RISK ASSESSMENT AND MANAGEMENT OF PETROLEUM TRANSPORTATION SYSTEMS OPERATIONS

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Abstract

Petroleum Transportation Systems (PTSs) have a significant impact on the flow of crude oil within a Petroleum Supply Chain (PSC), due to the great demand on this natural product. Such systems are used for safe movement of crude and/or refined products from starting points (i.e. production sites or storage tanks), to their final destinations, via land or sea transportation. PTSs are vulnerable to several risks because they often operate in a dynamic environment. Due to this environment, many potential risks and uncertainties are involved. Not only having a direct effect on the product flow within PSC, PTSs accidents could also have severe consequences for the humans, businesses, and the environment. Therefore, safe operations of the key systems such as port, ship and pipeline, are vital for the success of PTSs.

This research introduces an advanced approach to ensure safety of PTSs. This research proposes multiple network analysis, risk assessment, uncertainties treatment and decision making techniques for dealing with potential hazards and operational issues that are happening within the marine ports, ships, or pipeline transportation segments within one complete system. The main phases of the developed framework are formulated in six steps. In the first phase of the research, the hazards in PTSs operations that can lead to a crude oil spill are identified through conducting an extensive review of literature and experts' knowledge. In the second phase, a Fuzzy Rule-Based Bayesian Reasoning (FRBBR) and *Hugin* software are applied in the new context of PTSs to assess and prioritise the local PTSs failures as one complete system. The third phase uses Analytic Hierarchy Process (AHP) in order to determine the weight of PTSs local factors. In the fourth phase, network analysis approach is used to measure the importance of petroleum ports, ships and pipelines systems globally within Petroleum

Transportation Networks (PTNs). This approach can help decision makers to measure and detect the critical nodes (ports and transportation routes) within PTNs. The fifth phase uses an Evidential Reasoning (ER) approach and Intelligence Decision System (*IDS*) software, to assess hazards influencing on PTSs as one complete system. This research developed an advance risk-based framework applied ER approach due to its ability to combine the local/internal and global/external risk analysis results of the PTSs. To complete the cycle of this study, the best mitigating strategies are introduced and evaluated by incorporating VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) and AHP to rank the risk control options. The novelty of this framework provides decision makers with realistic and flexible results to ensure efficient and safe operations for PTSs.

Abbreviations

AAR	Association of American Railroads
ABS	American Bureau Shipping
AHP	Analytic Hierarchy Process
API	American Petroleum Institute
BBNs	Bayesian Belief Networks
BCA	Benefit-Cost Analysis
BDE	Banxia Decision Explorer
BN	Bayesian Network
BP	British Petroleum
BR	Bayesian Reasoning
C	Consequence
CBA	Cost-Benefit Analysis
CP	Compromise Programming
CPD	Conditional Probability Distribution
DAG	Directed Acyclic Graph
DoBs	Degrees of Belief
D_p	Probability risk event cannot be detected before it occur
EC	Expert Choice
EIA	U.S. Energy Information Administration
EMSA	European Maritime Safety Agency
ER	Evidential Reasoning
ETA	Event Tree Analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes and Effects Criticality Analysis

FRB	Fuzzy Rule-Based
FRBBR	Fuzzy Rule-Based Bayesian Reasoning
FRBN	Fuzzy Rule Based Bayesian Network
FRBR	Fuzzy Rule Based Bayesian Reasoning
FSA	Formal Safety Assessment
FST	Fuzzy Sets Theory
FTA	Fault Tree Analysis
FuRBaR	Fuzzy Rule-Based Bayesian Reasoning
H	Hazards
HASAW	Health and Safety at Work Act
HAZID	Hazard Identification
HSE	Health, Safety and Environment
IDS	Intelligent Decision System
IEA	International Energy Agency
IMO	International Maritime Organisation
ISGOTT	International Safety Guide for Oil Tankers and Terminals
ISPS	International Ship and Port Facility Security
ITOPF	International Tanker Owners Pollution Federation Limited
L	Likelihood
LD	Logical Decisions
MADA	Multi Attribute Decision Analysis
MADM	Multi Attribute Decision Making
MCDM	Multi Criteria Decision Making
MHIDAS	Major Hazard Incident Data Service
MPA	Maritime and Port Authority of Singapore

MPTNs	Maritime Petroleum Transportation Network
NIS	Negative Ideal Solution
SAW	Simple Additive Weighting
S_c	Consequence Severity
SNA	Social Network Analysis
SMS	Safety Management System
OCIMF	Marine terminal baseline criteria and assessment questionnaire
OPA	Oil and Pipelines Agency
OPEC	Organization of the Petroleum Exporting Countries
QRA	Quantitative Risk Assessment
P	Probability
Paris MOU	Paris Memorandum of Understanding
PERSGA	Program for the Environment of the Red Sea and Gulf of Aden
PIS	Positive Ideal Solution
PHA	Preliminary Hazard Analysis
PHMSA	Pipeline and Hazardous Materials Safety Administration
P_l	Occurrence Probability
PSC	Petroleum Supply Chan
PTNs	Petroleum Transportation Networks
PTSs	Petroleum Transportation Systems
R	Risk
RPN	Risk Priority Number
RSSB	Rail Safety and Standards Board Limited
SOLAS	Safety of Life at sea
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution

UNCTAD	United Nations Conference on Trade and Development
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje Method

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Chapter 1: Introduction

1.1 Summary

This chapter contains the background of the research and an explanation of the principal research objective and sub-objectives which have been developed through a broad and comprehensive literature survey. The justification of the research study is also addressed in order to identify the importance of this study according to the industrial needs. A number of techniques and methods are highlighted in brief for consideration. Finally, the structure and scope of this research is outlined.

1.2 Research Background

Over the years, crude oil became one of the most important natural resources in almost every nation. This importance came from its impact on global, national, and local economies. Accordingly, the petroleum industry is one of the most popular and critical businesses. Year after year, the demand on this natural resource is continually increasing. Therefore, a safe transportation system for petroleum is essential in order to ensure the safe flow of this strategic resource.

The main purpose of any transportation system is to ensure the movement of people or cargo from point A to point B, within a business supply chain. In the petroleum industry, the transportation system connects the producers of the product to the final customers. The high demand for crude oil ensures the continuous need for Petroleum Transportation Systems (PTSs) (e.g. ports, ships, and pipelines). PTSs arrangements are characterised by huge infrastructures, which comprise sensitive and complex operations and time schedules, and expensive machinery. Due to the dynamic environment of PTSs, many potential risks and uncertainties are involved.

An operational accident within a transportation system leads not only to product loss but also to severe environmental, equipment, and human damage. Recovering from these losses may cost a business millions of dollars. For instance, in 2007, a major oil spill occurred near the Daesan port in South Korea due to a ship collision, in which a ship's hull was punctured. The consequences of the Hebei Spirit accident included damage to the ship and massive environmental damage due to the 11,000 tonnes of oil spilled (Kim *et al.*, 2010). In another incident, a cost of 750 million US dollars was estimated for the losses that followed a ship colliding in the North Sea in Norway (MARSH, 2014). In 2013, a major explosion occurred in an offshore terminal close to Brazil. This incident had negative consequences on both human and properties (250 million US dollars was estimated for property damages) (MARSH, 2016). In Vishakhapatnam, India, 37 people died and 100 were injured when 15 storage tanks of liquefied petroleum gas ignited during a ship's offloading operations (Chang and Lin, 2006; Clark *et al.*, 2001). Other disastrous accidents can be found in the 23rd and 24th edition of MARSH (1974 - 2013) and (1974 - 2015), ITOPF (2016) and (2017), and CONCAWE statistical reports.

These accidents have generated concern about the safety of existing PTSs. Notable organisations in the petroleum transportation industry strive to address historical accidents by establishing and continuously improving safety regulations. Those organisations include the International Maritime Organisation (IMO), the Program for the Environment of the Red Sea and Gulf of Aden (PERSGA), the Paris Memorandum of Understanding (Paris MOU), the International Ship and Port Facility Security (ISPS), the American Petroleum Institute (API), the Oil and Pipelines Agency (OPA), and the Pipeline and Hazardous Materials Safety Administration (PHMSA). These regulations aim to enhance the safety of the petroleum transportation operation within

Petroleum Transportation Networks (PTNs) by controlling and minimising risks within each system. Nevertheless, even with all these rules and regulations, accidents continue to occur. When an accident occurs, a system cannot implement its desired functions, hence causing a failure in PTSs (Baublys, 2007). Therefore, the safety of PTSs should be assessed and managed by the International Maritime Organization's Formal Safety Assessment (FSA) as one complete system. Risk assessment of petroleum port, ship and pipeline operations is a central route in maintaining the petroleum transportation industry's safe operations at operational platforms.

