lowest cost per unit risk reduction (CURR) value.

7.2. Support for research questions

Several research questions were identified in chapter 1 and have been addressed under the specific objectives of this study. These questions are revisited below using the results and the analysis of the research.

Question 1: Why small fishing vessel accidents occur and what are the causal factors?

This first research question concerns the understanding of the basis for small fishing vessel accidents and ways of identifying the causal factors of small fishing vessel accident. The question has specifically been addressed with objectives 1 and 3. Through a thorough review of existing literature, historic data, and accident and investigative reports, accident causal factors for small fishing vessels were identified. The modelling and analysis placed emphasis on critical risk influencing factors through the performance of sensitivity analysis. Human contributing factors due to operator’s unsafe actions, interactions with vessel design and fabrication, and factors associated with the operator’s environment are found to be the critical risk factors.

Specifically in objective 3, the utilization of direct field data through surveys, and interviews added a valuable contribution to the research. The study incorporated real-world perspectives and experiences to ensuring the relevance and applicability of the findings, by gathering information directly from fishermen, vessel operators, and crew members.

Question 2: How is a typical fishing vessel accident likely to happen and when will it happen?

The second research question was addressed under objectives 2 and 3 of the current study. The two objectives are related and aimed at developing a model capable of predicting how and when fishing accidents are likely to occur with emphasis on crew effectiveness. Also, utilizing direct field data through questionnaire surveys, and interviews added a valuable contribution to the research. Human contributing factors due to operator's unsafe actions, management inactions, factors related to vessel design and fabrication, and factors associated with the operator's environment are found to be the critical risk factors.

Question 3: Does the literature and data suggest that human and organizational factors have less impact on commercial fishing vessel accidents than the technical and environmental issues?

This question was addressed in objectives 1 and 4, which aimed at developing an approach to manage operational risk that considered the impact of technical and environmental factors, as well as human and organizational factors, and focused on identifying the most critical hazards to prevent accidents. Human and organizational contributing factors are determined significantly impact fishing vessel accident, are due to operator's unsafe actions, interactions with vessel design and fabrication, and factors associated with the operator's environment.

Question 4: What contribute to human error accidents and when are they likely to happen?

This research question has also been addressed by objective 3 of the study under which a hybrid model framework was developed, capable of utilizing both qualitative and quantitative data to identify fishing accident causal factors. This model also predicted when fishing accidents are likely to occur and identified the contribution of human error.

Question 5: How do we know which hazard(s) to focus on in terms of accident prevention?

The fifth research question was addresses under objective 4 of the study, through the development of an approach to manage operational risk that considers the impact of technical and environmental factors, as well as human and organizational factors, and focuses on identifying the most critical hazards to prevent accidents. This approach addresses both technical and human factors, recognizing their interconnectedness and the need for a holistic approach to accident prevention. The recommendations provided can guide the fishery industry in implementing effective safety measures and training programs.

By providing a rigorous yet simple-to-use operational risk management model, the study offers a valuable tool for analyzing and improving safety in small fishing vessel operations. The findings and recommendations have the potential to enhance safety practices, reduce accidents, and protect the lives and livelihoods of those involved in the industry.

7.3. Conclusions

Fishing vessel accidents, including capsizing, collision, and material failure, are indeed persistent issues in various countries, including Canada and Ghana.

In Canada, fishing is a significant industry, particularly in coastal regions. The country has a large fishing fleet that operates in diverse and sometimes challenging marine environments. Fishing vessel accidents, such as capsizing and collisions, have been a concern for safety authorities and the fishing industry. Several factors contribute to these accidents. Harsh weather conditions, including storms and rough seas, create hazardous situations for fishing vessels. Additionally, human error, equipment failure, and inadequate safety measures can also lead to accidents.

To address these challenges, the Canadian government and fishing industry stakeholders have implemented various measures. These include stricter safety regulations, improved training programs for fishermen, vessel inspections, and the promotion of safety awareness. The Canadian Coast Guard plays a crucial role in enforcing safety standards and responding to emergencies at sea.

In Ghana, fishing is a vital economic activity and a major source of livelihood for coastal communities. However, fishing vessel accidents, particularly capsizing and material failure, have been a significant concern in recent years. Several factors contribute to these accidents in Ghana. Overloading of vessels, lack of maintenance and repair, inadequate safety equipment, and poor training of fishermen are some of the contributing factors. Moreover, illegal, and unregulated fishing practices further exacerbate the risks.

The Ghanaian government has recognized the need to address fishing vessel accidents and has taken steps to improve safety. These efforts include the development and enforcement of regulations, promoting safety training programs, and enhancing surveillance and enforcement of fishing activities. Collaborative initiatives with international partners have also been established to improve safety standards and practices.

It is, however, worth noting that despite these efforts, fishing vessel accidents remain a complex challenge in both countries. A continued collaboration between government agencies, fishing industry stakeholders, and the international community is necessary to enhance safety measures, promote best practices, and reduce the occurrence of accidents at sea and inland waters. The current research study has attempted to systematically and methodically develop an innovative approach that has the potential to identify, assess, and manage the operational risks for small vessels. The novel approaches attempt to establish the complex link between the common causes of fishing vessel accident and operators' understanding and performance of tasks.

For objective one, a probabilistic methodology of object-oriented Bayesian network (OOBN), models capsizing accident scenario for small fishing vessel and identify the critical risk factors as inadequate training, and insufficient experience. Based on the critical factors, robust and practicable risk control measures were proposed for capsize prevention as follows: the training of more fishers in basic operational safety and stability; the use of experienced fishers on every voyage; and improving the integrity of vessels. The most practicable measure is that of training, and once fishermen receive basic safety and survival training, attention should then be shifted to refresher training, such as proposed in the Manila amendment of the STCW 2010 convention for which many member countries have seen positive improvements in safe operations for its seafarers after ratification.

In implementing objective two, a human factor accident model for small fishing vessels was proposed, and captured the core human error accident factors which were identified to be operator unsafe actions, the operational environment, and the fishing vessel itself. The model predicted the most critical accident causal factors through sensitivity analysis, as operator's unsafe actions, environmental factors, unsafe management, and vessel factors. Based on the findings, attention can therefore be focused on risk-reducing measures required to address the factors related to the operator's actions and management/ leadership since these factors are easier to mitigate and control.

Furthermore, objective three considered a hybrid approach that integrates two powerful analysis tools was applied to solve the problem of incomplete and non-existence of prior probability data for identified triggering events that cause accidents in small fishing vessels. The methodology used the evidence theory to analyze expert information to quantify the expert's judgment, and using results as prior probability data the study findings showed; current model demonstrated the capability for quantitative human factor assessment in small fishing operations, human factors to be a significant contributor to the main accident event, contributing almost 60 percent, and overall results showing machinery failure, environmental factors, vessel factors, and unsafe operator actions as the most influencing factors of accident occurrence.

Finally, objective four sought to undertake a quantitative analysis using the Bayesian network approach helps to model the risk management of small fishing vessel operation. To conduct a quantitative risk management analysis for a small fishing vessel, the first step is to identify and prioritize potential risks, such as weather-related risks, equipment failure, human error, and regulatory compliance. Next, is to gather relevant data on each identified risk, including historical environmental data, maintenance records, crew training records, accident and incident reports, and regulatory requirements. Applying quantitative methods, analyze the data and estimate the likelihood and potential impact of each risk. Afterwards, develop risk mitigation strategies based on the results of analysis, and continuously monitor and review implemented measures to ensure its effectiveness and to make necessary adjustments when need arises.

Several small fishing vessels accidental events were attributed to operator error and vessel and environmental factors. Based on the findings of the current research study it is proposed that a combination of administrative and personal protective equipment control measures be adopted by the stakeholders. These control measures as outlined in chapter six have either been proposed as part of previous safety studies or has been implemented for other industry applications and found to be working as intended. On this basis a list of the recommended risk control measures are below.

- Mandatory onboard safety equipment and requirement to always use them.
- Search and rescue process, and emergency preparedness.
- Development of safety regulations and standard operating procedures.
- Practice of safety culture by fisher people.

- Vessel licensing, certification, inspection and enforcing compliance.
- Promotion of education and training.
- Establish a safety awareness program and distribute safety publication materials.

7.4. Recommendations.

The knowledge and understanding gained from this study provide us with a significant potential to carry out further examination on risk management strategies for small fishing vessels.

The thesis proposes recommendations for a basic training in stability and safety awareness (use of PPEs and PSDs) program to help reduce the frequency of fishing vessel stability incidents. This task could be achieved through an education program that would be offered through a short course by specialized organizations such as the Marine Institute (NL, Canada) and Regional maritime university (Accra, Ghana). Training programs should be aimed towards operators who are currently exempted from undergoing formal stability training by Transport Canada and the Ghana Maritime Authority. This group's exemption is because of the inadequacies in the IMO revised STCW Convention and Code (2010 Manila amendments), which forms the basis for national regulations governing ocean going vessel operations. The document (i.e., STCW-F 95) does not include guidance on fishing vessels under 12 m LOA, although provisions are made for larger fishing vessels on how to ensure the much-needed skills and competencies are obtained. Therefore, such a training program will at least ensure safety of life at sea and offer protection and preservation of the marine environment.

Additionally, regulators must come up with modalities that can assist in the performance of a simple stability test such as an inclining experiment of the small fishing boats before issuing a license to the owner.

Lastly, an incident reporting culture should be cultivated among fishers to have records (both accidents and near-misses) of common hazards peculiar to the industry. This idea if well implemented by stakeholders could be one solution to the problem of lack of data on risk factors which analysts normally encounter while performing a risk analysis. An example is to develop a data collection and classification form which captures the information from the subject and categorizes the record.

8. Appendix

8.1. Appendix A: Expert elicitations

Centre for Risk, Integrity, and Safety Engineering (C-RISE)
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Questionnaire on Small Fishing Vessel Safety

Dear Participant,

The following questionnaire is designed to evaluate the probability of an event "Human factor accident of small fishing vessel" in the West Africa region (Ghana), based on experts' knowledge. To rate the failure probabilities of the safety barriers and finally make recommendations for appropriate risk management strategies to improve safety (i.e., risk reduction).

The personal information collected will help us to compute the weight of each criteria including "age", job tenure", "experience", and "education level" and to finally aggregate experts' opinions.

The questionnaire is divided into three parts. Part **1** includes personal information of expert based on defined criteria, whiles in part **2,** experts are asked to present which criterion is important than other ones. However, as a participant, you may skip any question that you do not wish to answer.

In this research the relative values of criteria as compared with each other are provided in five options as follows.

A: Very important

B: Moderately important

C: Equally important

D: Moderately unimportant

E: very unimportant

In part **3**, a list of events that may trigger human factor related accident for small fishing vessel is presented. To estimate the probability of each triggering event and rate the failure probabilities of the safety barriers, please express your opinion in quantified terms as follows.

Table 8-1

Related number	Judgment for probability
10	***Happening (H)***
9	***Certainly high (CH)***
8	***Very high (VH)***
7	***High(H)***
6	***Moderately high (MH)***
5	***Medium (M)***
4	***Moderately low (ML)***
3	***Low (L)***

2	***Very low (VL)***
1	***Certainly low (CL)***
0	***Not happening (NH)***

We thank you and honestly appreciate your valuable time and contribution to this research.

Part 1

Personal information

Place of service: Organizational position:

Date when the questionnaire was filled out:

- ✓ **Your Age:**
- ✓ **Your job tenure:**
- ✓ **Your experience in the filed:**
- ✓ **Your education level:**
  - o Ph.D.
  - o Master
  - o Bachelor
  - o Higher national diploma
  - o School level

Part 2

The following questions compare with each other the importance of the following criteria in order of the experts weighting.

1. How important is the criterion of “age” as compared with the criterion of “education level”?

A ☐ B ☐ C ☐ D ☐ E ☐

2. How important is the criterion of “age” as compared with the criterion of “job tenure”?

A ☐ B ☐ C ☐ D ☐ E ☐

3. How important is the criterion of “age” as compared with the criterion of “experience”?

A ☐ B ☐ C ☐ D ☐ E ☐

4. How important is the criterion of “education level” as compared with the criterion of “job tenure”?

A ☐ B ☐ C ☐ D ☐ E ☐

5. How important is the criterion of “education level” as compared with the criterion of “experience”?

A ☐ B ☐ C ☐ D ☐ E ☐

6. How important is the criterion of “job tenure” as compared with the criterion of “experience”?

A ☐ B ☐ C ☐ D ☐ E ☐

Part 3

Q1. Table.1 presents a list of accident triggering events leading to human factor accident of small fishing vessel. Please fill related number for probability (likelihood) in triggering events table.

Table 8-2. List of Identified accident triggering events for small fishing vessel (adopted from Obeng et al., 2022)

TAG	TRIGGERING EVENT	EXPERT OPINION: 0 = Not happening; 10 - Happening	
		YES	***NO***
TRE.1	Inadequate supervision/ leadership		
TRE.2	Regulatory & policy factors		
TRE.3	Unsafe operation		
TRE.4	Leadership & supervisory violations		
TRE.5	Training & competence		
TRE.6	Crew motivation		
TRE.7	Social & cultural factors		
TRE.8	Crew fitness for duty		
TRE.9	Fatigue		
TRE.10	Planning & communication		
TRE.11	Judgement error (wrong judgement)		
TRE.12	Tasking error (improper task)		
TRE.13	Crew violations		
TRE.14	Physical (natural) environmental		
TRE.15	Technological (ergonomically) environment		
TRE.16	Vessel design & fabrication		
TRE.17	Inspection & certification		
TRE.18	Socio-economic influence.		
TRE.19			
TRE.20			
TRE.21			
TRE.22			
TRE.23			
TRE.24			
TRE.25			
TRE.26			
TRE.27			
TRE.28			
TRE.29			
TRE.30			

Please provide in the blank cells in table.1, any further suggestion on accident triggering factor which in your opinion, might not have been captured in the list.

Q2. For accidents that occurs during operation of a small fishing vessel, we may agree that the layers of safety barriers (SB) are adequately captured in the underlisted.

SB1*-Monitoring and detection system (i.e., bilge level alarm)*

SB2*-Operator intervention (i.e., ensuring water tightness, use of damage control kits, pumping system, etc).*

SB3*-Onboard safety equipment (Built-in floatation, PFD, flares, distress signal, EPIRB).*

SB4*-Maritime search and rescue (M-SAR)*

Please fill related number for probability in Safety Barrier (SB) table.

Table 8-3. List of Safety barriers for small fishing vessel operations

TAG	SAFETY BARRIERS	EXPERT OPINION: 0 = Not happening; 10 - Happening	
		YES	***NO***
SB.1	Monitoring and detection system failure		
SB.2	Operator intervention failure		
SB.3	Onboard safety equipment failure		
SB.4	M-ASR failure		

Q3. From your experience with small fishing vessel safety issues over the years, please list and give a brief explanation in the order of preference/importance some risk management measures that in your opinion when implemented, can help mitigate or reduce the risk of accident occurring.

The research team acknowledge your honest cooperation. Please check out the questionnaire again to make sure that no question in each part was missed, and then return it.

8.2. Appendix B: Detailed Expert elicitations results

Table 8-4. Experts' profile and background information.

Expert	Title	Age	Experience	Job tenure	Education
1	*Regulator*	37 years	15 years	5 years	*Masters*
2	*Academic*	35 years	10 years	10 years	*PhD*
3	*Academic*	75 years	40 years	40 years	*Masters*
4	*Regulator*	50 years	20 years	20 years	*Higer Diploma*
5	*Operator*	73 years	24 years	7 years	*Bachelors*
6	*Regulator*	43 years	15 years	15 years	*Higer Diploma*

Table 8-5. Identified factors and their corresponding occurrence probability in qualitative terms.