This research investigates the uncertainties of petroleum transportation operations. The research attempts to develop a novel approach that directly influences operational risks, as it enables petroleum supply chain operators to monitor, mitigate, and control the impact and consequences of those risks. Important questions considered in this research include the following: Will the implemented research framework and models affect the operations in petroleum port, ship and pipeline systems? What are the hazards and risks involved in petroleum transportation operations? How might the proposed novel risk models benefit PTSs operations? How do we implement the proposed research framework and models in case studies?

In summary, within this research, first the existing problems in the petroleum port, ship and pipeline systems operations are investigated and critically reviewed, and the major hazards are identified. Second, the research's framework aimed at developing a preferred approach for PTSs operations is presented. Third, the research applies the following mathematical tools: centrality measures, Failure Modes and Effects Analysis (FMEA), Fuzzy Rule Based Bayesian Network (FRBBN), Analytic Hierarchy Process (AHP), Evidential Reasoning (ER) and VIseKriterijumska Optimizacija I

Kompromisno Resenje Method (VIKOR) method. Finally, the proposed research framework and models are applied to case studies.

1.3 Aim of the Investigation

The research aims to develop a novel risk assessment methodology for estimating, controlling, and monitoring the operational risks in PTSs. This research will benefit the petroleum industry by allowing operators to better control PTSs hazards and thereby ensure safe operation for petroleum transportation as a complete system. In order to accomplish the research's aim, the following objectives are addressed:

1. To review comprehensively previous research in order to identify the problems that are associated with petroleum port, ship and pipeline systems operations and consider all traditional risk assessment methods.
2. To identify and analyse the Petroleum Transportation Networks (PTNs) vulnerabilities that need to be considered while carrying out safety assessments of petroleum supply chains.
3. To develop a new quantitative hybrid Fuzzy Rule Based Bayesian Reasoning (FRBBN) for evaluating the risk level of each component involved in Petroleum Transportation Systems (PTSs) operations.
4. To develop an advanced risk assessment framework for Petroleum Transportation Networks (PTNs) using Analytic Hierarchy Process (AHP) and Evidential Reasoning (ER) approach.
5. To design a risk-based decision-making support system that offers a systemic approach capable of improving the decision-making process of PTSs operations and implementation of those operations in the petroleum industry.

6. To perform test cases and numerical analysis to validate the proposed framework and models.

These objectives are accomplished across chapters 2, 3, 4, 5, and 6. The first objective is accomplished with the literature review in chapter 2. The centrality measures, FRBBN, AHP, and ER techniques are applied in chapters 3, 4, and 5, respectively to accomplish the second, third and fourth objectives. The VIKOR method is applied in chapter 6 for improving the safety within this system (objectives 5). Finally, the case study objective is accomplished within chapters 3, 4, 5, and 6 (see Figure 1.1).

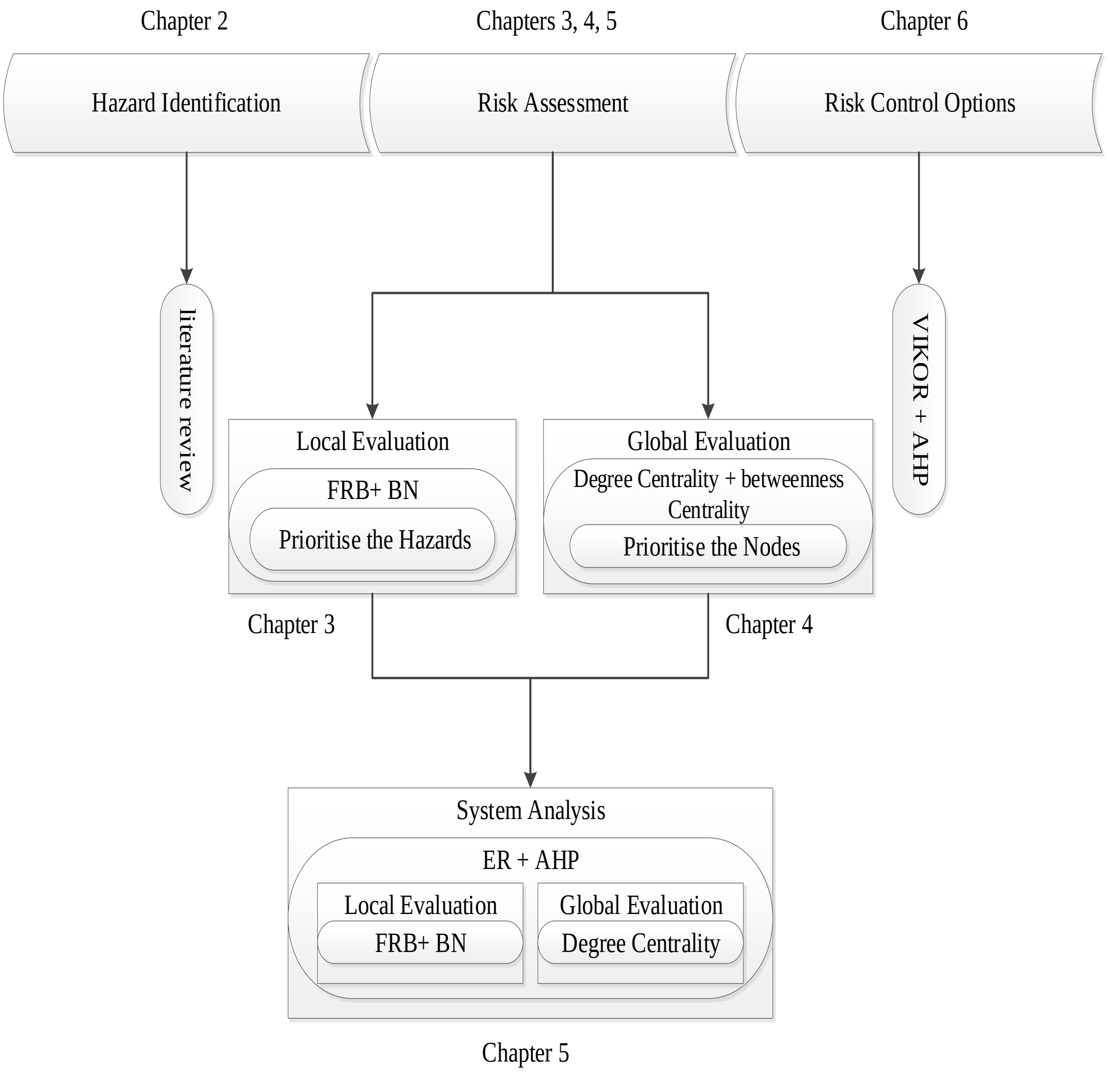

Figure 1.1: Risk management framework for PTSs operation

1.4 Thesis Outline

This research comprises seven chapters, as shown in Figure 1.2.