TAG	TRIGGERING EVENT	EXPERT$_#1	EXPERT_#2	EXPERT_#3	EXPERT_#4	EXPERT_#5	EXPERT_#6
TRE.1	Inadequate supervision/ leadership	L (3)	L (3)	MH (6)	L (3)	L (3)	L (3)
TRE.2	Regulatory & policy factors	L 3	VL (2)	L (3)	M (5)	VL (2)	MH (6)
TRE.3	Unsafe operation	ML, (4)	ML (4)	MH (6)	MH (6)	M (5)	M (5)
TRE.4	Leadership & supervisory violations	M (5)		VL (2)	M (5)	L (3)	MH (6)
TRE.5	Training & competence	M (5)	ML (4)	M (5)	M (5)	M (5)	L (3)
TRE.6	Crew motivation	L (3)	ML (4)	L (3)	VL (2)	L (3)	L (3)
TRE.7	Social & cultural factors	L (3)	CL (1)	NH (0)	VL (2)	L (3)	ML (4)
TRE.8	Crew fitness for duty	ML, (4)	VL (2)	M (5)	L (3)	L (3)	H (7)
TRE.9	Fatigue	L (3)	ML (4)	MH (6)	L (3)	ML (4)	VL (2)
TRE.10	Planning & communication	ML (4)	CL (1)	L (3)	M (5)	M (5)	MH (6)
TRE.11	Judgement error (wrong judgement)	ML (4)	ML (4)	L (3)	M (5)	M (5)	H (7)
TRE.12	Tasking error (improper task)	ML (4)	ML (4)	VL (2)	ML (4)	M (5)	VL (2)
TRE.13	Crew violations	L (3)	L (3)	L (3)	ML (4)	M (5)	VL (2)
TRE.14	Physical (natural) environmental	ML (4)	L (3)	NH (0)	ML (4)	ML (4)	M (5)
TRE.15	Technological (ergonomically) environment	VL (2)	ML (4)	L (3)	VL (2)	L (3)	ML (4)
TRE.16	Vessel design & fabrication	ML (4)	ML (4)	ML (4)	L (3)	ML (4)	M (5)
TRE.17	Inspection & certification	M (5)	ML (4)	L (3)	ML (4)	ML (4)	L (3)
TRE.18	Socio-economic influence.	ML (4)	ML (4)	NH (0)	VL (2)	M (5)	M (5)
TAG	SAFETY BARRIERS						
SB.1	Monitoring and detection system failure	VL (2)	ML (4)	CL (1)	L (3)	L (3)	L (3)
SB.2	Operator intervention failure	L (3)	M (5)	M (5)	L (3)	VL (2)	ML (4)
SB.3	Onboard safety equipment failure	M (5)	M (5)	CL (1)	M (5)	M (5)	ML (4)
SB.4	M-ASR failure	M (5)	VL (2)	CL (1)	MH (6)	M (5)	L (3)

Note: TRE = triggering event; SB = safety barrier; NH = not happening; CL = certainly low; VL = very low; L = low; M L = moderately low; M = medium; MH = moderately high; H = high; VH = very high; CH = certainly high; H=happening

Table 8-6. Expert #1 assignment of event probabilities for small fishing vessel accident triggering factors.

	EXPERT #1			
TAG	TRIGGERING EVENT	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	*NO*	*Yes or No*
TRE.1	Inadequate supervision/ leadership	3	5	**2**
TRE.2	Regulatory & policy factors	3	5	**2**
TRE.3	Unsafe operation	4	5	**1**
TRE.4	Leadership & supervisory violations	5	4	**1**
TRE.5	Training & competence	5	4	**1**
TRE.6	Crew motivation	3	5	**2**
TRE.7	Social & cultural factors	3	5	**2**
TRE.8	Crew fitness for duty	4	3	**3**
TRE.9	Fatigue	3	5	**2**
TRE.10	Planning & communication	4	3	**3**
TRE.11	Judgement error (wrong judgement)	4	5	**1**
TRE.12	Tasking error (improper task)	4	5	**1**
TRE.13	Crew violations	3	5	**2**
TRE.14	Physical (natural) environmental	4	5	**1**
TRE.15	Technological (ergonomically) environment	2	3	**5**
TRE.16	Vessel design & fabrication	4	5	**1**
TRE.17	Inspection & certification	5	4	**1**
TRE.18	Socio-economic influence.	4	5	**1**

Table 8-7. Expert #2 assignment of event probabilities for small fishing vessel accident triggering factors.

	EXPERT #2			
TAG	TRIGGERING EVENT	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	*NO*	*Yes or No*
TRE.1	Inadequate supervision/ leadership	3	4	**3**
TRE.2	Regulatory & policy factors	2	5	**3**
TRE.3	Unsafe operation	4	4	**2**
TRE.4	Leadership & supervisory violations			
TRE.5	Training & competence	4	2	**4**
TRE.6	Crew motivation	4	3	**3**
TRE.7	Social & cultural factors	1	5	**4**
TRE.8	Crew fitness for duty	2	5	**3**
TRE.9	Fatigue	4	4	**2**
TRE.10	Planning & communication	1	5	**4**
TRE.11	Judgement error (wrong judgement)	4	3	**3**
TRE.12	Tasking error (improper task)	4	4	**2**
TRE.13	Crew violations	3	5	**2**
TRE.14	Physical (natural) environmental	3	5	**2**
TRE.15	Technological (ergonomically) environment	4	4	**2**
TRE.16	Vessel design & fabrication	4	3	**3**
TRE.17	Inspection & certification	4	2	**4**
TRE.18	Socio-economic influence.	4	4	**2**

Table 8-8. Expert #3 assignment of event probabilities for small fishing vessel accident triggering factors.

	EXPERT #3			
TAG	**TRIGGERING EVENT**	**EXPERT OPINION: 0 = Not happening; 10 - Happening**		**Incomplete knowledge**
		YES	***NO***	***Yes or No***
TRE.1	Inadequate supervision/ leadership	6	3	**1**
TRE.2	Regulatory & policy factors	3	4	**3**
TRE.3	Unsafe operation	6	4	**0**
TRE.4	Leadership & supervisory violations	2	2	**6**
TRE.5	Training & competence	5	5	**0**
TRE.6	Crew motivation	3	4	**3**
TRE.7	Social & cultural factors	0	0	**10**
TRE.8	Crew fitness for duty	5	5	**0**
TRE.9	Fatigue	6	3	**1**
TRE.10	Planning & communication	3	4	**3**
TRE.11	Judgement error (wrong judgement)	3	4	**3**
TRE.12	Tasking error (improper task)	2	7	**1**
TRE.13	Crew violations	3	3	**4**
TRE.14	Physical (natural) environmental	0	0	**10**
TRE.15	Technological (ergonomically) environment	3	4	**3**
TRE.16	Vessel design & fabrication	4	5	**1**
TRE.17	Inspection & certification	3	1	**6**
TRE.18	Socio-economic influence.	0	0	**10**

Table 8-9. Expert #4 assignment of event probabilities for small fishing vessel accident triggering factors.

	EXPERT #4			
TAG	**TRIGGERING EVENT**	**EXPERT OPINION: 0 = Not happening; 10 - Happening**		**Incomplete knowledge**
		YES	***NO***	***Yes or No***
TRE.1	Inadequate supervision/ leadership	3	6	**1**
TRE.2	Regulatory & policy factors	5	3	**2**
TRE.3	Unsafe operation	6	2	**2**
TRE.4	Leadership & supervisory violations	5	3	**2**
TRE.5	Training & competence	5	3	**2**
TRE.6	Crew motivation	2	6	**2**
TRE.7	Social & cultural factors	2	6	**2**
TRE.8	Crew fitness for duty	3	5	**2**
TRE.9	Fatigue	3	5	**2**
TRE.10	Planning & communication	5	3	**2**
TRE.11	Judgement error (wrong judgement)	5	3	**2**
TRE.12	Tasking error (improper task)	4	4	**2**
TRE.13	Crew violations	4	4	**2**
TRE.14	Physical (natural) environmental	4	4	**2**
TRE.15	Technological (ergonomically) environment	2	6	**2**
TRE.16	Vessel design & fabrication	3	5	**2**
TRE.17	Inspection & certification	4	4	**2**
TRE.18	Socio-economic influence.	2	6	**2**

Table 8-10. Expert #5 assignment of event probabilities for small fishing vessel accident triggering factors.

	EXPERT #5			
TAG	TRIGGERING EVENT	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	***NO***	***Yes or No***
TRE.1	Inadequate supervision/ leadership	3	5	**2**
TRE.2	Regulatory & policy factors	2	7	**1**
TRE.3	Unsafe operation	5	4	**1**
TRE.4	Leadership & supervisory violations	3	6	**1**
TRE.5	Training & competence	5	3	**2**
TRE.6	Crew motivation	3	6	**1**
TRE.7	Social & cultural factors	3	6	**1**
TRE.8	Crew fitness for duty	3	5	**2**
TRE.9	Fatigue	4	5	**1**
TRE.10	Planning & communication	5	4	**1**
TRE.11	Judgement error (wrong judgement)	5	3	**2**
TRE.12	Tasking error (improper task)	5	4	**1**
TRE.13	Crew violations	5	3	**2**
TRE.14	Physical (natural) environmental	4	5	**1**
TRE.15	Technological (ergonomically) environment	3	6	**1**
TRE.16	Vessel design & fabrication	4	4	**2**
TRE.17	Inspection & certification	4	5	**1**
TRE.18	Socio-economic influence.	5	4	**1**

Table 8-11. Expert #6 assignment of event probabilities for small fishing vessel accident triggering factors.

	EXPERT #6			
TAG	TRIGGERING EVENT	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	***NO***	***Yes or No***
TRE.1	Inadequate supervision/ leadership	3	6	**1**
TRE.2	Regulatory & policy factors	6	3	**1**
TRE.3	Unsafe operation	5	2	**3**
TRE.4	Leadership & supervisory violations	6	4	**1**
TRE.5	Training & competence	3	6	**1**
TRE.6	Crew motivation	3	5	**2**
TRE.7	Social & cultural factors	4	4	**2**
TRE.8	Crew fitness for duty	7	3	**0**
TRE.9	Fatigue	2	7	**1**
TRE.10	Planning & communication	6	3	**1**
TRE.11	Judgement error (wrong judgement)	7	2	**1**
TRE.12	Tasking error (improper task)	2	6	**2**
TRE.13	Crew violations	2	7	**1**
TRE.14	Physical (natural) environmental	5	4	**1**
TRE.15	Technological (ergonomically) environment	4	6	**1**
TRE.16	Vessel design & fabrication	5	3	**2**
TRE.17	Inspection & certification	3	6	**1**
TRE.18	Socio-economic influence.	5	4	**1**

Table 8-12. Expert #1 assignment of safety barrier probability for small fishing vessel operation

	EXPERT #1			
TAG	SAFETY BARRIERS	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	***NO***	***Yes or No***
SB.1	Monitoring and detection system failure	2	6	2
SB.2	Operator intervention failure	3	5	2
SB.3	Onboard safety equipment failure	5	4	1
SB.4	M-SAR failure	5	4	1

Table 8-13. Expert #2 assignment of safety barrier probability for small fishing vessel operation

	EXPERT #2			
TAG	SAFETY BARRIERS	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	***NO***	***Yes or No***
SB.1	Monitoring and detection system failure	4	3	3
SB.2	Operator intervention failure	5	2	3
SB.3	Onboard safety equipment failure	5	2	3
SB.4	M-SAR failure	2	4	4

Table 8-14. Expert #3 assignment of safety barrier probability for small fishing vessel operation

	EXPERT #3			
TAG	SAFETY BARRIERS	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	***NO***	***Yes or No***
SB.1	Monitoring and detection system failure	1	2	7
SB.2	Operator intervention failure	5	4	1
SB.3	Onboard safety equipment failure	1	1	8
SB.4	M-SAR failure	1	1	8

Table 8-15. Expert #4 assignment of safety barrier probability for small fishing vessel operation

	EXPERT #4			
TAG	SAFETY BARRIERS	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	***NO***	***Yes or No***
SB.1	Monitoring and detection system failure	3	5	2
SB.2	Operator intervention failure	3	5	2
SB.3	Onboard safety equipment failure	5	4	1
SB.4	M-SAR failure	6	3	1

Table 8-16. Expert #5 assignment of safety barrier probability for small fishing vessel operation

	EXPERT #5			
TAG	SAFETY BARRIERS	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	***NO***	***Yes or No***
SB.1	Monitoring and detection system failure	3	6	1
SB.2	Operator intervention failure	2	7	1
SB.3	Onboard safety equipment failure	5	3	2
SB.4	M-SAR failure	5	3	2

Table 8-17. Expert #6 assignment of safety barrier probability for small fishing vessel operation

	EXPERT #6			
TAG	SAFETY BARRIERS	EXPERT OPINION: 0 = Not happening; 10 - Happening		Incomplete knowledge
		YES	***NO***	***Yes or No***
SB.1	Monitoring and detection system failure	3	5	2
SB.2	Operator intervention failure	4	5	1
SB.3	Onboard safety equipment failure	4	5	1
SB.4	M-SAR failure	3	5	2

Table 8-18. A summary of selected experts input for used for quantitative analysis.

				EXPERT #1			EXPERT #2			EXPERT #3		
NO	**ROOT CAUSE**	**SYMBOL**	**TRIGGERING EVENT**	*Yes*	*No*	*Yes or No*	*Yes*	*No*	*Yes or No*	*Yes*	*No*	*Yes or No*
1	**Human (operator & organizational) factors**	*TRE.1*	Inadequate supervision/ leadership	***0.3***	***0.5***	***0.2***	***0.3***	***0.6***	***0.1***	***0.3***	***0.5***	***0.2***
2		*TRE.2*	Regulatory & policy factors	***0.3***	***0.5***	***0.2***	***0.5***	***0.3***	***0.2***	***0.2***	***0.7***	***0.1***
3		*TRE.3*	Unsafe operation	***0.4***	***0.5***	***0.1***	***0.6***	***0.2***	***0.2***	***0.5***	***0.4***	***0.1***
4		*TRE.4*	Leadership & supervisory violations	***0.5***	***0.4***	***0.1***	***0.5***	***0.3***	***0.2***	***0.3***	***0.6***	***0.1***
5		*TRE.5*	Training & competence	***0.5***	***0.4***	***0.1***	***0.5***	***0.3***	***0.2***	***0.5***	***0.3***	***0.2***
6		*TRE.6*	Crew motivation	***0.3***	***0.5***	***0.2***	***0.2***	***0.6***	***0.2***	***0.3***	***0.6***	***0.1***
7		*TRE.7*	Social & cultural factors	***0.3***	***0.5***	***0.2***	***0.2***	***0.6***	***0.2***	***0.3***	***0.6***	***0.1***
8		*TRE.8*	Crew fitness for duty	***0.4***	***0.3***	***0.3***	***0.3***	***0.5***	***0.2***	***0.3***	***0.5***	***0.2***
9		*TRE.9*	Fatigue	***0.3***	***0.5***	***0.2***	***0.3***	***0.5***	***0.2***	***0.4***	***0.5***	***0.1***
10		*TRE.10*	Planning & communication	***0.4***	***0.3***	***0.3***	***0.5***	***0.3***	***0.2***	***0.5***	***0.4***	***0.1***
11		*TRE.11*	Judgement error (wrong judgement)	***0.4***	***0.5***	***0.1***	***0.5***	***0.3***	***0.2***	***0.5***	***0.3***	***0.2***
12		*TRE.12*	Tasking error (improper task)	***0.4***	***0.5***	***0.1***	***0.4***	***0.4***	***0.2***	***0.5***	***0.4***	***0.1***
13		*TRE.13*	Crew violations	***0.3***	***0.5***	***0.2***	***0.4***	***0.4***	***0.2***	***0.5***	***0.3***	***0.2***
14	**Environment factors**	*TRE.14*	Physical (natural) environmental	***0.4***	***0.5***	***0.1***	***0.4***	***0.4***	***0.2***	***0.4***	***0.5***	***0.1***
15		*TRE.15*	Technological (ergonomically) environment	***0.2***	***0.3***	***0.5***	***0.2***	***0.6***	***0.2***	***0.3***	***0.6***	***0.1***
16	**Vessel factors**	*TRE.16*	Vessel design & fabrication	***0.4***	***0.5***	***0.1***	***0.3***	***0.5***	***0.2***	***0.4***	***0.4***	***0.2***
17		*TRE.17*	Inspection & certification	***0.5***	***0.4***	***0.1***	***0.4***	***0.4***	***0.2***	***0.4***	***0.5***	***0.1***
18		*TRE.18*	Socio-economic influence.	***0.4***	***0.5***	***0.1***	***0.2***	***0.6***	***0.2***	***0.5***	***0.4***	***0.1***
19	**Safety barriers**	*SB.1*	Monitoring and detection system failure	***0.2***	***0.6***	***0.2***	***0.3***	***0.5***	***0.2***	***0.3***	***0.6***	***0.1***
20		*SB.2*	Operator intervention failure	***0.3***	***0.5***	***0.2***	***0.3***	***0.5***	***0.2***	***0.2***	***0.7***	***0.1***
21		*SB.3*	Onboard safety equipment failure	***0.5***	***0.4***	***0.1***	***0.5***	***0.4***	***0.1***	***0.5***	***0.3***	***0.2***
22		*SB.4*	Maritime search and rescue (M-SAR) failure	***0.5***	***0.4***	***0.1***	***0.6***	***0.3***	***0.1***	***0.5***	***0.3***	***0.2***

Table 8-19. Summary of subject-matter expects' suggestions for risk control and mitigation measure for small fishing vessel.