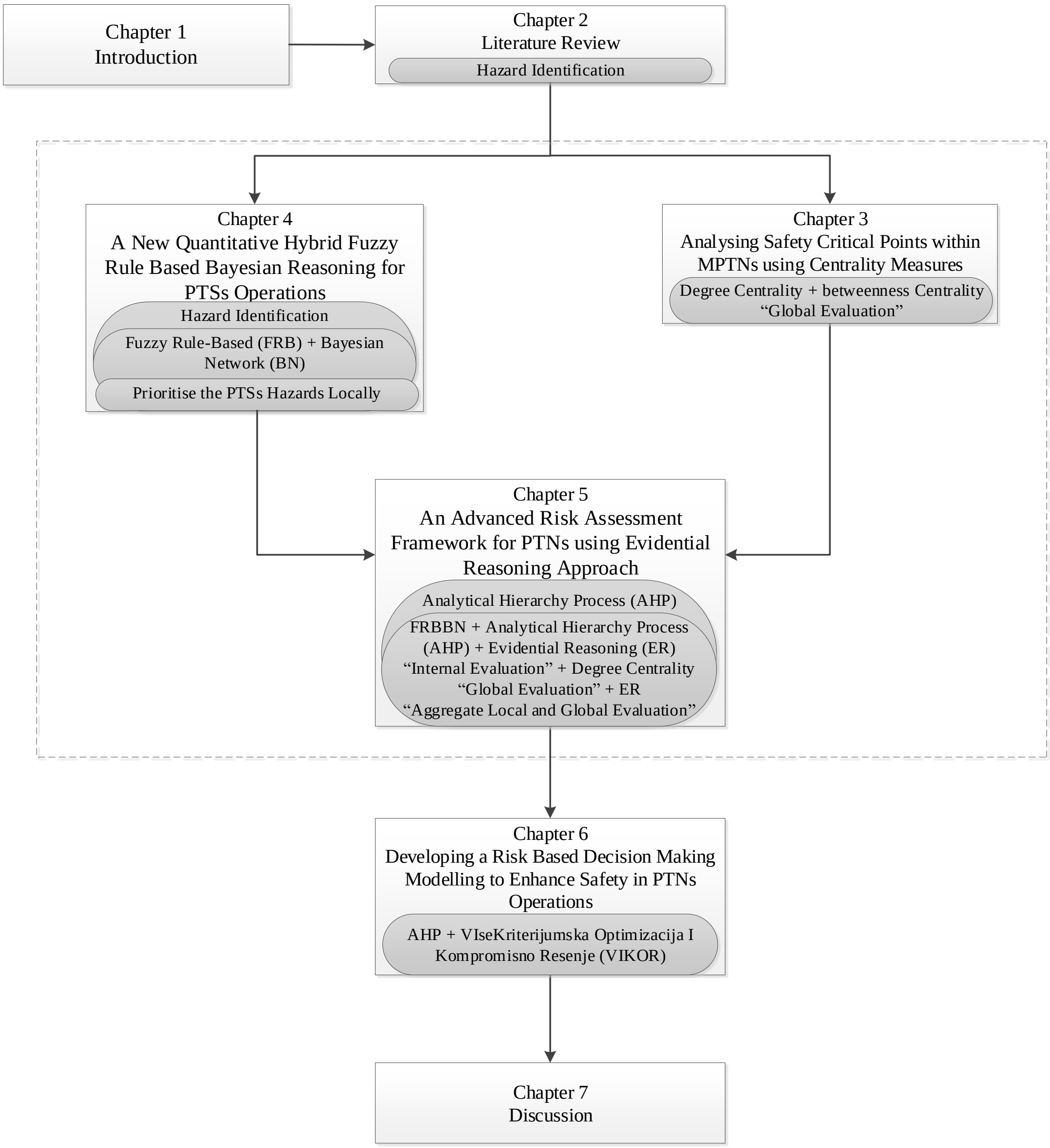

Figure 1.2: Thesis outline

These seven chapters are defined in more detail as follows:

Chapter 1 starts with a background of the research. An explanation of the aim and objectives of the study follows. To identify the importance of this study, the research justification is then presented. A list of the techniques employed to accomplish the aim of this research is presented. The chapter concludes with this outline of the study. Finally, this chapter ends with a statement on the scope of the research.

Chapter 2 presents the significant literature review undertaken to appropriately organise this research. This literature review provides the basic foundation that guides the research. Several relevant conference papers, journal articles, books and websites reviewed to accomplish the aim of this chapter were presented. The review explains in detail the typical hazards and risk reliability of PTSs operations. Moreover, the major causes and/or risk factors in the petroleum port, ship and pipeline systems operations are defined and analysed to provide an understanding of risk identification and analysis.

Chapter 3 analyses the maritime petroleum transportation network. Furthermore, this chapter introduces the centrality measures technique used to evaluate the global network of PTSs. This technique is then applied to a real maritime transportation system. This chapter accomplishes the 2nd objective and part of the 4th objective described in Section 1.2.

Chapter 4 analyses the hazards associated with PTSs in order to prioritise and identify the most significant hazards within such systems. Within this chapter, a hybrid Fuzzy Rule Based Bayesian Reasoning (FRBBR) model is introduced due to the high level of uncertainty in petroleum port, ship, and pipeline operations.

Chapter 5 analyses petroleum transportation as a complete system in order to evaluate the safety level of this system. The novelty of this chapter is through combining the external and internal evaluations presented in chapters 3 and 4, respectively. To aggregate the internal with the external evaluations, the AHP and ER techniques are introduced.

Chapter 6 identifies the best solution from a list of identified risk-control options in order to mitigate the PTSs' most significant hazards, as identified in chapter 4. To accomplish this chapter, VIKOR is used to analyse different alternatives (i.e. risk-control options) with respect to several criteria. Furthermore, the AHP technique is used to evaluate the weight associated with each criterion.

Chapter 7 discusses the research model and its capability in assessing petroleum terminals and transportation modes. The chapter also addresses and discusses how the system risk-control options can be achieved. Furthermore, the research contribution of the knowledge presented in this research is discussed. Finally, the chapter offers recommendations for possible future study that could improve the developed model.

The references and the appendices, which include some of the data that could not be presented in the main chapters, are delivered at the end of the research.

1.5 Research Justification

Crude oil is an important product for various businesses. The transportation systems that move this natural product from the production site to the final customer are therefore of great concern to stakeholders, organisations, and the public. This concern has been amplified due to the rapid increase in crude/refined petroleum transportation and in the number of associated accidents. The operation of PTSs, like the operation of any other systems, is associated with hazards. These unwanted hazard events are a threat to the environment and public due to the harms that follow failures. Identifying the hazards that are associated with PTSs helps decision makers to mitigate or even eliminate them, which in turn makes the transportation system safer and more efficient in certain and uncertain situations.

This study could be instrumental in enhancing the safety level of petroleum transportation operations, which must take into consideration the past accidents in the industry. Namely, this research responds to the lack of a risk management framework that addresses the safe operation of petroleum transportation as one complete system. The study thus helps to fill the research gap on safety processes for complex systems like PTSs operations. To accomplish its objectives, this research uses the International Maritime Organization’s Formal Safety Assessment (FSA) technique to identify, analyse, and manage the hazards associated with PTSs operations, which entails a great deal of uncertainty. There is a need for this research because this study addresses petroleum transportation as a system (i.e. ports and maritime transportation). This study evaluates PTSs both internally and externally to ensure the safety of the transportation system.

1.6 Research Contributions

Unlike other petroleum industry related research, this research proposes a framework for analysing and managing PTSs as one complete system under uncertainty. Overall, the main aim of this research was to identify, evaluate, and propose a way of controlling PTSs’ operational risks.

1.7 Research Scope

The scope of study is briefly explained in Figure 1.3. The literature review on PTSs highlights that several researchers have focused intensively on the petroleum supply chain. The petroleum supply chain has three parts: the exploration phase, the production phase, and finally the distribution and delivery of the crude oil or refined products to the final customer (An *et al.*, 2011). Within this research, PTSs, which are employed in the third phase, are highlighted.

The transportation system that moves crude oil around the world involves many ports and transportation modes. Pipelines, trains, ships, and trucks are the transportation modes that ensure the flow of the product through the petroleum supply chain. Most petroleum is still transported around the world via tankers and/or pipelines to reach the end user. Therefore, this research focuses on analysing the ports, ships, and pipelines within the global PTS in order to achieve all the objectives described in Section 1.2.

Within this study, a local PTS is explored and evaluated internally and externally. Several ports and transportation routes are associated with this transportation system.

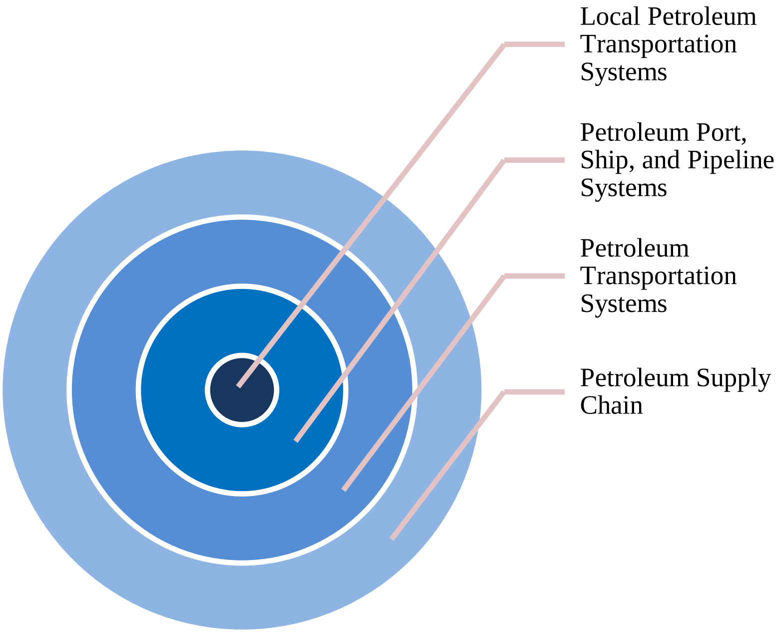

Figure 1.3: Research scope

Chapter 2: Literature Review

2.1 Summary

This chapter reflects the importance of the literature to this study. The petroleum supply chain stages are reviewed, followed by individual discussion of the petroleum transportation means, which include inland and water transportation systems. The chapter also briefly reviews the transportation systems of crude oil. The operations for each of the involved systems are discussed in depth in this chapter. In each case, the numerous historical accidents that have taken place within each system are noted. This chapter next provides a review on the risk assessment of petroleum transportation systems (PTSs). Different risk assessment and decision-making approaches such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), and Fuzzy Sets Theory (FST) are described. Furthermore, this chapter demonstrates in depth the risks that are involved within these transportation systems.

2.2 Introduction

The petroleum industry boom has fuelled the growth of major transportation systems for crude petroleum and derivatives such as petrol, kerosene, and oil. Since the first boom in the oil industry in the 19th century (Balcilar *et al.*, 2015) several transportation systems have been established based on the nature of the areas through which this natural resource must pass. This system of major transportation includes rail transportation, shipping, pipelines, track transportation, and petroleum ports (Coyle *et al.*, 2010).

The petroleum industry supply chain has five major stages (Varma *et al.*, 2008). The first stage is exploration, followed by production, transportation, refining, and finally storage and delivery to the end customer (An *et al.*, 2011). Many operational actions take place at each stage. For example, in the exploration and production stages, activities may include seismic geological operations, drilling processes, and reservoir extractions (AL-Othman *et al.*, 2008; Sinha *et al.*, 2011). The refining stage entails complex chemical processes; these processes transform the extracted crude oil into several final products (e.g., liquefied petroleum gas, diesel, and kerosene) that are useful to numerous industries (Papageorgiou, 2009; Yue *et al.*, 2014).

Petroleum Transportation Systems (PTSs) involve many methods to ensure that petroleum and its refined products reach the final customers through connections between different industry supply chains. PTS means are comprised of land transportation systems (i.e. rail, pipelines, and truck transportation systems), sea transportation (i.e. shipping), and petroleum ports (Coyle *et al.*, 2010). Through the years, PTSs have rapidly improved. The safety of land and sea transportation systems and petroleum ports has been taken into consideration. In enhancing the operational practices of these systems, several technologies have been incorporated in order to enhance safety and reliability (McCoy, 2008). As a result, modern PTSs are becoming more and more oriented towards the safety of the environment, humanity, and equipment, while ensuring the safe delivery of crude products to various destinations within the supply chain.

PTSs safety is a vital subject due to the growth of the petroleum industry. PTSs connect the petroleum industry chains that are used for the transportation of crude oil and other hazardous refined petroleum products. These transportation systems are responsible for carrying flammable products with high risk potential for humans, businesses, and the environment (John *et al.*, 2014a). Therefore, PTS safety demands high attention in order to avoid any unwanted consequences. This research entails an in-depth risk assessment of the transportation systems of petroleum. As noted above, petroleum is transported by several means, including pipelines, ports, shipping, rail carriers, and truck tanks. In addition to port transportation system, this study focuses on risk assessment for sea transport, namely ship transportation system, and for the pipeline transportation system. Therefore, this chapter aims to present a brief literature review about PTSs' operations in these two areas. To accomplish this aim, the chapter is divided into three sections. The chapter starts with an overview of the petroleum transportation chain, with a particular focus on PTSs operation and the associated historical accidents. Within the first section, the research gap that this thesis aims to address is identified. The second section describes the methodology traditionally used for management of PTSs. Well-known and popularly used assessment techniques are discussed in this section. Finally, the third section identifies the existing hazards in each operational system. The chapter ends with a brief conclusion.

2.3 Overview of Petroleum Transport

Petroleum transport is the movement of crude oil from its origin to its final destination. This movement is considered one of the foundations of the petroleum industry. PTSs play a critical role in the flow of crude oil within a Petroleum Supply Chain (PSC). PTSs enable the movement of crude and/or refined products from starting point (i.e. production sites or storage tanks) to their final destinations, via land and/or sea. During the crude oil journey through the PSC, multiple systems are involved. Ports and transportation modes are the basic elements in PTSs. Petroleum ports, ships, trucks, rail, and pipelines represent the transportation elements structures of PTSs.

Petroleum ports comprise a major element within PTSs. Ports are mostly designed for the reception of crude oil that comes by water or land transportation. Ports are typically used to transport petroleum locally or internationally to serve the port market (John *et al.*, 2014a; Wang and Cullinane, 2008). Ports are considered to be the last point that separates land and ocean; they connect land transportation systems to sea transportation systems. In other words, ports act as a middleman between the landmass and waterway (Fleming and Hayuth, 1994).

Ships, specifically oil tankers, are well-known sea transportation means. Marine oil tankers are used for local and global transportation of crude oil from one port to another. Product tanker, Panamax, Aframax, Suezmax, Very Large Crude Carrier (VLCC), and Ultra Large Crude Carrier (ULCC) are terms used to classify petroleum ships based on the tanker size. Tankers have the ability to carry a huge amount of crude oil, thus facilitating movement of the product across the oceans (Song and Panayides, 2012). Petroleum ships are considered to be the most convenient way of transporting large volumes of crude oil across oceans (Coyle *et al.*, 2010; Ismail and Karim, 2013).

Trucks and **rail** are two transportation means used to move crude oil by land. While trucks employ a single tank, trains travelling along rails can employ several tank cars (Yan and Crookes, 2010; Shunping *et al.*, 2009). Trucks are usually used to transport refined oil from storage areas to the final destination. Unlike other modes of transportation, trucks are usually used to transport smaller volumes of flammable products as gas and diesel (Pootakham and Kumar, 2010). Trucks are used to deliver the product to areas that other transportation modes cannot reach or to deliver small volumes of the hazardous product (Yan and Crookes, 2010). On the other hand, the rail transportation system uses special tanks to move crude oil by train, taking the product to its final destination, often the refinery (Shunping *et al.*, 2009). Unlike trucks, trains can pull multiple tanks. As a result, the rail system is capable of transporting much larger volumes of petroleum by land (Association of American Railroads, 2017). Rail carriers are a cost effective mode of transporting oil and can be used to transport crude oil to the refinery as well as refined oil from the refinery to different distribution channels (Shunping *et al.*, 2009; Coyle *et al.*, 2010).

Pipelines are the most common and cost effective mode of transporting petroleum by land (Herrán *et al.*, 2010; Coyle *et al.*, 2010). Pipelines are mainly used to transport crude oil extracted in the production stage to the refineries and the storage facilities (Pootakham and Kumar, 2010). Pipelines are also used to deliver finished refined petroleum products from the refinery to the customer. A number of factors such as pumping stations are involved in pipeline systems, which aim to ensure continuous flow over long distances (MirHassani and Ghorbanalizadeh, 2008). Checkpoints are placed along pipelines to observe the crude or refined products and make sure that it is not affected during transportation. Constructing the pipeline system is expensive. However, once pipelines are in place, operation costs are low compared to operation costs of other land transportation means (Coyle *et al.*, 2010). Therefore, pipeline systems have become the most used and safest oil transportation mode for land transportation (Herrán *et al.*, 2010).

To ensure the smooth flow of the product within the system, tankers and pipelines are the two most commonly used transportation modes (Pootakham and Kumar, 2010; Herrán *et al.*, 2010). While ports act as a connecting point between the transportation modes, pipelines and tankers are used for inland and sea transportation respectively. The U.S. Energy Information Administration (2014) highlight that, in 2013, 56.5 million barrels of oil per day (bbl/d) were transported by sea. In other words, about 63% of total world crude oil production (i.e. 90.1 million bbl/d) is moved using PTSs. In addition, the U.S. Energy Information Administration (2017) stated that, 96.7 million bbl/d was the total world production of crude oil, where 58.9 million bbl/d (i.e. about

61% of the total production) was carried via sea transportation systems in 2015. It highlights the rapid growth in crude oil production and its high demand market. The great demand on this critical product led to an increase in the quantity of crude oil that was transported within the PTSs (i.e. 2.4 million bbl/d increase in crude oil movement).

The nature of petroleum supply chains necessitates prioritizing safety and performing risk management. PTSs risk management plays a critical role in ensuring the transportation system resilience in the context of PSC. Previous PTSs scholars have researched various aspects of the transportation modes involved in petroleum transportation. For example, MirHassani (2008) investigated sea and land transportation modes, including marine vessels, pipelines, rails, and road tankers, from a management perspective. According to MirHassani (2008), pipelines are considered as the most reliable and economic petroleum transportation mode via land, while tankers are the most economic mode for transporting huge volumes of crude oil by sea. Underwood and Waterson (2013) highlight that the number one priority in any transportation system and most especially within transporting crude oil or other hazardous products is safety.

No transport mode is considered 100% safe when it comes to transporting petroleum (Bersani *et al.*, 2010). However, some modes are considered to be safer than others. According to Green and Jackson (2015), when transporting petroleum products over a very long distance on land, pipelines are the safest option. However, pipelines still entail numerous hazards, including the risk of leaks (Aroh *et al.*, 2010). Restrepo *et al.* (2009) observed that pipeline leakages might not actually happen along the pipeline; instead other involved factors, such as human error at pumping stations, tend to be the cause. Accordingly, Restrepo *et al.* (2009) suggest that if human error is minimised at the sub-stations, leakage could go down to a negligible level or even to zero. Spillage of these flammable products during transportation also poses a danger to the environment and to human lives (Sovacool, 2008). Therefore, any mode of transport to be used should incorporate a means of protecting the environment as incarnate the product movement (Rausand, 2013).