No	Expert	Risk management measures
1	***Expert #1***	(1) Development and improvement on regulation and enforcement targetd at small fishing vessel. (2) Based on regulation proper certification can be enforced. (3) Based on regulation boat design will require improvement. (4) Developed training and certification process for personel manning the boats. (5) Education on safety systems and equipment. (6) Documentation of incidents to help guide reviews. (7) Development of SAR processes that cater for the peculiar situation of small boats. (8) Develop stakeholder engagement targeted at cultural change and rethink of attitudes.
2	***Expert #2***	(1) Reliable and verifiable design and construction of small fishing vessel. (2) Regular maintenance of operational and safety critical systems, subsystems, and components. (3) Improved monitoring and detection methods. (4) Routine inspection and supervision by regulatory bodies. (5) Improved navigation. (6) Strict compliance to safety regulations by regulators and state agencies.
3	***Expert #3***	(1) Assign loadlines to prevent overloading and hence capsizing, especially during bumper harvest. (2) Ensure fishermen get weather warning information on regular basis. This may require some 2-way communication systems. (3) Ensure there is continous professional development and training to keep fishermen abreast of new developments and regulations.
4	*Expert #4*	(1) Onboard safety equipment (light, GPS, Radar and flags). (2) Regulatory and enforcement measures. (3) Proper agherence to operational procedures. (4) Training of Bosuns.
5	***Expert #5***	(1) Standardized design of canoes must be approved. (2) Standardized design of all canoes must be inspected and approved before registration, licensing, and access to subsidized inputs including outboard motors, and fishing gear. (3) Education/ sensitization of fishermen on safety issues for compliance. (4) Strict enforcement of approved standards coupled with sanctions for failure to comply.
6	***Expert #6***	(1) The use of PPEs onboard fishing canoes. (2) Lighting and GPS to help see properly during fishing. (3) Fishermen need basic training on safety at sea and other related issues.

8.3. Appendix C: Supplementary material for chapter 3

C1. The developed Small Fishing Trawler Capsize fault tree diagram (FTD).

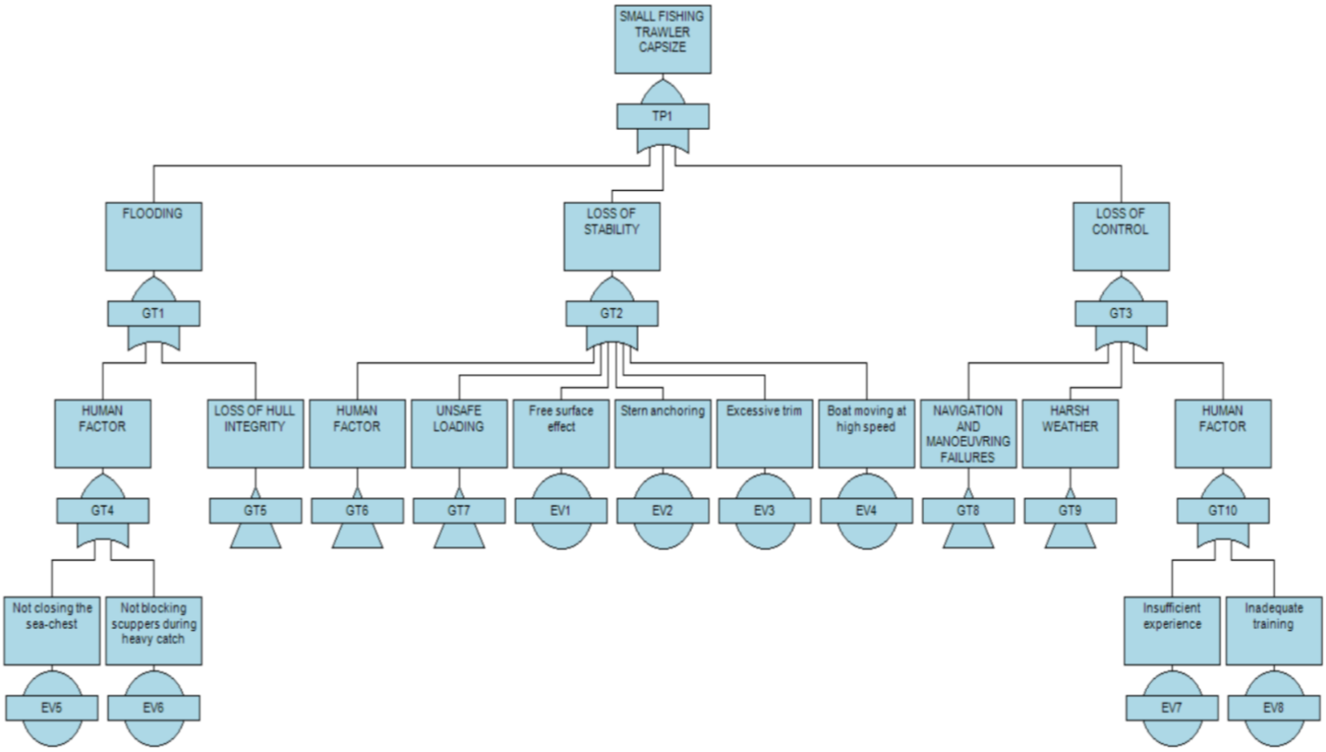

Figure 8.1. The developed fault tree for a small fishing vessel (trawler) capsize accident.

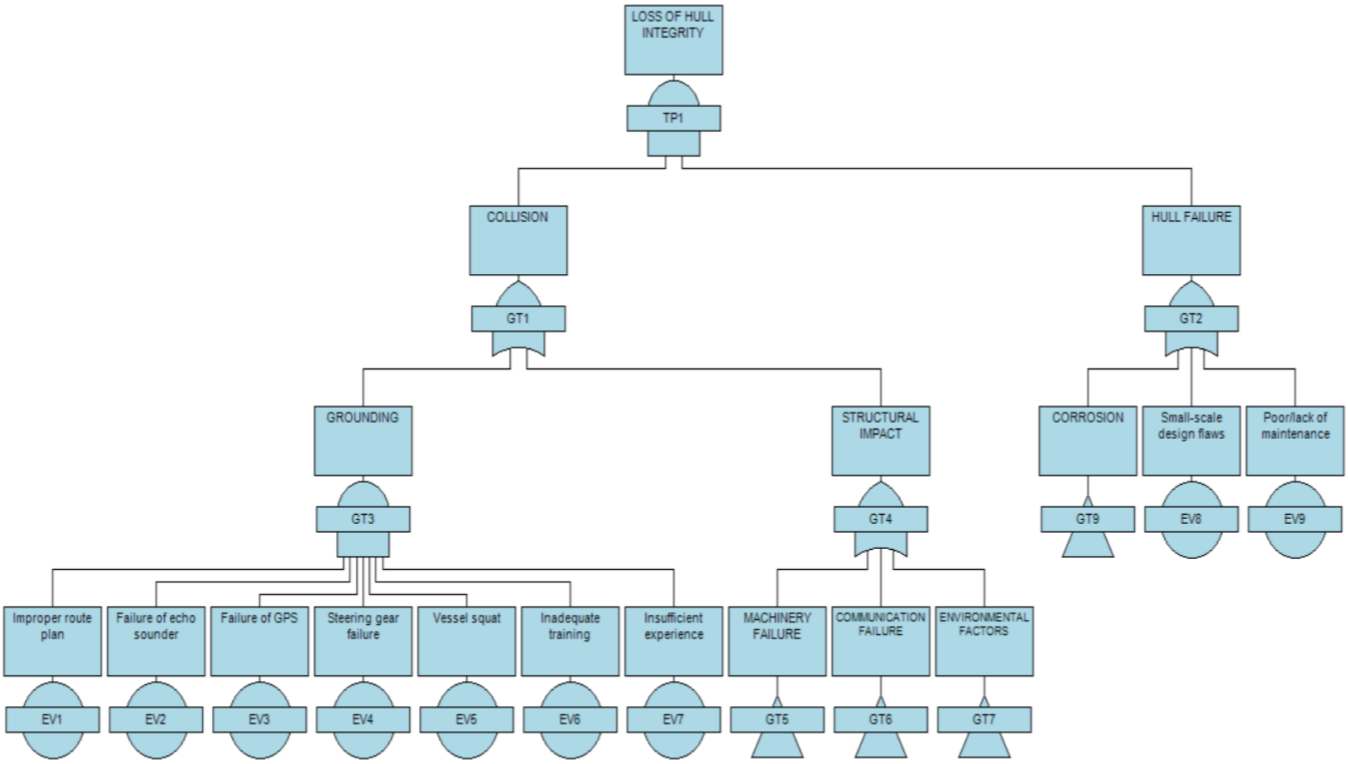

Figure 8.2. Loss of integrity section fault tree for a small fishing vessel (trawler) capsizes accident (continued).

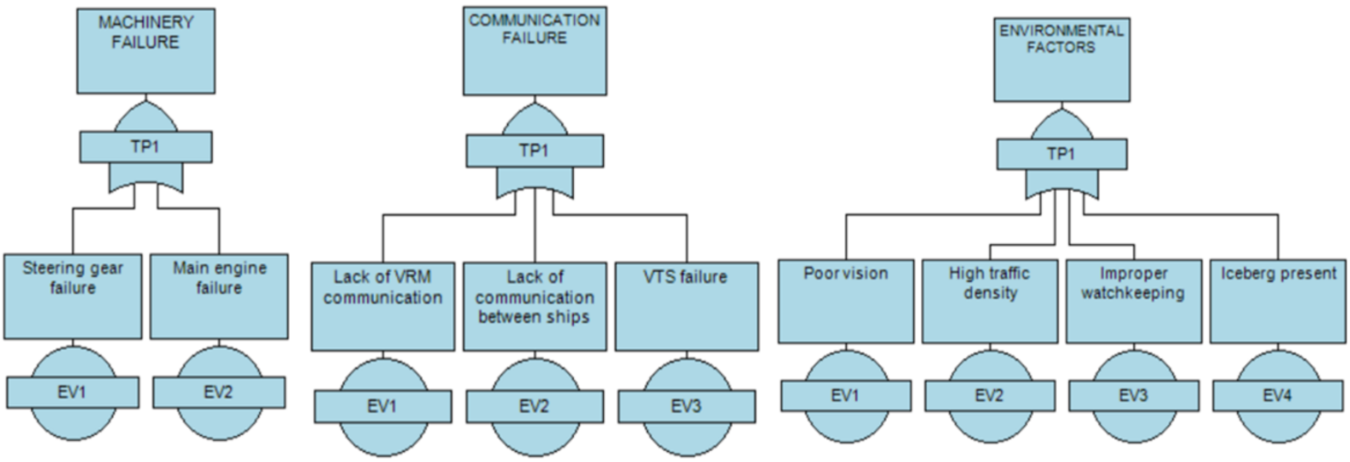

*Figure 8.3.*Machinery, communication, and environment section fault tree for a small fishing vessel (trawler) capsizes accident (continued).

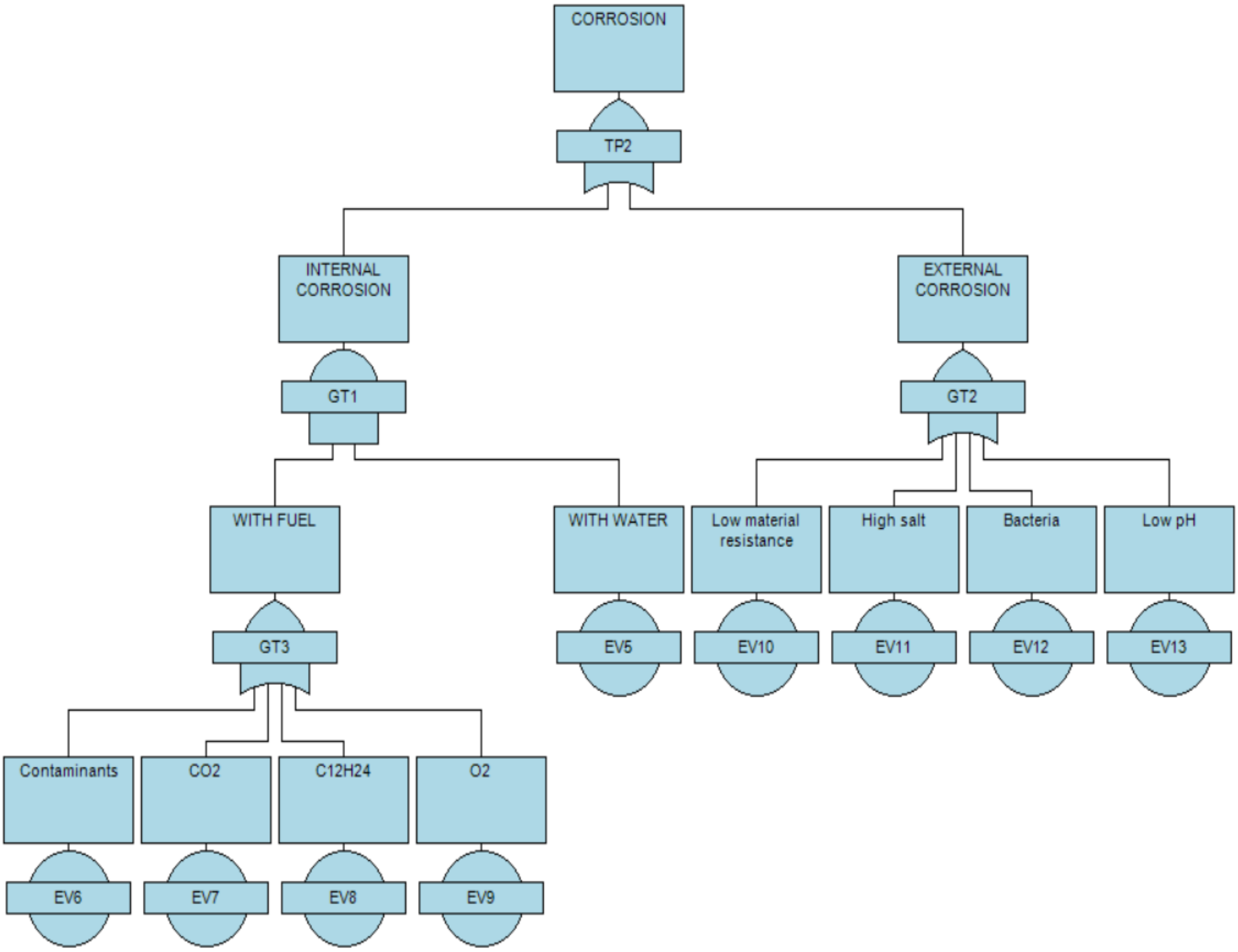

Figure 8.4. Corrosion section fault tree for a small fishing vessel (trawler) capsizes accident (continued).

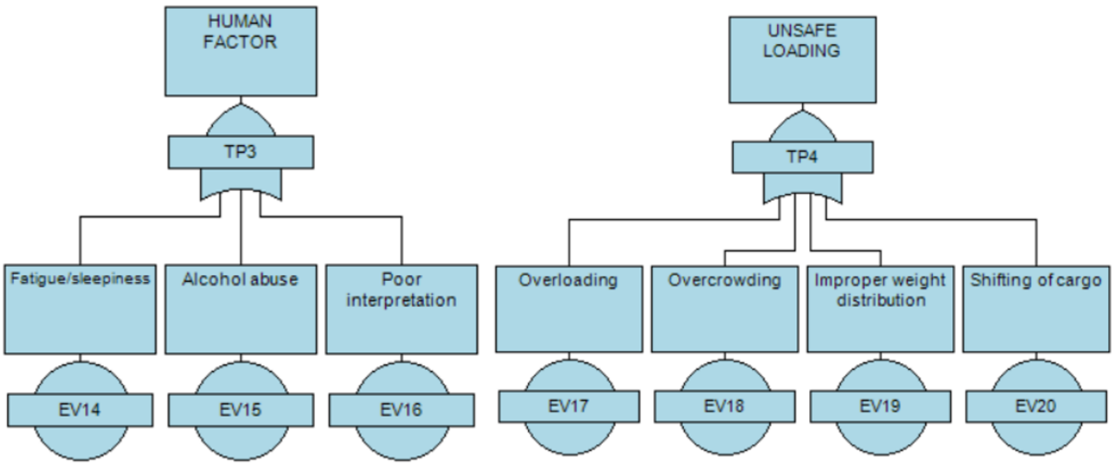

*Figure 8.5.*Human factor part fault tree for a small fishing vessel (trawler) capsizes accident (continued).

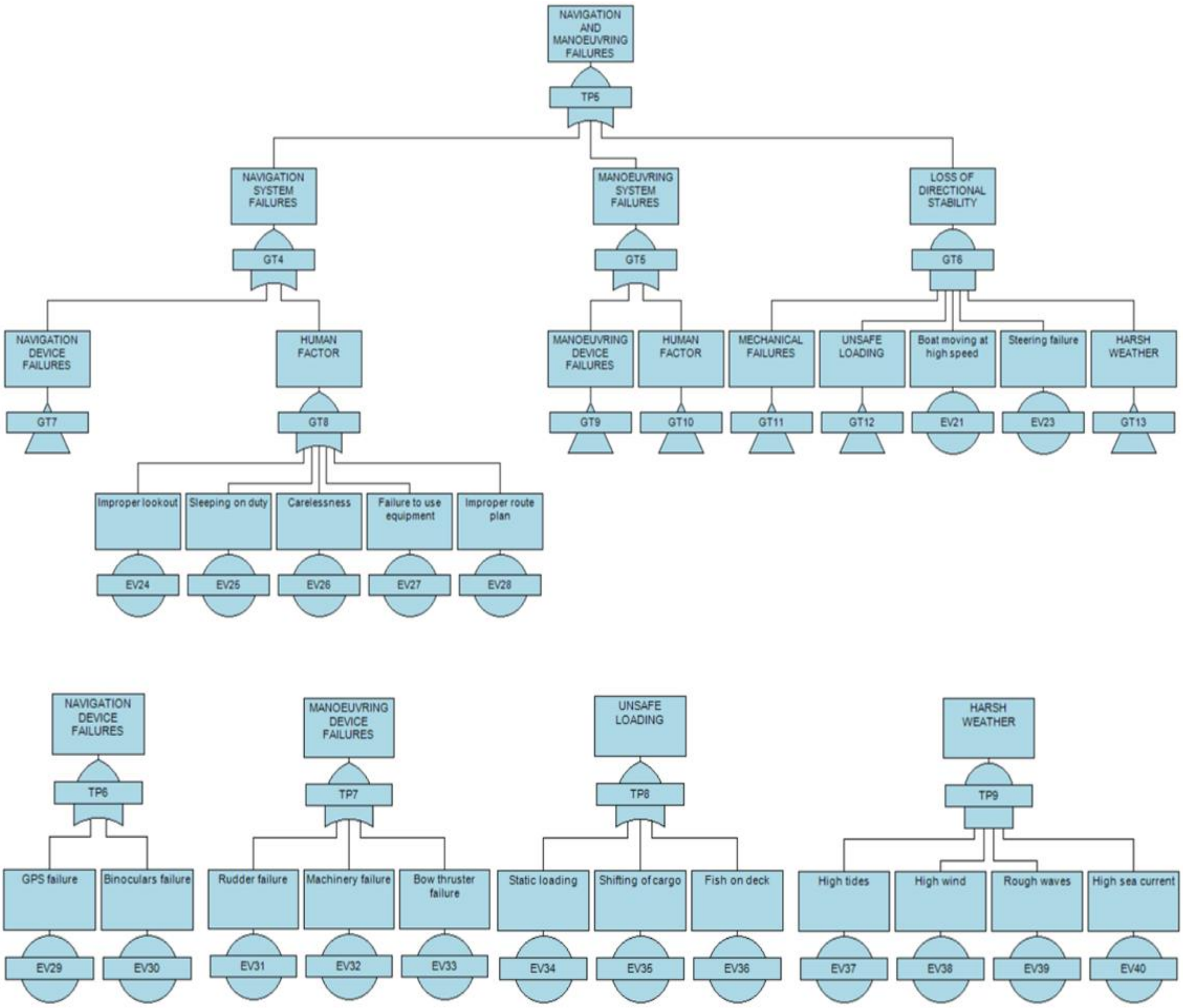

*Figure 8.6.*The developed fault tree for a small fishing vessel (trawler) capsizes accident (continued).

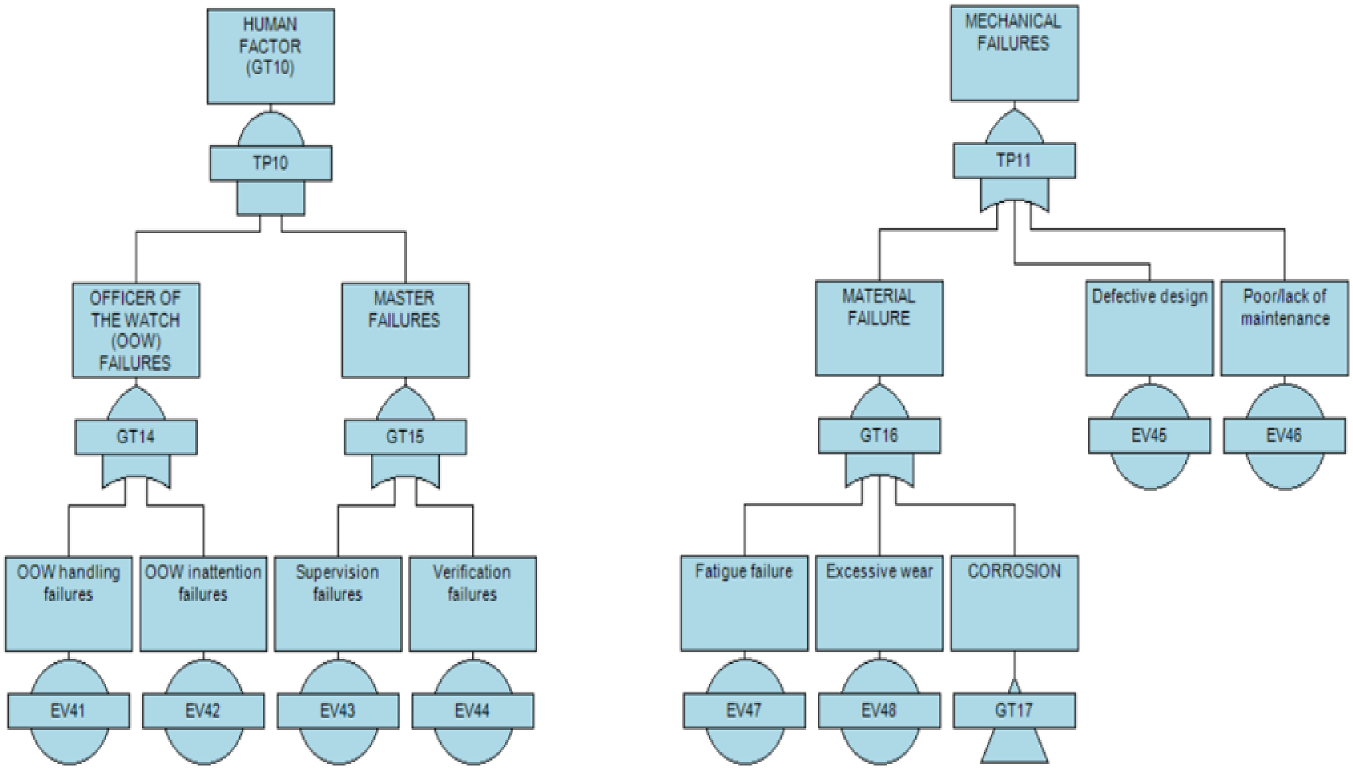

Figure 8.7. The developed fault tree for a small fishing vessel (trawler) capsizes accident (continued).

C2. Object-Oriented Bayesian Network (OOBN) for Small Fishing Trawler with its associated results.

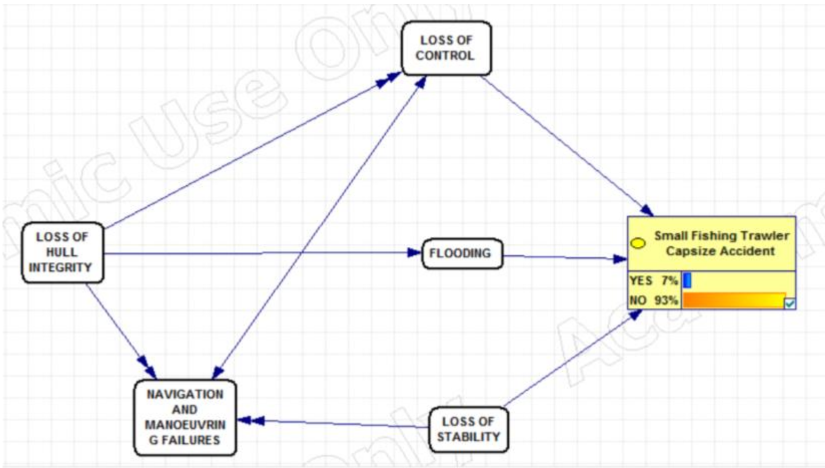

Figure 8.8. OOBN model probability for small trawler capsize.

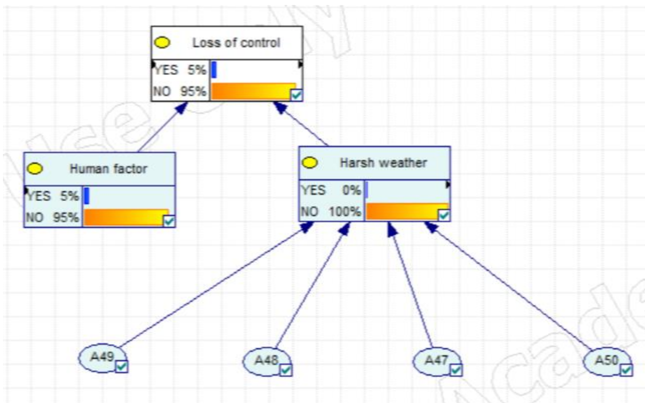

Figure 8.9. Sub-network probabilities for loss of control in the OOBN model.

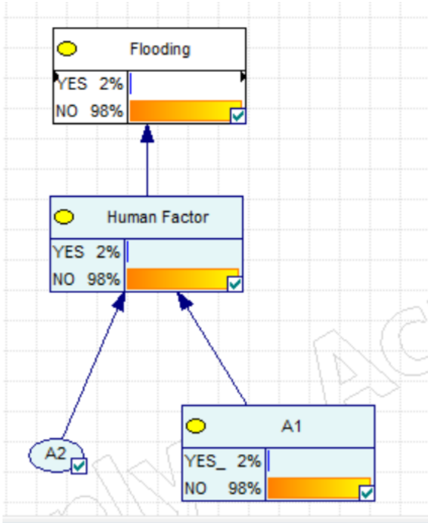

Figure 8.10. Sub-network probabilities for flooding in the OOBN model.

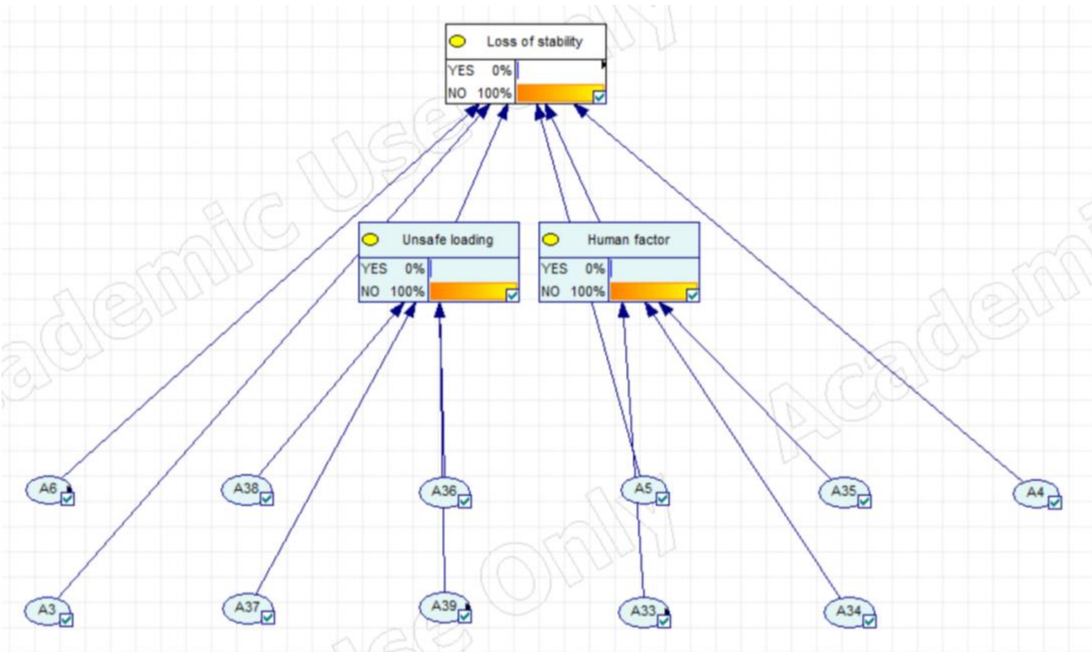

Figure 8.11. Sub-network probabilities for loss of stability in the OOBN model.

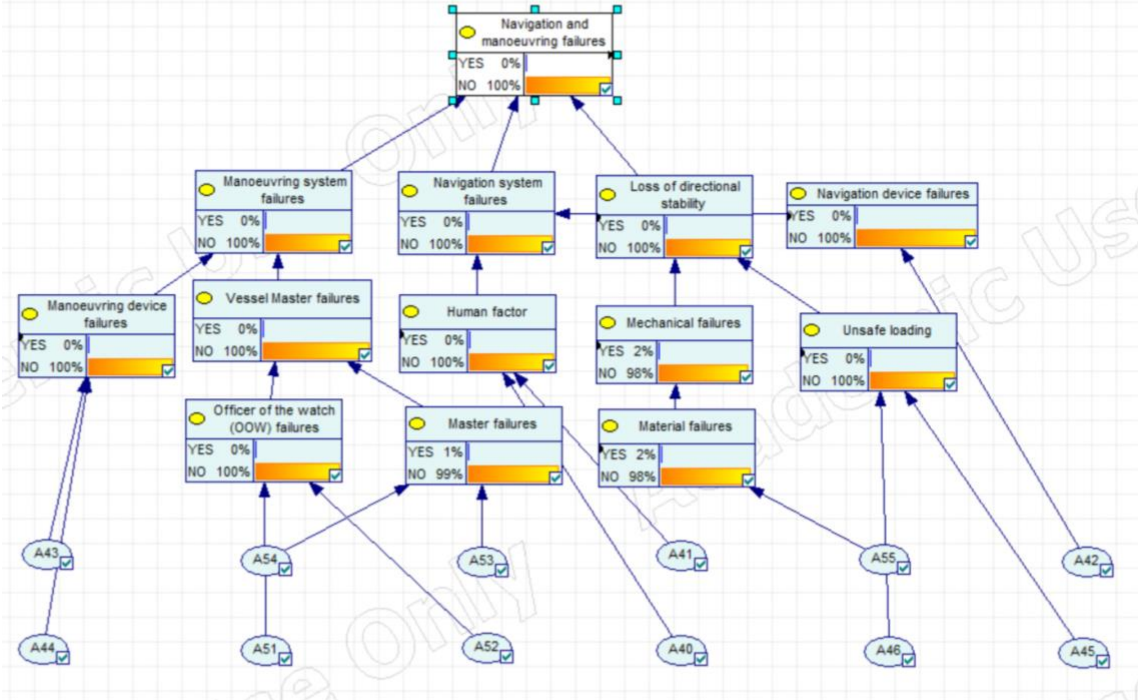

Figure 8.12. Sub-network probabilities for navigation and maneuvering failures in the OOBN model.