Researchers have done research on the impact of petroleum transportation on the environment. According to Petrova (2011), so long as the petroleum and its compounds are not exposed or leaked into the surface, the transportation remains harmless. However, if exposed or leaked to the surface, the products become a threat to nature. For instance, they could pose health risks to animals and cause deadly fires and explosions (Restrepo *et al.*, 2009). On the other hand, when considering transportation across continents and large water bodies, marine ships are the most effective and safest mode of transporting petroleum products (Song and Panayides, 2012). Researchers such as Psaraftis and Kontovas (2013) focused on transportation speed, due to its importance for the industry supply and its effect on the environment. Relvas *et al.* (2013) focused on finding fast solutions to the petroleum transportation scheduling problem.

Numerous studies have addressed the component level of the crude oil transportation supply chain. Ronen (1995) addressed the scheduling problem associated with transportation of crude oil and that problem's effect on refining and distributing heavy products (such as base stock for lube and residual oil) and light products (such as gasoline, kerosene, and diesel oil). Ronen (1995) proposed partitioning in scheduling formulations to minimise cost and set packing to maximise profit. Catchpole (1962) focused on the tactical planning of the product flow. The researcher proposed a liner programme that planned the crude oil flow from the production stage to the refinery and the refined products flow from the refinery to the customer. The programme considers the cost and demand of the products as stochastic factors.

Sear (1993) developed a model for refined products transportation in an oil company's downstream supply chain. Sear (1993) also delivered a calculation matrix for estimating the transport cost. Through using an approximation algorithm based on problem decomposition and function approximation, Cheng and Duran (2004) developed a simulation model for planning world-wide crude oil transportation and a Markov decision module. Cheng and Duran's (2004) model is for stochastic optimal control of inventory and transportation systems. Li *et al.* (2012b) developed a dynamic fuzzy logic model to meet the unbalanced demand and production of crude oil which affects the market activity in maritime transportation.

Overall, petroleum production and consumption is highly associated with nations' development. Also, the produced petroleum and its refined products pass through various stages within the industry supply chain. Transporting this natural product ensures its movement till reaching its final destination. PTSs are considered to be one of the critical stages within the petroleum supply chain. A failure within this system might lead to a disaster in the petroleum industry. Such systems are complex because they often operate in a dynamic environment. Consequently, the systems' key components (i.e. ports and transportation modes) must operate in a safe condition to ensure the success of PTSs. Therefore, it is crucial to identify and assess the hazards affecting PTSs to ensure the overall safety and reliability of the systems.

2.4 Petroleum Transportation Systems Operations

PTSs compose a critical part of the petroleum supply chain. The connections within PTSs form a complex system. This is demonstrated by the fact that there are multiple systems (i.e. ports, tankers and pipelines) engaged within its operations. As a result, PTSs operations are highly associated with unwanted hazards that might strike any point within the system which might lead to system failure.

As mentioned previously, PTSs consist of two attributes: ports and transportation modes. Effective operation of these two attributes ensures that petroleum is successfully transported through PTSs. Still, accidents might occur within ports, ships, or pipelines. Such an accident would negatively affect the product flow throughout the Petroleum Transportation Networks (PTNs). Therefore, crude oil flow between two points may be affected by an accident which might occur at any stage within the PTSs. To avoid possible risks in PTSs operations, the dynamic environment of PTSs needs to be investigated. Such investigation can deliver control options for unwanted hazards that threaten proper operation of PTSs. Ports, ships, and pipelines systems compose the three main systems that operate within PTSs.

Ports comprise the first operation system within PTSs. Within the ports area, several operational activities take place in order to ensure that the crude product is successfully transported through the system (Mokhtari *et al.*, 2012). Offloading and loading the crude oil are among the major activities at petroleum ports (Trbojevic and Carr, 2000). Loading or offloading operations could be either the first or last operational activity at the ports system. Offloading involves transferring crude oil from a newly arrived tanker into a petroleum terminal; loading, which occurs upon the crude oil's departure to another destination port, is the opposite process (Ronza *et al.*, 2006; Trbojevic and Carr, 2000). Between offloading and loading operation, several other operational activities, such as pumping the product, also occur at petroleum ports. These forms of operation require equipment such as pipes and pumps to guarantee the operational process and product movement within the ports system (ISGOTT, 2006). In addition, as ports act as a middleman between land and water transportation, in some scenarios ports also act as a temporary storage space for cargo (Wang *et al.*, 2013a). Ports usually have warehouses in which the products to be transported are temporarily stored awaiting their turn to be loaded into the tankers (Chang and Lin, 2006). Dolman and Van Ettinger (2013) define ports system as intermodal connectors that connect the land and sea systems. An effective port operation ensures that the products are safely transported (Dolman and Van Ettinger, 2013). Generally, all the operations in the ports aim at ensuring efficient and effective loading and offloading of petroleum to and from the vessels and storage tanks.

Ships constitute the second system in PTSs operations. While the ports system connects trade between local and oversea markets, ship transportation enables transporting of petroleum for short and long distances across waters (Coyle *et al.*, 2010). The sea transportation system is designed to transport the crude or refined products in bulk across the sea. In general, compared with other transportation modes (i.e. land transportation systems), sea transportation is cheaper over long distances (Coyle *et al.*, 2010). Since the first tanker set sail in 1886, vessels have grown in size (Papanikolaou, 2016). This growth has led to an increase in the size of cargo that can be transported by sea in every ship. However, growth in vessel size has not eliminated the disasters that follow accidents in this system.

After 9/11, measures were put in place due to the security issues for sea transportation (Harrald, 2005). The International Ship and Port Facility (ISPS) code (2003), for example, became part of SOLAS (i.e. the International Convention for the Safety of Life at Sea). These measures have had a drastically positive impact on ships, ports, and governments. ISPS is mandatory for SOLAS parties, who must construct, equip, and operate their ships as per SOLAS minimum safety standards. These measures are regulated to improve the safety and security of the maritime industry (Mazaheri and Ekwall, 2009).

On tankers, several operations activities take place. Examples include ensuring the vessel is operating in safe conditions in open waters and when the ship enters port areas; loading and discharging the crude product at the port; ensuring that the pressure within the ship hull is at a safe level; and keeping the equipment in good condition for a safe operation (Mahfouz, 2009; Uğurlu, 2016; ISGOTT, 2006). Qualified staff members (i.e. engineers and captains) are required on board to provide the required services in everyday activities and emergency situations (Riahi *et al.*, 2012; Uğurlu, 2016).

Pipelines system is one of the most common means of crude oil transportation. According to Herrán *et al.* (2010), low-carbon steel or low-alloy steel are the materials usually used to construct transportation system pipes. Pipelines are usually located at a depth of about 1 to 1.5 meters underground (HSE, 2008). Within PTSs, the crude product is commonly pumped through pipelines, and pump stations located alongside the pipelines ensure the product flow within the pipes (Coyle *et al.*, 2010). At present, over 60 countries have pipeline systems were USA and Russia have the longest networks (El-abbasy *et al.*, 2015). Pipelines need to be protected against damage such as abrasion, corrosion, and even impacts in order to ensure the product flow within the system (Rajasekar *et al.*, 2010).

In addition, maintenance of pipelines should not be neglected. Maintenance schedules need to be put in place to ensure an effective, efficient and safe transfer of petroleum and petroleum products through the system pipelines (Yuhua and Datao, 2005). Such activities necessitate regular inspection via a process known as pigging. Pigging is an operational process that uses an inspection device (pigs) to maintain the system pipes. This technological operation is used to identify and detect any abnormal happenings along the pipe such as the presence of dents, corrosion, cracks, and any other mechanical damage (Esmaeilzadeh *et al.*, 2009). After detecting damage in the pipes, the operators must then carry out measures to fix those problems and improve the condition of the pipeline. The ‘smart pigs’ used for inspecting the status of the pipes are at times also used to clean any paraffin wax that may be deposited on the pipe or any other deposited materials; these machines are then received at the other end of the pipe (Anifowose *et al.*, 2012).

Research on the ports and transportation modes industry mainly relates to the legislation and safety acts. Such policies include the Application of the Employers’ Liability (Compulsory Insurance) Act 1969, the Health and Safety at Work Act (HASAW) 1974, and the Oil Pipeline Act (1956) (amended by the Oil Pipeline Act 1965) (ABS, 2003; OCIMF, 2008; HSE, 2017; Aroh *et al.*, 2010). The research has demonstrated the applicability of quantitative and qualitative risk analysis approaches. Many sources have discussed comprehensively the issues of safety cases and safety reports; Safety Management System (SMS); Formal Safety Assessment (FSA); Health, Safety and Environment (HSE); ISPS Code; Safety Case Regulations; and Quantitative Risk Assessment (QRA).