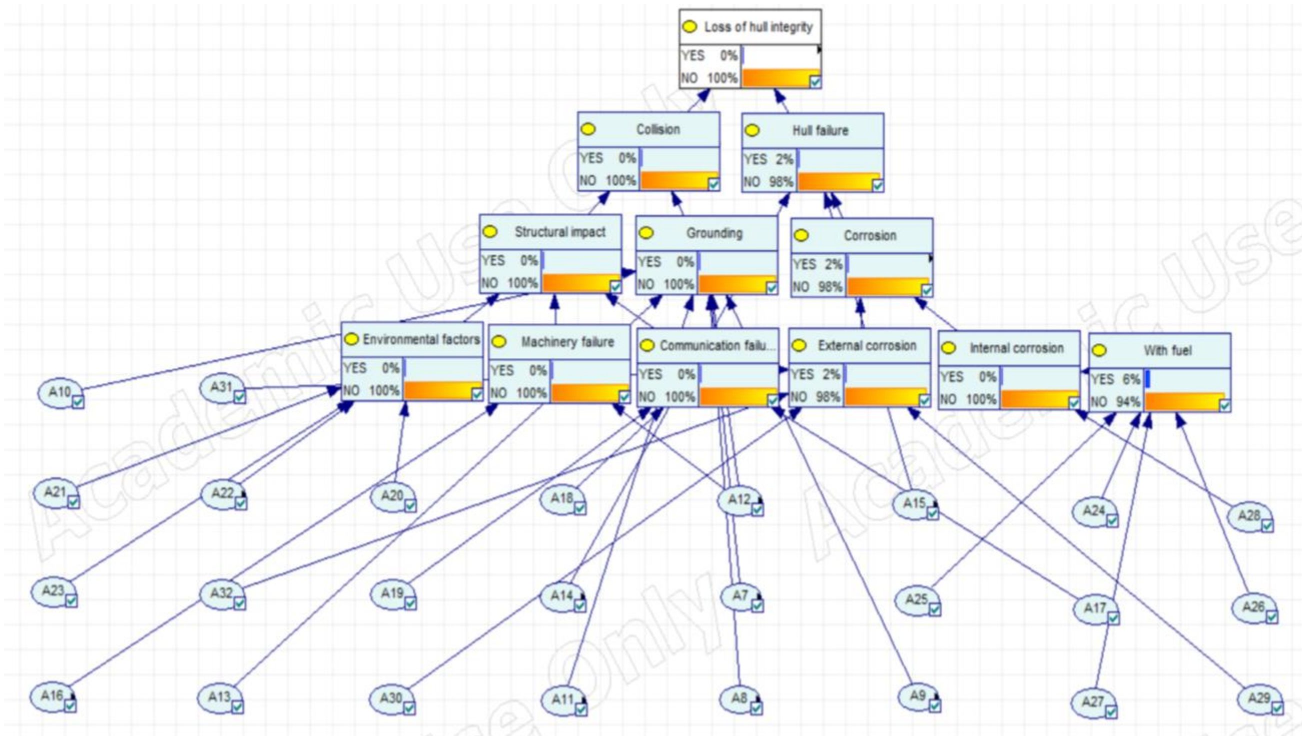

Figure 8.13. Sub-network probabilities for loss of hull integrity in the OOBN model.

8.4. Appendix D: Supplementary material for chapter 4

D1. OOBN Sub-groups for HFA-SFV Accident Network.

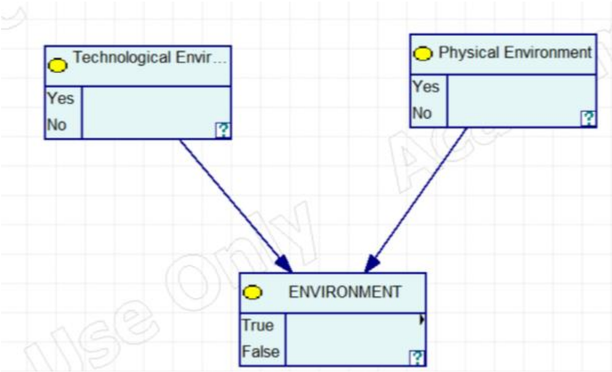

Figure 8.14. Sub-category OOBN for environmental factors.

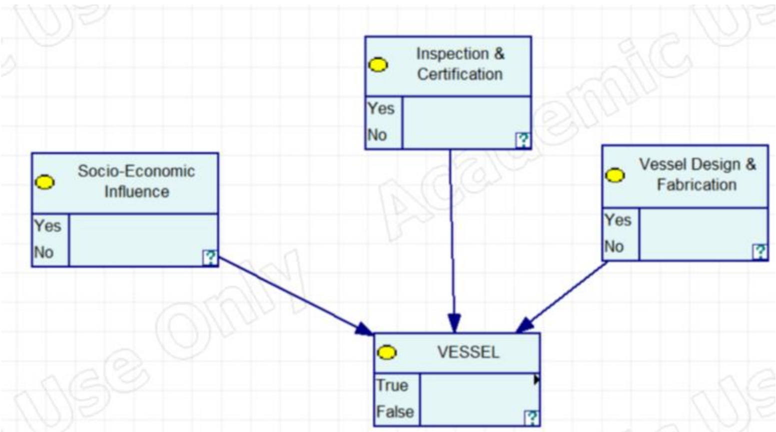

Figure 8.15. Sub-category OOBN for vessel factors.

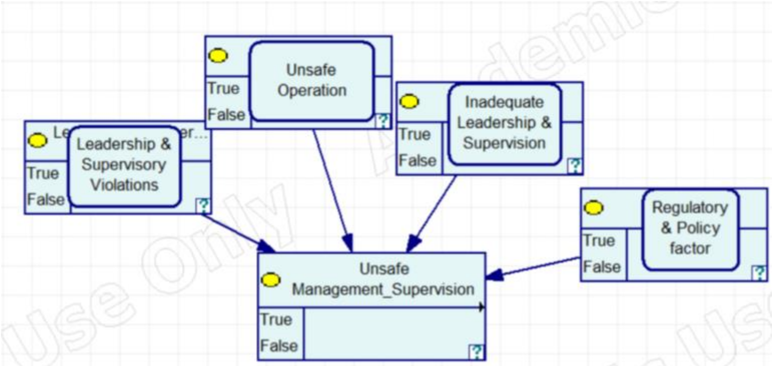

Figure 8.16. Sub-category OOBN for unsafe management factors.

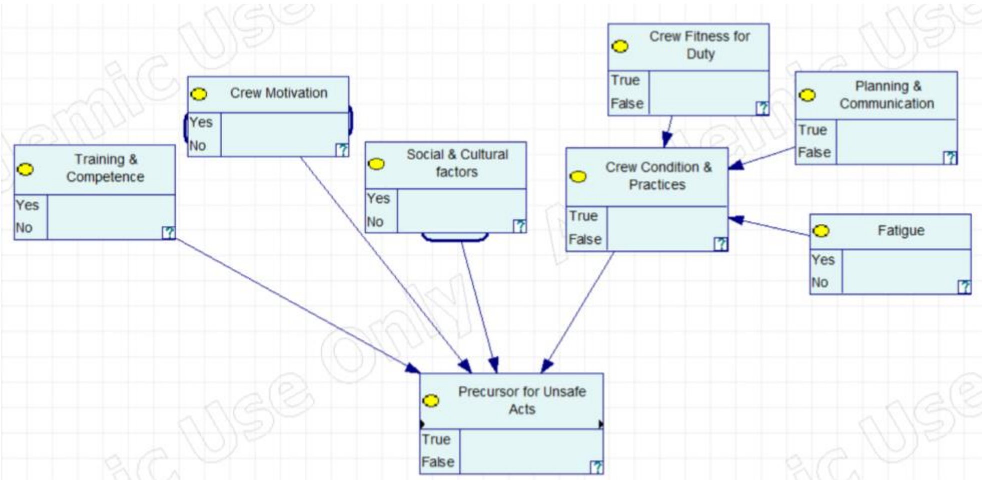

Figure 8.17. Sub-category OOBN for precursor for unsafe acts of operator.

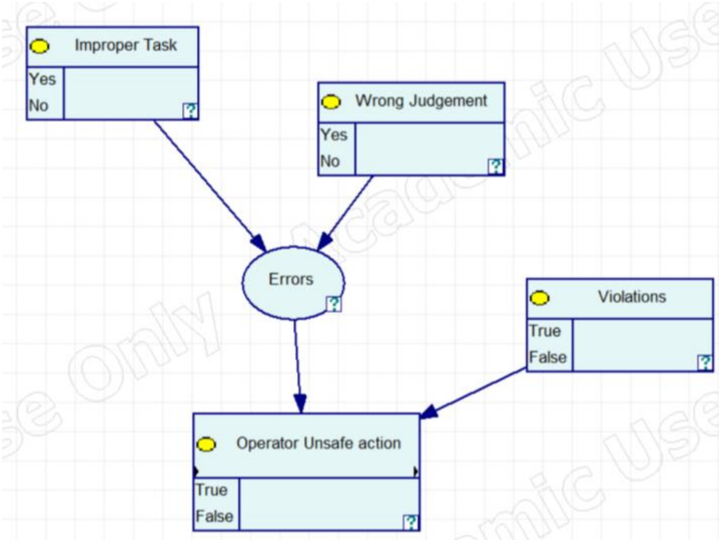

Figure 8.18. Sub-category OOBN for operator's unsafe actions.

D2. Probabilities for OOBN Sub-groups human error events

Table 8-20. Prior and posterior probabilities of basic human factor causal events under environment.

No	***Event***	***Prior probability***	***Posterior probability***
1	Environment (intermediate)		
2	Physical Environment (intermediate)		
3	Adverse/ harsh weather (D.11)	1.00E-01	0.013898425
4	Shoaling at boundaries to ocean (D.12)	1.00E-02	0.010248763
5	Poor visibility (D.13)	3.00E-03	0.003126767
6	Present of obstruction (submerged objects, obstacles) (D.14)	2.00E-02	0.020609089
7	Technological Environment (intermediate)		
8	Poorly designed equipment (D.21)	1.00E-01	0.10826804
9	Lack/ inadequate PPE's (D.22)	1.00E-02	0.010144437
10	Faulty/ Poorly maintained PPE's (D.23)	1.00E-01	0.11113335
11	Lack of warning and danger signs indicator on equipment (D.24)	1.00E-02	0.010091074

Table 8-21. Prior and posterior probabilities of basic human factor causal events under vessel.

No	***Event***	***Prior probability***	***Posterior probability***
1	Vessel design & fabrication (intermediate)		
2	Faulty design (E.11)	1.00E-01	0.101881

3	Improper fabrication (E.12)	3.00E-02	0.030197145
4	Difficult to maintain vessel (E.13)	2.00E-02	0.02020367
5	Poor stability (E.14)	1.00E-01	0.10052481
6	Inspection & certification (intermediate)		
7	Improper permit for fishing quota (E.21)	1.00E-02	0.010339671
8	No proper license acquisition by master (E.22)	1.00E-02	0.010256217
9	Vessel not passing periodic inspection (E.23)	2.00E-03	0.002068878
10	Socio-economic influence (intermediate)		
11	Fisher people's ability to acquire and maintain a sea-worthy vessel for fishing (E.31)	1.00E-03	0.001003751
12	Poor maintenance of vessel (E.32)	1.00E-02	0.010073662
13	Social and economic pressure (E.33)	2.00E-02	0.020109186

Table 8-22. Prior and posterior probabilities of basic human factor causal events under operator's unsafe actions.

No	***Event***	***Prior probability***	***Posterior probability***
1	Errors (intermediate)		
2	Wrong judgement (intermediate)		
3	Improper lookout (C.11)	1.00E-02	0.010090729
4	Follow improper procedure (C.12)	3.00E-02	0.031530088
5	Over confidence (C.13)	1.00E-01	0.1008421
6	Improper route plan (C.14)	1.10E-02	0.011046087

7	Interpretation failure (C.15)	1.33E-02	0.013898425
8	Incorrect task (intermediate)		
9	Inattention failure (C.21)	1.00E-01	0.10156227
10	Lack of knowledge (C.22)	1.00E-02	0.010203546
11	Poor technique (C.23)	1.00E-02	0.010185858
12	Violations (intermediate)		
13	Failure to proceed at a safe speed (C.31)	1.00E-02	0.010022723
14	Ignoring the use of PPE's or lack of maintenance (C.32)	1.00E-01	0.10352222
15	Carrying load above limit (C.33)	3.00E-02	0.030112138
16	Operating vessel without proper licensing (C.34)	1.00E-02	0.010280141

Table 8-23. Prior and posterior probabilities of basic human factor causal events under precursor for unsafe acts.

No	***Event***	***Prior probability***	***Posterior probability***
1	Crew practices & condition (intermediate)		
2	Crew fitness for duty (intermediate)		
3	Physically fatigued (B.11)	3.00E-02	0.030019331
4	Mental fatigue (B.12)	2.00E-02	0.020040364
5	Crew self-medicating (B.13)	3.00E-03	0.003001981
6	Alcohol and drug abuse (B.14)	3.00E-03	0.003004004
7	Impairment due to health or from intoxication of medication (B.15)	2.00E-03	0.002004707
8	Planning & communication (intermediate)		

9	Effective communication among crew (B.21)	1.00E-02	0.010011782
10	Inadequate planning (route selection) (B.22)	2.00E-02	0.020001184
11	Interpretation failure (B.23)	1.30E-02	0.013003358
12	Failure to back-up (B.24)	1.00E-02	0.010013971
13	Breakdown in communication procedures (B.25)	3.00E-02	0.030006877
14	Fatigue (intermediate)		
15	Insufficient rest prior to duty (B.31)	1.00E-02	0.010004341
16	Working long shift without break (B.32)	2.00E-02	0.02001061
17	Stress (B.33)	1.00E-03	0.00100132
18	Insufficient reaction time (B.34)	1.00E-02	0.01002038

Table 8-24. Prior and posterior probabilities of basic human factor causal events under crew motivation.

No	***Event***	***Prior probability***	***Posterior probability***
1	Crew motivation (intermediate)		
2	Greed (intermediate)		
3	Crew greediness informs bad decisions (B.41)	2.00E-02	0.020001691
4	Misplaced motivation (B.42)	1.00E-03	0.00100005
5	Morale of crew (intermediate)		
6	Positive morale among crew (B.51)	1.00E-02	0.01000086
7	Incentive for the crew (bonus payment), benefits, profit sharing (B.52)	1.00E-03	0.001000179

Table 8-25. Prior and posterior probabilities of basic human factor causal events under crew training and competence.

No	***Event***	***Prior probability***	***Posterior probability***
1	Training & competence (intermediate)		
2	Inadequate training (B.61)	2.50E-01	0.25047737
3	Lack of skill and proper qualification of crew (B.62)	1.00E-01	0.10115224
4	Insufficient experience. (B.63)	2.30E-01	0.23066129
5	Lack of education (B.64)	1.50E-01	0.15025293
6	Unintelligence or poor aptitude (B.65)	1.00E-02	0.010116198

Table 8-26. Prior and posterior probabilities of basic human factor causal events under social and cultural factors.