The safety of system operations is a prime concern for operating companies due to the high economic and financial impact of safety apart of failures (Elsayed *et al.*, 2009). Recent studies have highlighted the importance of PTSs’ safety in the movement of crude oil. A careful literature review has revealed that several studies have been conducted on operational risk and reliability relating to PTSs. Siddiqui and Verma’s (2013) research outlined a risk assessment methodology for estimating the risk of transporting crude oil internationally via ship tankers. Eliopoulou *et al.* (2012) performed a risk assessment study of historic medium and large oil tanker accidents.

Markowski and Mannan's (2009) research presented a risk assessment framework for the hazards of long-distance transportation of flammable cargo through pipelines. Uğurlu *et al.* (2015) investigated the Global Integrated Shipping Information System (GISIS) data for collision and grounding oil tanker accidents from 1998 to 2010. The researchers carried out a Fault Tree Analysis (FTA) in order to perform risk assessment on the collision and grounding accidents. In their work, the consequences of the present hazards were categorised into three categories: economic loss, pollution, and death or injures. Based on the investigated system, the economic loss consequence gains the bigger chair between the two accidents.

A risk assessment framework presented by Mokhtari *et al.* (2011) helps to evaluate the overall risk level of petroleum seaports and terminals in their complex environment. Within this research, the researchers carried out Fuzzy Set Theory and Evidential Reasoning (ER) techniques. Due to the uncertainties associated with this complex system, the researchers started by applying FST to evaluate the hazards associated with the operations and management of the ports and terminals. The researchers then used the ER approach in order to synthesise the system risk factors necessary for assessing the petroleum seaports and terminals. The work of Rao and Raghavan (1996) discussed the hazards identification techniques for ships and for port installations. Through applying cause–consequence analysis, the researchers identified the hazard events associated with port installations and discussed the effect of spills of this flammable product. Pak *et al.* (2015) carried out a safety analysis technique to identify which factors influence ports' safety. The researchers collected and analysed the factors by applying the fuzzy Analytic Hierarchy Process (AHP) to ship captains' perspectives of five ports, as data were generally unavailable or lacking.

Yuhua and Datao (2005) analysed the failures associated with oil and gas transmission pipelines by using fuzzy fault tree analysis. The authors in this research introduced fuzzy set theory for its effectiveness in treating the fuzzy events involved in fault tree analysis in order to decrease the errors of conventional fault tree analysis. Dziubiński *et al.* (2006) took into account individual and societal risk in order to perform a risk assessment methodology for analysing the basic events of pipeline failures and their probable consequences. In order to perform risk assessment for long distance pipelines, the researchers presented a combination of qualitative and quantitative pipeline assessment techniques. Combination of both types of techniques offered the possibility of a complete risk assessment. In the work of El-abbasy *et al.* (2015), the condition of oil and gas pipelines was assessed through considering several factors; unlike most studies with this focus, corrosion was not the only focal factor. The researchers performed a simulation test on an offshore gas pipeline in Qatar in order to test the module performance.

Emovon *et al.* (2015) developed two novel methodologies due to the limitations associated with traditional Failure Modes and Effects Analysis (FMEA) in order to prioritise the risk associated with marine machinery systems. The novelty of these two methodologies was the integration of the averaging technique firstly with Vlsekriterijumska Optimizacija Ikompromisno Resenje (VIKOR), and secondly with the Compromise Programming (CP) technique in order of ranking of risk of failure modes. In the work of Martins and Maturana (2013), human reliability in the operation of an oil tanker was analysed by using Bayesian Belief Networks (BBNs). The researchers aimed to determine the most likely sequence of hazardous events and thereby identified which of the presented activities should receive more attention in order to eliminate/reduce the operation risk as significantly as possible. Ismail and

Karim (2013) analysed the accident cycle in sea transportation over a period of 47 years from 1964 to 2011, covering spills equal to and over 1,000 tonnes. According to the research, the total spill volume of the analysed period was 4.27 million tonnes. The causes of these spills were classified into several factors such as navigation error, national conditions, mechanical and maintenance factors, and engine failure. Moreover, the analysis revealed that spill volume has been decreasing in recent years, as confirmed by the annual reports presented by International Tanker Owners Pollution Federation Limited (2016).

A careful literature review has revealed that most PTSs studies have been conducted on operational risk and reliability at a segment/local level, i.e. from the perspective of ports, ships, or pipelines (e.g. Elsayed *et al.*, 2009; El-abbasy *et al.*, 2015; Mokhtari *et al.*, 2011; Yuhua and Datao, 2005; Siddiqui and Verma's, 2013; Eliopoulou *et al.*, 2012) instead of from a system-wide perspective. Regarding the petroleum supply chain, most existing literature on PTSs has focused on security, health, safety, and environmental protection at the local level instead at the system level. The literature indicates that the safe operation of petroleum ports and transportation modes for PTSs safety as complete systems has been specifically discussed only on very rare occasions. In other words, none of the mentioned research and other research in the PTSs domain has conducted a specific or even generic risk/safety assessment methodology or framework for evaluating a PTSs as one complete system. Within the context of supply chains and specifically within PTSs, optimal risk controls at segment/local levels may not necessarily ensure the highest safety at the system/global level. The literature review has therefore revealed a research gap that urgently needs to be filled.

2.5 Petroleum Transportation Systems Operations Accidents

Transporting petroleum product within PTSs is usually associated with various hazards. PTSs hazards can lead to fatal accidents within the system due to failures in the transportation process (Jo and Ahn, 2005). Anifowose *et al.* (2012) mentioned several factors involved in PTSs that might affect the safety of the system. The human factors are one of the most significant factors that can cause accidents. One example of a failure due to the human factor is poor operational processes in the flow of the petroleum, which might lead to the product spilling and in turn to explosions or fires (Yuhua and Datao, 2005).

Historically, transporting the crude product by pipeline has been proven to be the safest and most effective means of transporting petroleum. Spills in pipelines are very rare, and a high percentage of the spills that do occur usually happen due to operation failure, (Hasan *et al.*, 2010). For example, since 1897, with length more than 2000 km, over 60 countries with pipeline systems have been using pipelines for transporting petroleum and refined products for domestic and international purposes for more than a century (Zhang and Bai, 2008; El-abbasy *et al.*, 2015). This proves that pipeline transport is the safest and most economical inland transportation mode for transporting petroleum products compared to other systems. However, if an accident does occur within the pipeline system, the consequences are severe for the economy and environment (Petrova, 2011). Due to the long-lasting effects, the area’s economy can also be negatively affected. Research done with safety bodies such as the US Department of Transport has shown that most of the pipeline infrastructure in use today was installed about 40 years ago, back in the 1970s (Petrova, 2011). Thus, despite pipelines being the safest system, a petroleum spill could occur at any time simply due to the old age of the system itself.

Spillages of this crude product pose a threat to both flora and fauna (Restrepo *et al.*, 2009). Spilling on land can lead to the death of plants as well as abnormalities in the animals that depend on the environment for food (Anifowose *et al.*, 2012). Other than a direct effect on life, these spillages can have an unfavourable effect on the economic status of the area. If spillage occurs, people may choose to move from that area into other areas (Sosa and Alvarez-Ramirez, 2009). This movement was observed in the case of an Enbridge pipeline; when the spillage occurred, people who owned homes in the area sold them.

Historically PTSs accidents/incidents have been happening since transportation systems were first used to move this flammable liquid within the system. This section could not possibly outline the full history of all the operation accidents that have ever occurred within PTSs. Tables 2.1, 2.2 and 2.3 therefore outlines some of the most catastrophic PTSs accidents. These historical PTSs accidents dictate the importance of this research. This study aims to estimate, control, and monitor the PTSs operational risks as further presented in chapters 4, 5, and 6.

Table 2.1: Historical petroleum port accidents

No	Date	Location	Accident description
1	21/12/1985	Naples, Italy	An explosion occurred at a marine petroleum products terminal due to tank overfill. This explosion destroyed several of the terminal facilities and nearby business and residential constructions (Chang and Lin, 2006).
2	16/07/2010	Dalian, China	Over 1500 tonnes of crude oil spilled into the Yellow Sea due to a pipeline rupture and an explosion at Dalian Xingang oil port. This explosion caused a severe fire which destroyed approximately 200 m of oil pipeline. As a result, the operation was disrupted for almost two weeks (Zhang *et al.*, 2013a)

Table 2.2: Historical pipeline transportation system accidents

No	Date	Location	Accident description
1	05/11/1977	Abqaiq, Saudi Arabia	Motor vehicles destroyed a 30-inch-diameter crude oil pipeline transportation system (MARSH, 2014).
2	07/08/1997	Fairbanks, Alaska, USA	A fire occurred at a pipeline transportation system due to operator mistake. The operator started operation while the strainer cover plate was open that released and ignited oil (MARSH, 2016).
3	25/07/2010	Calhoun County, Michigan, USA	In 2010, at the south of Michigan state near Marshall, Michigan, a pipeline ruptured due to an operator failure, spilling an estimated 843,444 gallons of crude oil wile transporting the product from Canada to the US (Killian, 2010).
4	05/12/2016	Belfield, North Dakota, USA	A rupture in the Belle Fourche Pipeline leaked about 530,000 gallons of oil. The cause of the rupture has not been revealed (Nicholson, 2017).

Table 2.3: Historical ship transportation system accidents

No	Date	Location	Accident description
5	06/12/1985	Kharg Island, Gulf of Iran	A NOVA oil tanker, which is a very large crude carrier (VLCC), collided with another huge oil tanker (an ultra large crude carrier (ULCC)) due to a lack of special operating process (lights on both vessels) during the Iran–Iraq war. The spilled oil from this accident was approximately 70,000 tonnes. Furthermore the flag state of NOVA ship states that the collision damaged five of the ship tanks (ITOPF, 2016).
6	30/03/1994	Fujairah, United Arab Emirates	Two tankers (BAYNUNAH and SEKI) collided near the Fujairah coast. This accident led to 16000 tonnes of crude oil being spilled into the Gulf of Oman due to a rupture on the ship body (ITOPF, 2016).
7	27/07/2003	Karachi, Pakistan	30,000 tonnes of oil was spilled while the tanker entered Karachi Port, Pakistan due to ship grounding. The grounded ship was transporting 67,800 tonnes of crude oil for a refinery in Karachi (ITOPF, 2016).

This research focuses mainly on petroleum transportation operation by seaports, shipping, and pipeline transportation. Other means of crude oil transportation modes such as railroads and road transport are uncommonly used for the movement of this product. Still, like other transportation modes, these two modes are also prone to accidents. Some of the major causes of accidents on railroads include poor infrastructure, the designs of the car tanks, intersections where railway lines and roads usually cross, poor assembling of the train, and human factors and errors (Nicolet-Monnier and Gheorghe, 2013). However, due to the scope of the research and the uncommon usage of these systems, railroads and road transport are not involved in this study.

2.6 Risk Assessment of PTSs

The above mentioned accidents, which compose an incomplete list of all the many accidents throughout history, highlight that the transportation of petroleum is accompanied by the occurrence of unforeseen risks which may have severe and even fatal consequences (Soszynska, 2010). A safe PTS requires safety/risk assessment in managing the system.

Formal Safety Assessment (FSA) is the most systematic methodology for assessing risks and evaluating the costs and benefits of different options (Wang, 2002; Rosqvist and Tuominen, 2004; Quangen *et al.*, 2007; Kontovas *et al.*, 2009). According to the International Maritime Organisation (IMO), FSA is a structured and systematic methodology designed for improving marine safety, for life, health, marine environments, and property protection, through utilising risk and cost benefit assessments which lead to decisions (IMO, 2002). FSA is designed as a tool for decision makers that aims to mitigate risk and enhance maritime safety through utilising risk analysis and cost benefit assessment. In other words, the FSA mechanism is built on risk assessment and the cost benefit analysis for enhancing maritime safety (Wang and Trbojevic, 2007). FSA consists of the following five steps:

Step 1: Identification of hazards.

Step 2: Assessment of risks that arise from the identified hazards.

Step 3: Risk-control options for controlling the risks that are defined in step 2.

Step 4: Cost benefit assessment of the risk-control options.

Step 5: Recommendations for decision making based on the information derived in the previous steps.

Risk assessment is a key element for maintaining the overall safety of PTSs and ensuring the safe transportation of crude oil. Risk assessment has been applied in many industries for its ability to analyse and manage the risk factors that influence systems' safety. Risk assessment is defined as a comprehensive estimation of the probability and the degree of the possible consequences in a hazardous situation in order to select appropriate safety measures (Wang and Trbojevic, 2007). In short, risk assessment is a vital tool for system safety. According to Bersani *et al.* (2010), risk assessment process is carried out in three major phases. The first phase is Hazard identification (HAZID). In this phase, any risk that is likely to arise during the project in question is identified. Once the hazards are identified, the second phase is analysing the risk. In this phase, the structure and form of risk are examined in detail. Furthermore the causes and effects behind the risks are evaluated. The fatality of the risks and the measure of damage, together with whom or what it could affect, are identified. The final step of analysing is the risk mitigation stage. During this stage, ways of preventing the risks from occurring are identified. Once identified, the safety measures are put in place.

Risk assessment provides an effective method for the safety of a system. Through an effective safety analysis and risk management programme, it is possible that all major accidents and losses of life and resources can be avoided (Mokhtari *et al.*, 2012). A hazard within a system is identified based on the knowledge that people (e.g. researchers and operators) have gained from past events. For instance, risks that may occur due to flammable products activities tend to be viewed as more deadly than those that occur due to the risks associated with transport of other products (Bersani *et al.*, 2010). Different methodologies are used in risk assessment in PTSs. Such approaches include the Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Bow-Tie method and the Fuzzy Sets Theory (FST) (Nicolet-Monnier and Gheorghe, 2013). These tools are used to identify risks and to assess those risks' probabilities and losses. Within the subject of petroleum transportation, many high environmental risks are associated with the occurrence of accidents within PTSs. Specifically, leakage is considered to be one of the major risks that might occur due to a failure in PTSs operation. Whether the transport is by pipelines, sea, railways, or road transport, PTSs can face a great risk of leakage. During pipeline transportation, leakage could be a result of corrosion on the pipe or a crack (Restrepo *et al.*, 2009). A default material at manufacturing stage can also lead to leakage. In transportation by waterways, leakage can occur as a result of several possible accidents, such as collision of the tanker with another ship or with a different object. Human error in loading and transporting the petroleum and extreme weather conditions such as strong winds are also risk factors that threaten the safety of tankers in both overseas and port areas (Zaman *et al.*, 2015; Uğurlu, 2016). Leakage in petroleum terminals might occur due to equipment conditions or a human error by the operators (Mokhtari *et al.*, 2012).

Leakages have severe consequences for the economy and environment. Regarding the environment, petroleum contains hydrocarbons, which are dangerous to living creatures and harmful to plants, and hence leakages can lead to complications and abnormalities in the environment (Bandowe *et al.*, 2014; Mzoughi and Chouba, 2011). If the product leaks in oceans, it might leads to the death of the creatures that live in the water, and its wider effects may be fatal and long lasting (Bandowe *et al.*, 2014; Mzoughi and Chouba, 2011).

Accidents can be controlled by following some regulatory measures and safety codes. In the United States and Nigeria, for example, the regulations are contained in the Pipeline and Hazardous Materials Safety Administration (PHMSA) and Nigerian National Petroleum Corporation respectively (Park and Park, 2011). Prevention measures for these accidents include lagging the pipelines externally and internally by coating material; constantly monitoring the state of the transportation items such as the terminals, tankers, and pipelines; and minimising human error by ensuring that the persons in charge are highly qualified for their role and are keen and careful with details (HSE, 2008; Wang, 2002; ISGOTT, 2006; Hoppe, 2005). The transportation mode equipment and ports should also be constantly monitored to ensure that they are operating in good condition. The risk assessment tools listed above should always be used to foresee faults and take preventative measures against system failure (Eckle and Burgherr, 2013). Petroleum industry scholars and other industries' risk-based researchers have proposed quantitative, qualitative, or hybrid data (i.e. a combination of quantitative and qualitative data) in order to identify, assess, and mitigate industry risks (Khan *et al.*, 2015).

2.7 Existing Risk Assessment Methodology for Petroleum Transportation Systems

As summarised previously, the operation of PTSs is a high-risk process. Risk assessment provides an effective method for identifying, assessing, and mitigating hazards to ensure the safety of a system. An effective safety analysis and risk management programme can allow decision makers to avoid most or even all major accidents that are associated with the system. As explained previously, the risk assessment process consists of three major phases for system safety which are as follows:

- Hazard Identification Phase
- Risk Evaluation Phase
- Risk Mitigation Phase

In risk assessment, a number of key words are regularly used to describe a related action. Therefore, a clear understanding of risk assessment related phrases such as risk and hazards is important for flow of this study. The following are a sample of words relevant to risk assessment:

- Event, an action that occurs in a specific place and may or may not involve people.
- Incident, an event that has the potential to harm lives or businesses (HSE, 2004).
- Accident, an event that results in harm to lives or businesses (HSE, 2004).
- Hazard, a situation that is likely to cause harm to humans, property, the environment, and businesses (Trbojevic and Carr, 2000).

- Risk, the measure for unwanted hazards in term of the likelihood and consequences severity of the unwanted hazard (Mokhtari *et al.*, 2012).
- Consequences, the results that fallows the occurrence of a particular event (John *et al.*, 2014a).

2.7.1 Hazard Identification (HAZID) Phase

Hazard Identification (HAZID) is the first phase in any risk/safety assessment. HAZID is a well-documented and widely used method in risk assessment (Kianmehr *et al.*, 2013; Andersen and Mostue, 2012). The Institute of Risk Management (2002) states with reference to HAZID "*Hazard identification should be approached in a methodical way to ensure that all significant activities within the organisation have been identified and all the risk factors flowing from these activities are defined.*" In other words, the method systematically assesses the possible hazards of a system and the associated factors that have the potential to cause a significant consequence to humans, properties, and the environment.