No	***Event***	***Prior probability***	***Posterior probability***
1	Social & Cultural factors (Intermediate)		
2	Believes which affects the fishing activities in a particular community (B.71)	1.00E-03	0.00100229
3	Accepts and practice safety culture (B.72)	1.20E-02	0.012053933
4	Society's risk perception about SFV operations (B.73)	1.00E-02	0.010033824

Table 8-27. Prior and posterior probabilities of basic human factor causal events under unsafe management and leadership.

No	***Event***	***Prior probability***	***Posterior probability***
1	Regulatory / policy factors (intermediate)		
2	Inadequate government regulations for SFV operations (A.11)	3.00E-03	0.003026571
3	IMO rules & regulations not fully ratified by government (A.12)	2.00E-02	0.020257684
4	Maritime authority improperly issues licensing, not conducting inspections and enforces requirement (A.13)	3.00E-02	0.030507538
5	Inadequate leadership (intermediate)		
6	Inadequate oversight and guidance (A.21)	2.00E-03	0.002005572
7	Inadequate prescribed training and certification of crew (A.22)	1.00E-02	0.010019162
8	Non-availability of operational equipment (A.23)	3.00E-03	0.003017715
9	Unsafe operation (intermediate)		
10	Failure to correct wrong procedures (A.31)	3.00E-02	0.030421598
11	Continuous use of known defective/ improper equipment (A.32)	3.00E-02	0.030058254
12	Known deficiencies in training (Inadequate training). (A.33)	1.00E-01	0.10179536
13	Nonperformance of proper operational risk assessment. (A.34)	3.00E-03	0.003003783
14	Leadership/ supervisor violations (intermediate)		
15	Failure to implement and enforce standard operating procedures by government agency (A.41)	3.00E-02	0.030062683
16	Fisherpeople association's leadership disregard for existing rules and regulations (A.42)	3.00E-03	0.003003944

B3. Numerical results of BN/ OOBN Sub-groups.

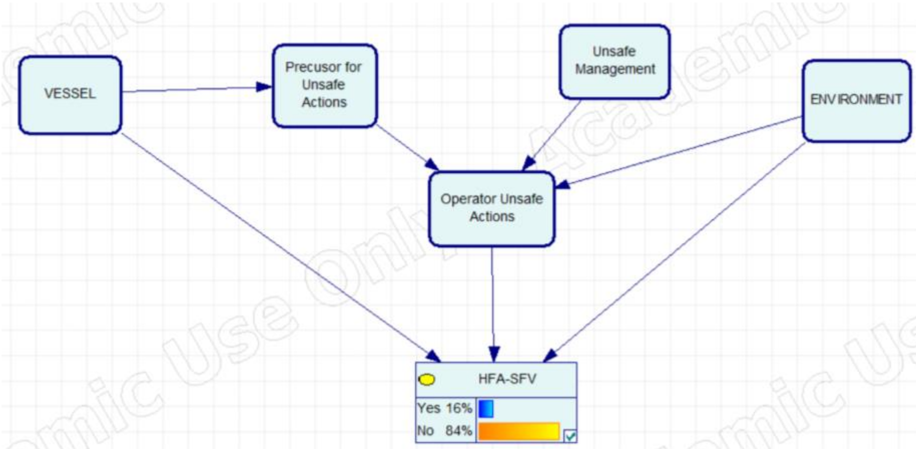

Figure 8.19. Results for Small fishing Vessel Human Factor accident.

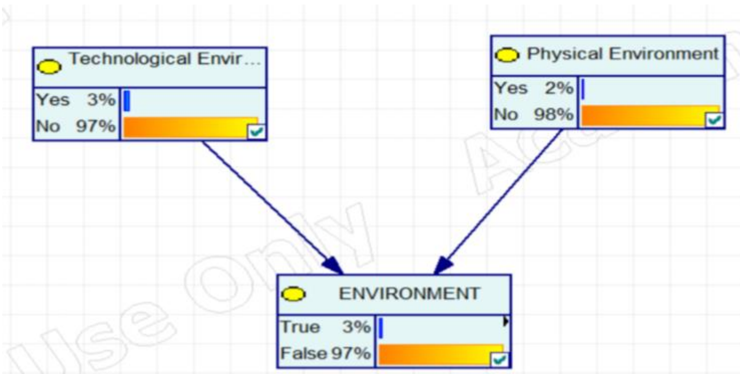

Figure 8.20. Results for Environmental factors

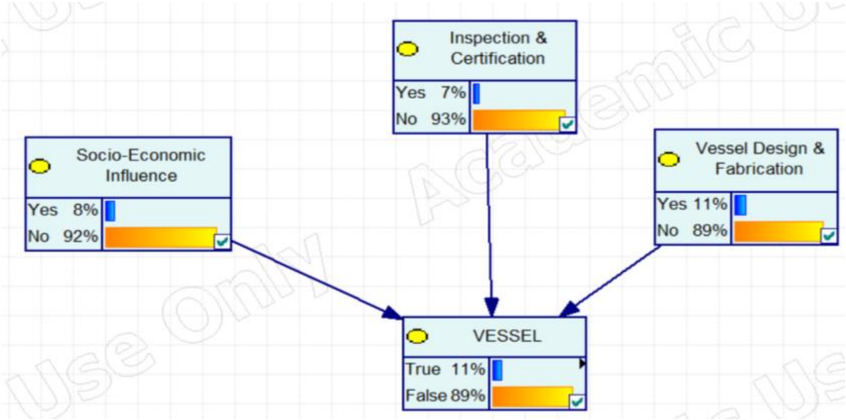

Figure 8.21. Results for Vessel factors.

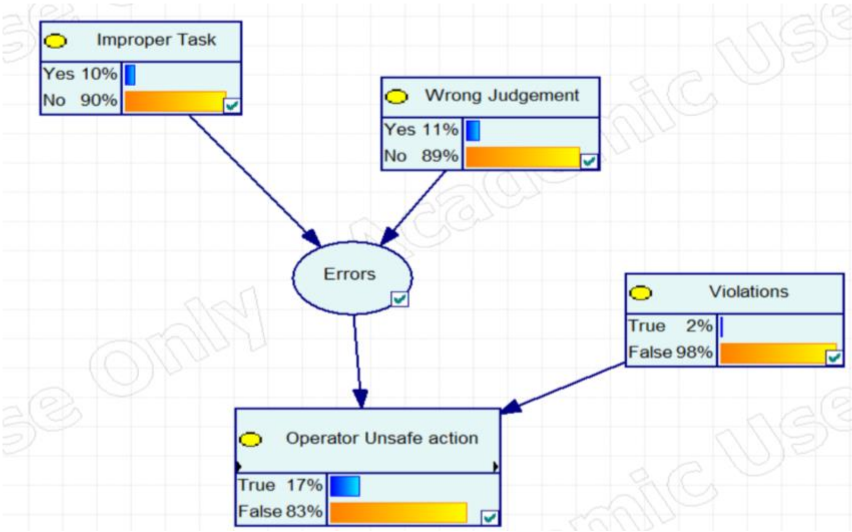

Figure 8.22. Results for operator unsafe actions.

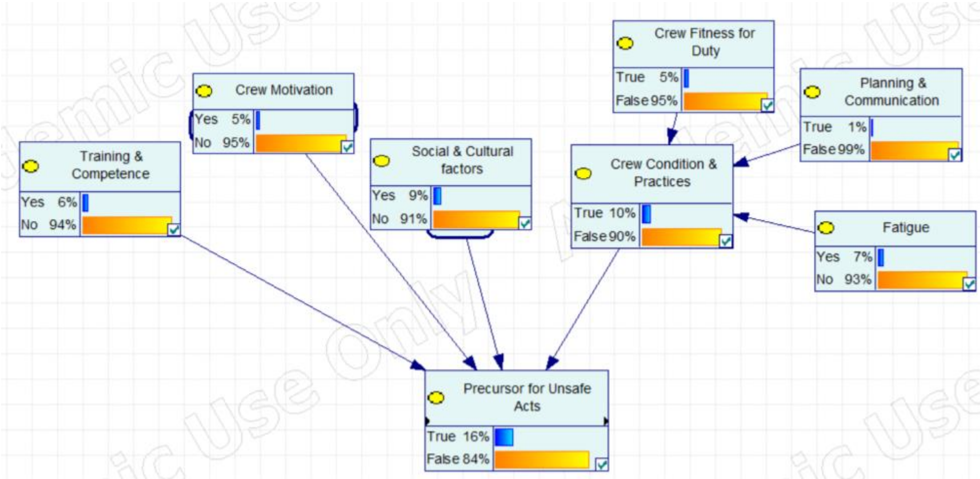

Figure 8.23. Results for precursor for unsafe acts.

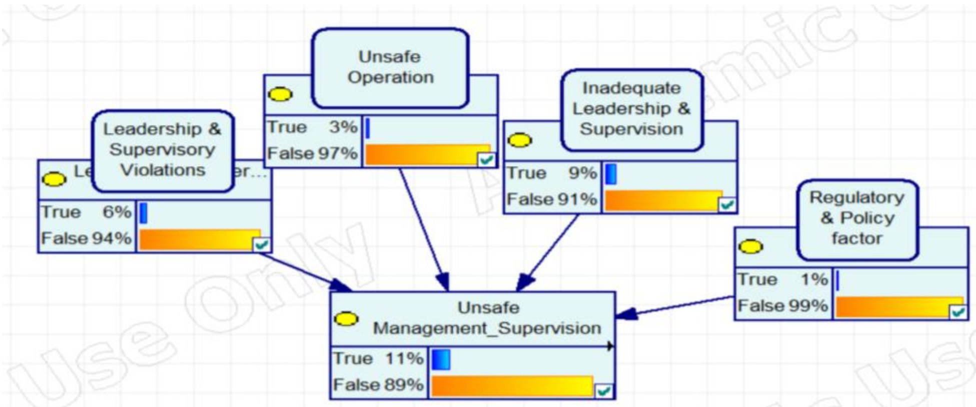

Figure 8.24. Results for unsafe management and leadership.

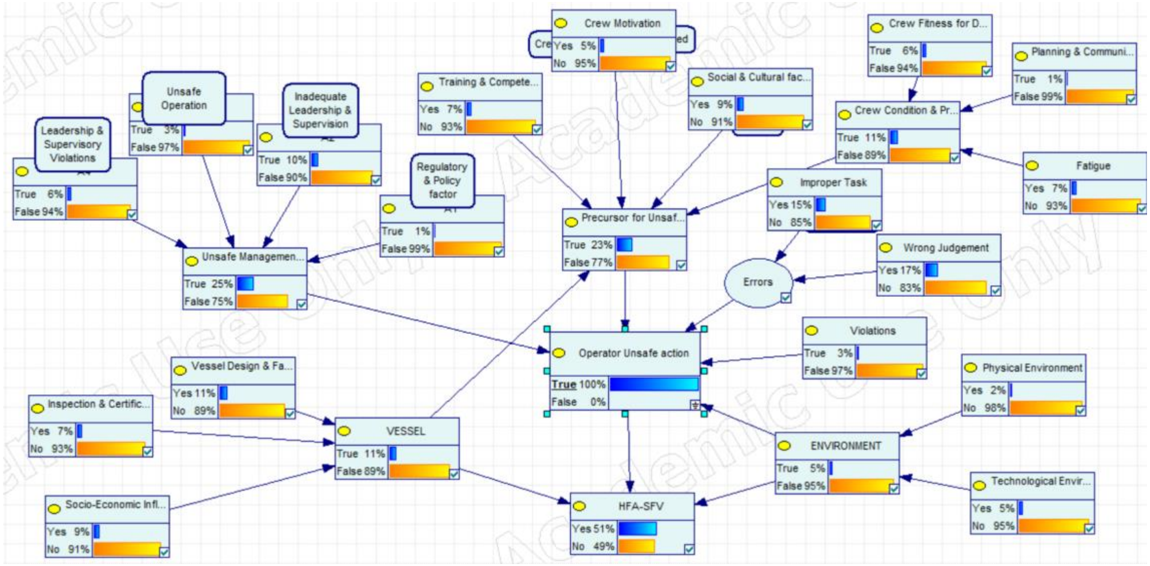

Figure 8.25. Numerical result of HFA-SFV BN when evidence is placed on the operator unsafe action.

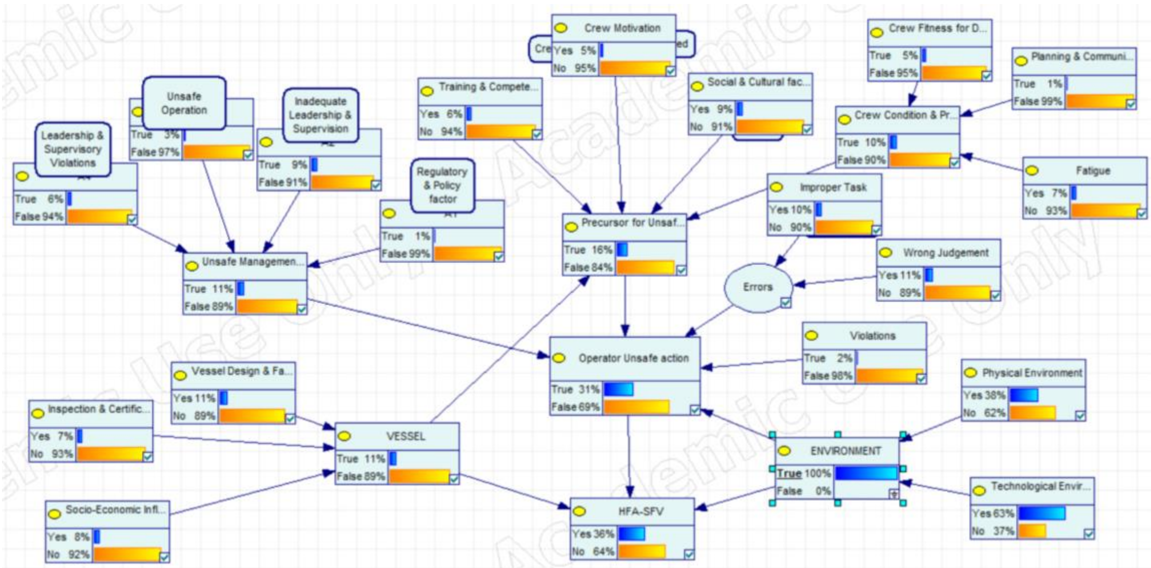

Figure 8.26. Numerical result of HFA-SFV BN when evidence is placed on the environmental factor.

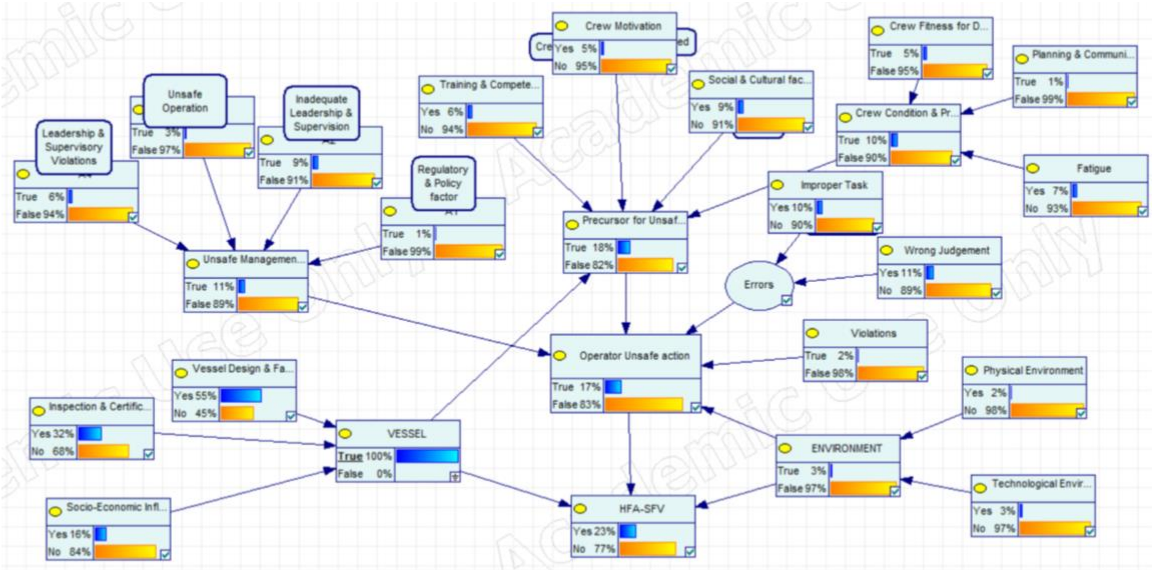

Figure 8.27. Numerical result of HFA-SFV BN when evidence is placed on the vessel.

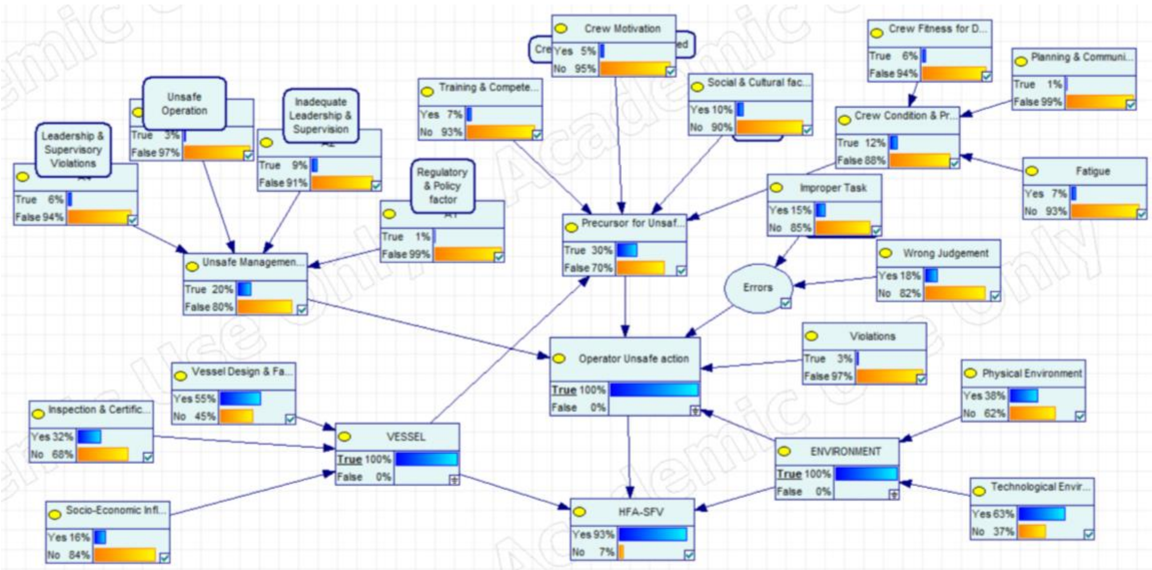

Figure 8.28. Numerical result when evidence of operator unsafe action, environmental effect, and vessel effect.

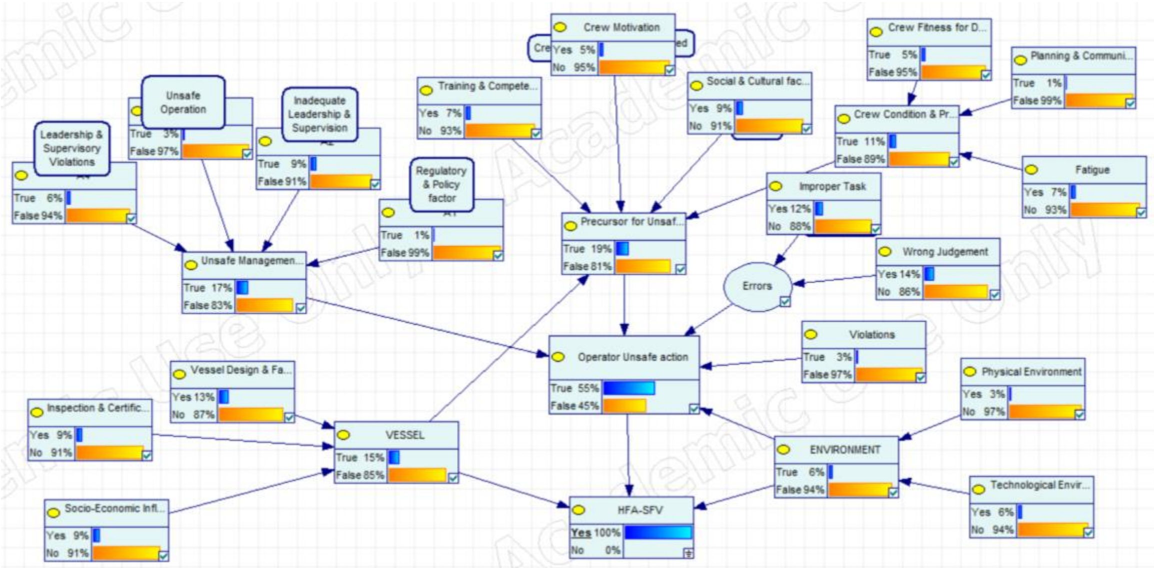

Figure 8.29. Numerical results when evidence is placed on human factor accident (TE = 1).

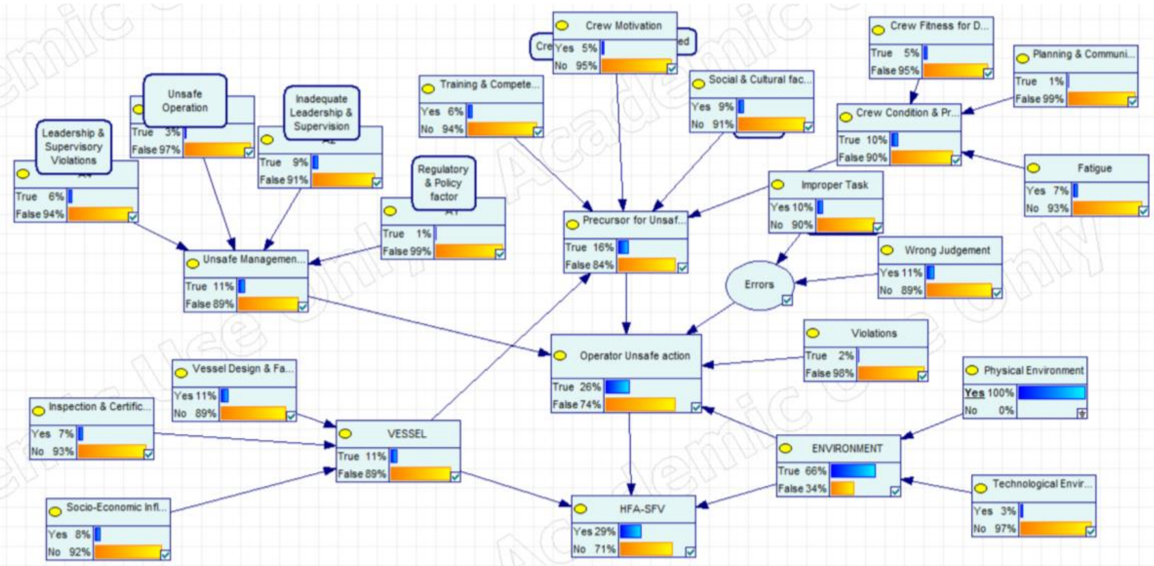

Figure 8.30. Numerical results when evidence is placed on physical environment.

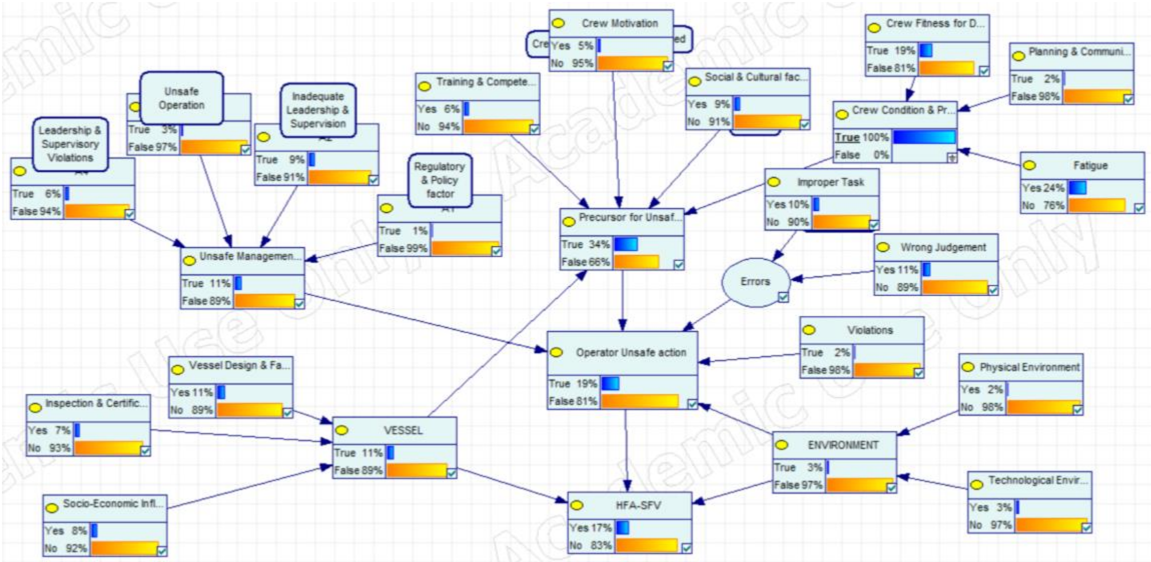

Figure 8.31. Numerical results when evidence is placed on crew condition and practices.

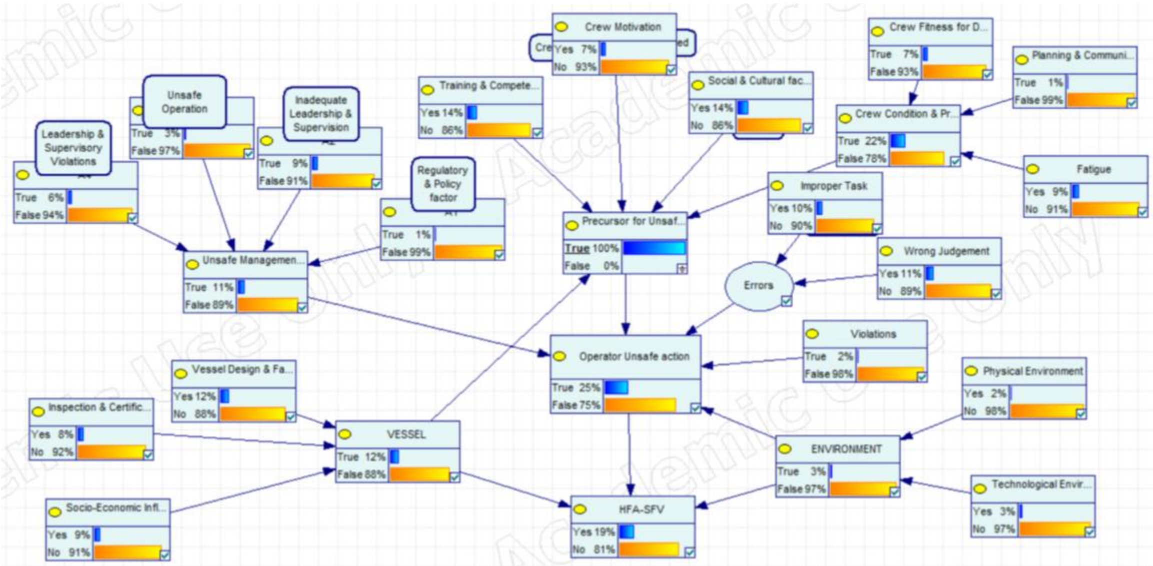

Figure 8.32. Numerical results when evidence is placed on precursor for unsafe acts.

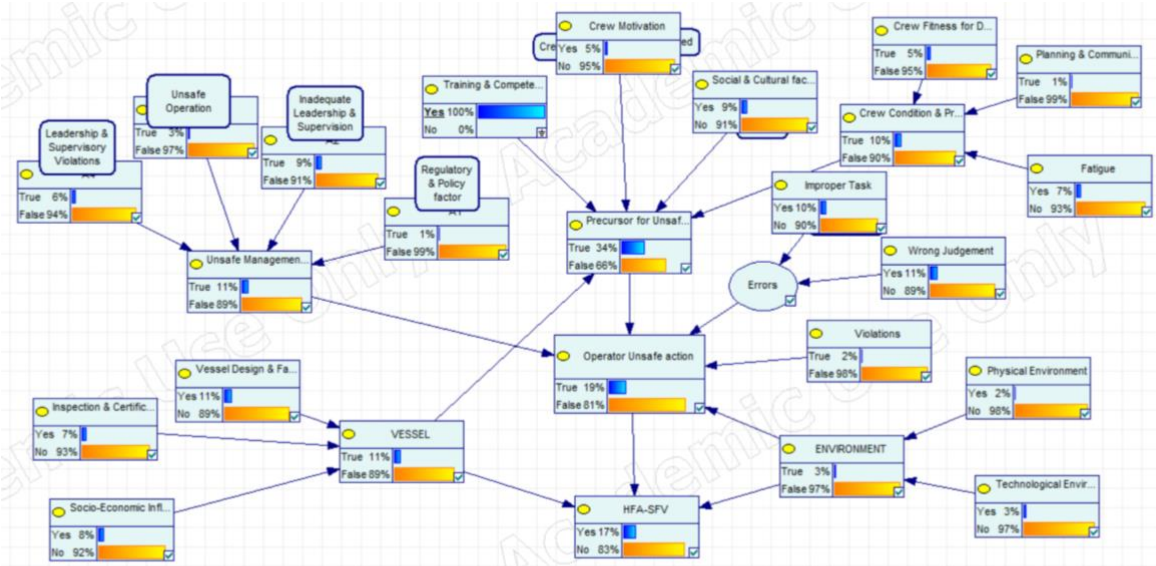

Figure 8.33. Numerical results when evidence is placed on training and competence.

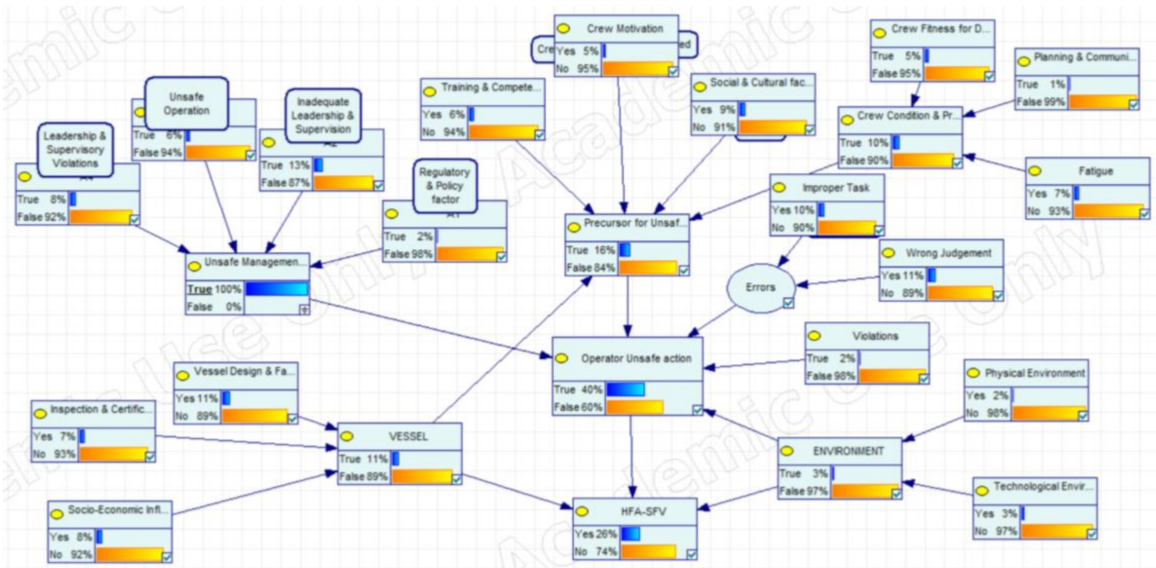

Figure 8.34. Numerical results when evidence is placed on unsafe management.

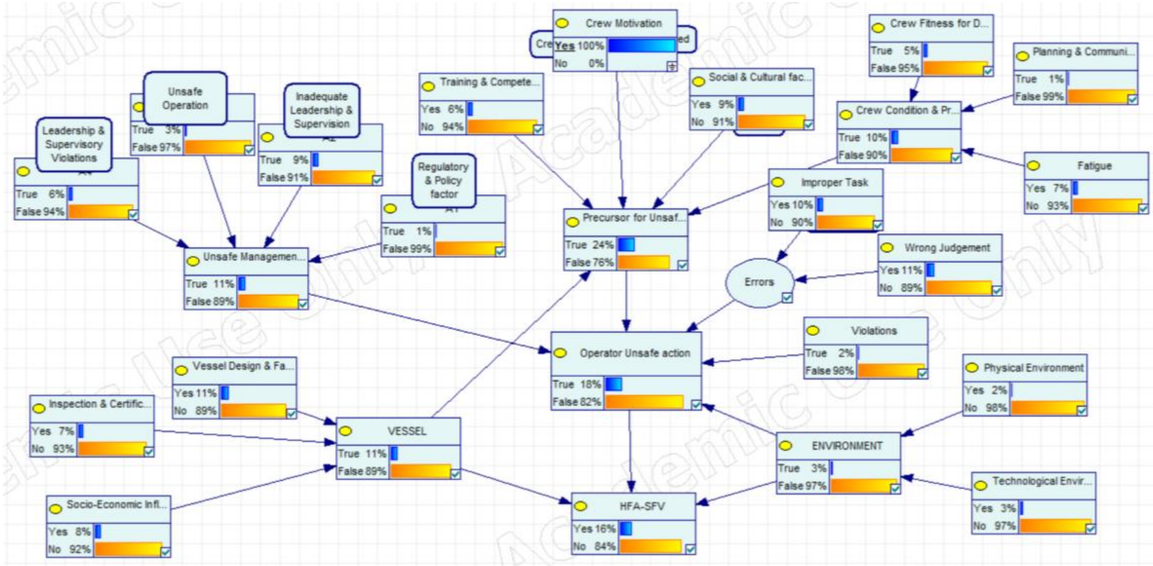

Figure 8.35. Numerical results when evidence is placed on crew motivation.

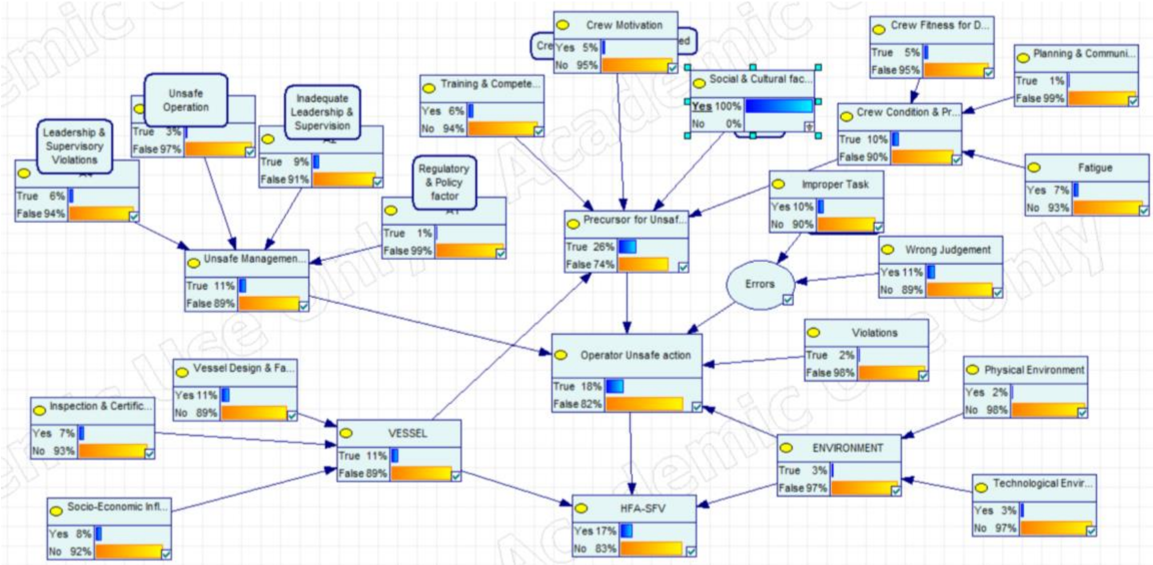

Figure 8.36. Numerical results when evidence is placed on social and cultural factors.

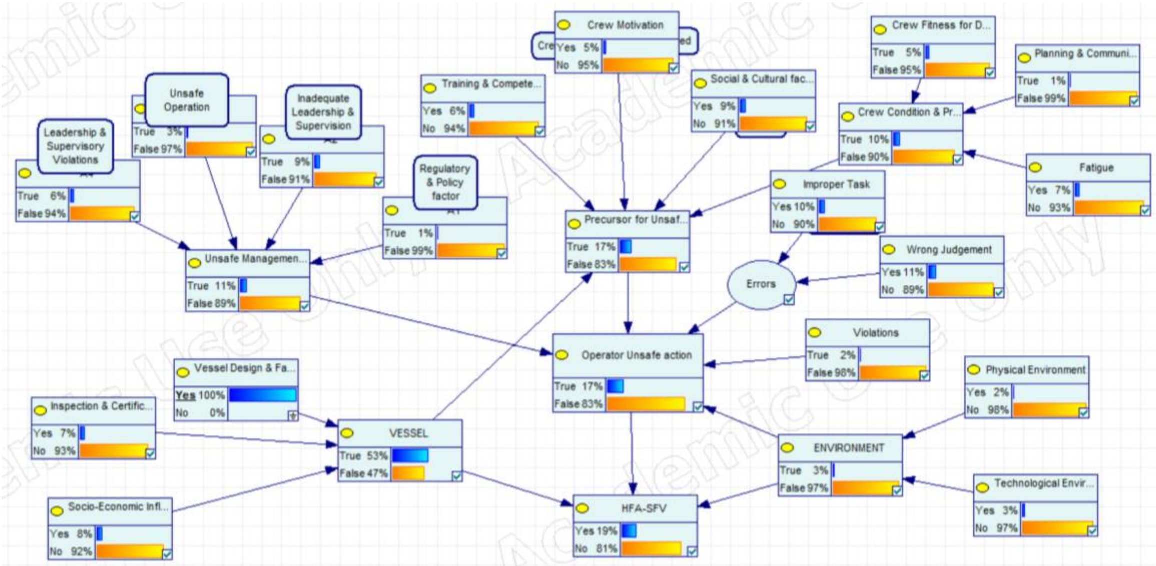

Figure 8.37. Numerical results when evidence is placed on vessel design and fabrication.

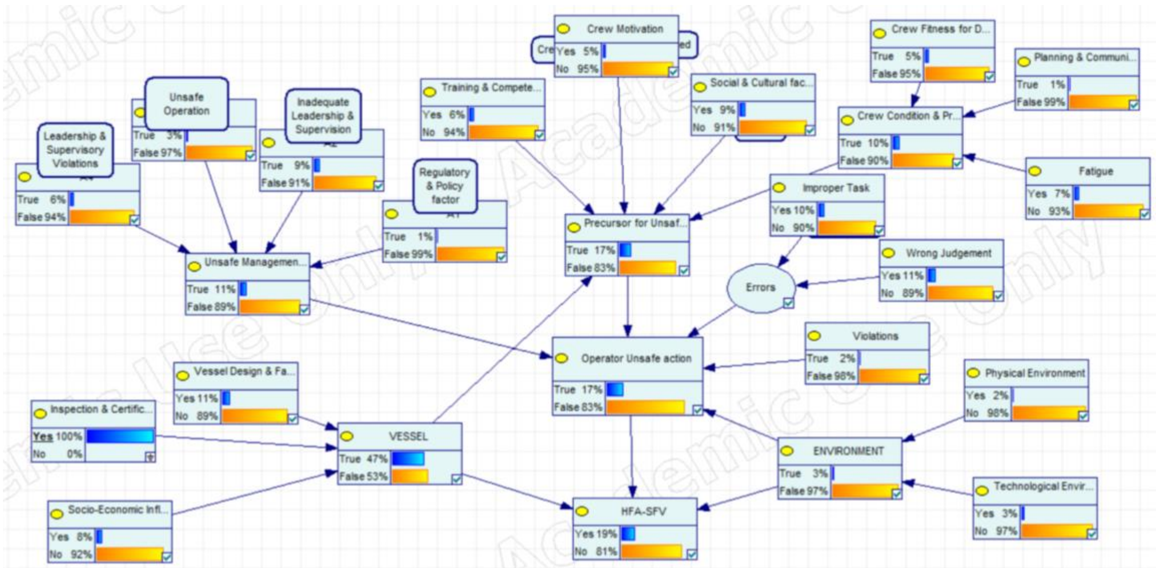

Figure 8.38. Numerical results when evidence is placed on vessel inspection and certification.

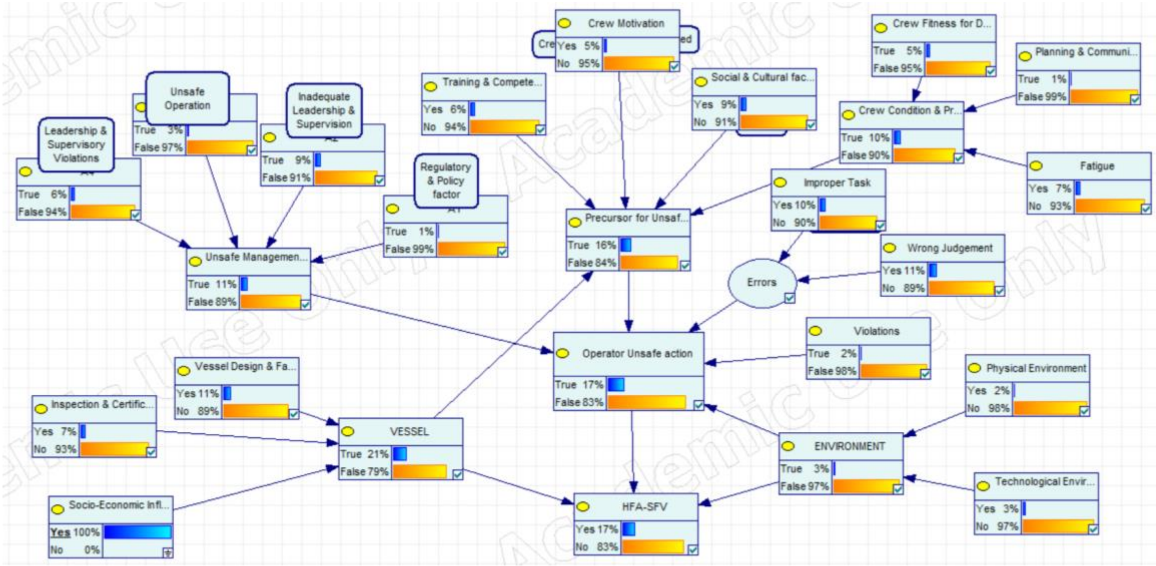

Figure 8.39. Numerical results when evidence is placed on socio-economic influence.

D4. Case-Study Generic Small Fishing Vessel and its characteristics.

Table 8-28. Design features for the model small fishing vessel considered for case study.

Type of Vessel	Small fishing vessel
Estimated tonnage	3.2 tonne
Length (LOA)	7.5 m
Breadth	2.62 m
Propulsion	25-60 Hp (19-45kW)
Speed	10-25 knots
Range	2 – 25 Miles from shore
Cargo	Crates, tote boxes, fishing gear, bait, gasoline fuel
Crew	3-4 members.
Fishing tackle	Drag net (trawl), Gillnets.
Fishing area	NL/NS/BC Inshore waters.
Haul	Herring, salmon, cod, lobster, swordfish, trash fish (bycatch).
Ownership	Private/Master.
Key features	Enclosed fishing deck; power block on hydraulic davit for net handling, bilge pump.

Key/ Legend

The list below illustrates the various items found on the diagrams below.

1) Outboard motor: speed (10-25 knot); 25-60 Hp.
2) Gasoline fuel storage tanks.
3) Safety equipment.
4) Crates.
5) Totes boxes.
6) Crew members (3-4).
7) Fishing gear/ tackle (Gillnet).
8) Power block on hydraulic davit for net handling.
9) Enclosed fishing deck.
10) Bilge pump.

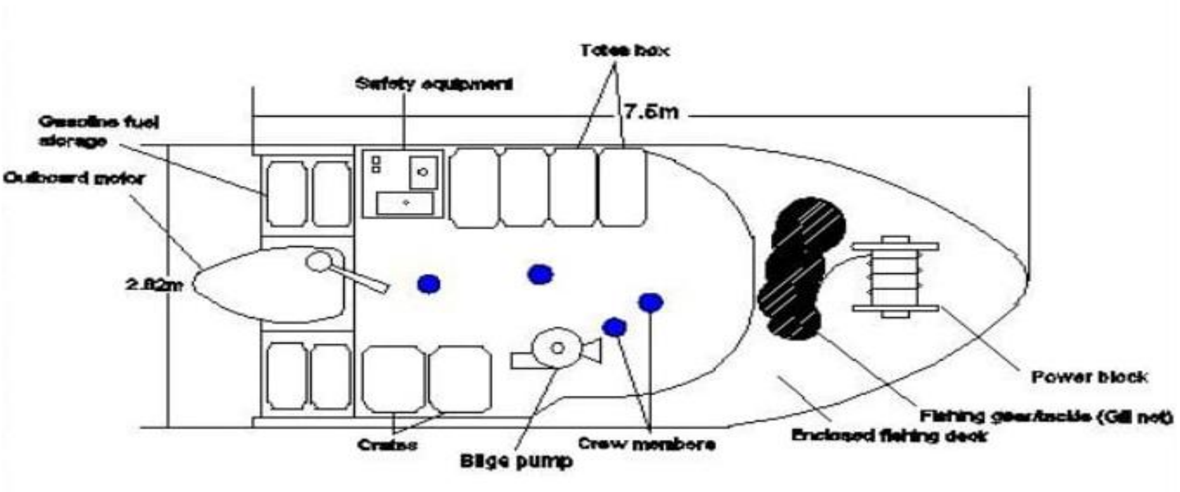

Figure 8.40. Plan view of generic small fishing vessel used for case study analysis.

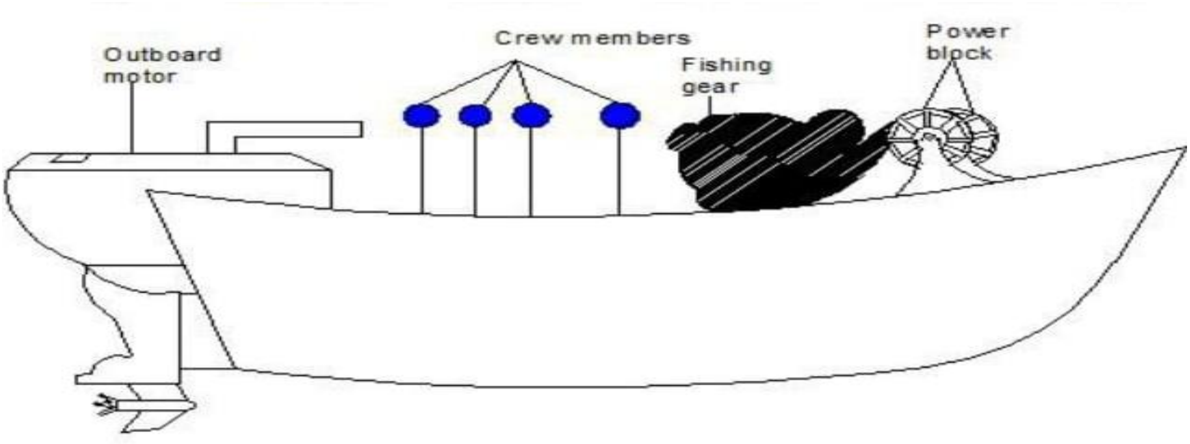

Figure 8.41. Side view of generic small fishing vessel used for case study analysis.