In this study, HAZID is used to assess systematically the potential hazards and problems associated with the transportation system of the petroleum industry. Any hazards or problems that could harm PTS operations are considered. This phase can be used in the assessment of individual activities, for example, in assessing a system that needs to be upgraded, modified, replaced, or improved (Yin *et al.*, 2012). According to Gould *et al.* (2012), the HAZID process is the beginning of three major assessment phases. The phases start with identifying the hazards threatening the system. Once the hazards associated with the system have been identified, they can be further evaluated by the appropriate risk assessment techniques. Once identified, the measure of the risk is determined, and finally safety measures are added. Hazard identification techniques include literature search, Hazard and operability (HAZOP) studies, Failure Modes and Effects Analysis (FMEA), what-if analysis, Preliminary Hazard Analysis (PHA), Progressive Loss of containment Analysis Optimising Prevention (PLANOP), physical inspection, organisational charts, flow charts, and check-lists. These techniques have been recommended and used by various authors due to their potential to identify the hazards and associated events that might occur within a system (ABS, 2003; Dickson, 2003; Wang, 2002; Pasman *et al.*, 2009; Marhavilas *et al.*, 2011; Groso *et al.*, 2012; Khan and Abbasi, 1998). Groso *et al.* (2012) recommended combining two or more HAZID techniques to obtain better results in identifying a system's hazards. Literature search is one of the techniques that have been adopted in this study. This technique saves time and costs, as the required risk-based data has already been gathered (Saunders *et al*., 2007). To obtain better results in identifying PTSs hazards, what-if analysis, which is a brainstorming approach, is used. What-if analysis is a popular technique and possibly one of the oldest HAZID methods; it involves simply asking a series of questions that begin with 'what if' (Khan and Abbasi, 1998; Kavianian *et al.*, 1992; Golfarelli and Rizzi, 2010).

The HAZID phase has a number of advantages when applied to an operating system. The phase provides an early identification of hazards and potential problems before they actually occur in the system (Kianmehr *et al.*, 2013). In other words, this phase enables the prevention of the occurrence of hazards through identifying the possible hazards associated within an operating system. In the case of PTSs, HAZID is applied in different petroleum companies and plants for identifying the petroleum transportation operational hazards in order to ensure the safe flow of the petroleum product as well as the safety and health of the system's operational staff and the environment as a whole. For instance, in the pipeline transportation system, HAZID is used to identify the possibility of leaks occurring and the causes of these leaks such as cracks and corrosion along the pipelines (Esmaeilzadeh *et al.*, 2009). HAZID also provides a platform for evaluating hazards that could cause system failure.

HAZID is applied to every system involved in the movement of petroleum products in order to reduce system risks. In the transportation of petroleum by ship, HAZID assessment has helped to identify fires and explosions as one of the major system risks that should be taken into consideration (Eckle and Burgherr, 2013). According to studies by Yin *et al.* (2012), undetected leaks from tankers that may occur during loading might be the cause of these fires. For example, a leak accidentally exposed to high temperatures might cause a fire along the line of the leak, and if the line gets to the tank containing the petroleum, an explosion could occur. A crude oil spill might also occur during a ship collision or even ship grounding, which can lead to fatal consequences.

2.7.2 Risk Evaluation Phase

Risk analysis is a procedure carried out by analysts to identify, outline, and examine in detail the potential dangers facing persons, organisations, or corporate bodies (Chun-rong, 2012). Systems such as PTSs are complex because they involve unpredictable and vague events. The nature of the petroleum supply chain requires that PTSs transport flammable products which might harm animals and humans, the environment and construction. Therefore, the assessment phase plays a critical role in minimising risks that might occur to businesses and the environment (Dawotola *et al.*, 2011). This process involves assessment of the overall risk by gathering information about the occurrence probability and consequence severity of the hazards (Dziubiński *et al.*, 2006; John *et al.*, 2014a; Goerlandt and Montewka, 2015). This information is gathered via qualitative and quantitative techniques (Khan *et al.*, 2015). Risk analysis enables the concerned parties to find out what dangers organisations, individuals, and even corporations would face in natural, equipment or human-caused unwanted events. Identifying those dangers allows additional protection measures to be taken. When evaluating the risk model, the model is scrutinised so that decision makers can have a clear picture to make a practical decision. This process is important during the first stage of risk assessment, as the model selected must be able to concretise what it is supposed to measure. After assessing the risks, safety measures are taken to prevent the risks from occurring. This is known as risk mitigation (Phase 3). Risk analysis can be carried out through a number of methodologies such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Evidential Reasoning (ER) approach.

2.7.2.1 Failure Modes and Effects Analysis (FMEA)

Failure Modes Effects and Analysis (FMEA) is a step-by-step procedure which is capable of describing something that could go wrong during an operation (Jiang *et al.*, 2017). It describes how a system that is put in place can fail to do what it is expected to do. According to Chun-rong (2012), FMEA is a widely used method that plays a part in eliminating problems before they occur in operations and systems. FMEA is a well-known safety/risk analysis technique used in the maritime and petroleum industries. In the 1960s in the United States, the FMEA technique was developed and adapted in the aerospace industry for enhancing the industry’s safety and reliability levels. The FMEA technique is well known for its ability to handle both qualitative and quantitative assessment (Henley and Kumamoto, 1996; Wang and Ruxton, 1997). This technique has been applied in many studies on addressing safety and risk assessment problems (Jiang *et al.*, 2017; Emovon *et al*., 2015; Liu *et al.*, 2015; Wang and Trbojevic, 2007).

The technique has also been integrated into the early stage of designing systems. According to Ravi Sankar and Prabju (2001), the advantages of this method are that it allows for processes to be improved while considering the Likelihood (L), Consequence (C), and Probability (P) of system failures. The technique thereby builds project confidence by eliminating the concerns that the system would otherwise face in the future. The technique is carried out in four steps (Chun-rong, 2012). The first step involves the identification of the ways in which the project, system, or product can actually fail. After identifying the areas where the business could fail, the measure of risk that could be brought about by this failure is identified together with the causes of the risk. A course of action is then identified to prevent the failure, and that plan is used to validate design.

2.7.2.2 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a systematic analysis technique used in safety/risk analysis studies to evaluate system failures (Dawotola *et al.*, 2009). During an Air Force study contract for the Minuteman Launch Control System in the early 1960s, Watson developed FTA. Since the early 1970s, FTA has become perhaps the most widely used technique in risk assessment research (Henley and Kumamoto, 1996; Andrews and Beeson, 2003). The well-known method examines a system from top to bottom to detect if the system is in an undesirable state at any level. The system is analysed using the probability of the unwanted events at the lower levels (base events) to identify which series of events led to the failure (Dawotola *et al.*, 2009). FTA starts with an unwanted event, for example, petroleum failing to reach its destination during pipeline transportation. This unwanted event in FTA would be the modal top output. The lower events are the tree inputs. The technique has been widely used for its ability in estimating the probability of a failure. To identify the probability of an unwanted or ‘top’ event, the lower events have to be analysed backwards, tracing back the system failure (Lavasani *et al.*, 2015a). In the example given, consider that FTA reveals that in the pipeline transportation, a problem exists in one of the pump stations. Specifically, a pump engine is not properly working, and as a result, petroleum is not being pumped. The engine failure may be due to technical problems or human error. In this case, according to FTA analysis, the top failure in the system resulted from a number of lower occurrences, which could include technical problems or human error and the resulting failure of a pump engine. The FTA is, however, mainly analysed by the possibility of the base trigger occurring (Senol *et al.*, 2015).

FTA is a safety/risk analysis technique that can be used to handle both quantitative and qualitative risk assessment problems. It can be used in HAZID and risk evaluation. The technique is a deductive reasoning approach, and it is probably the most widely used technique for hazard identification and risk estimation for its ability to analyse systems with diverse sizes for risk assessment purposes (Peng *et al.*, 2016; Mokhtari *et al.*, 2011; Lindhe *et al.*, 2009; Yuhua and Datao, 2005; Lavasani *et al.*, 2015b). The hierarchy of a fault tree is based on multiple gates constructed to clarify the causes of a failure or an event. “AND” and “OR” are the two logic gates used in this process. Both help define the route to the top event. In other words, these two gates clarify the event’s connection with the occurrence of the unwanted event (Wang and Trbojevic, 2007). Within the fault tree graphical modal, the AND gate is employed if the all the inputs result in the output. On the other hand, if less than all of the inputs result in the output, the OR gate is used. The modal logic gates define the calculation formula in order to obtain the unwanted event assessment (Lavasani *et al.*, 2012).

2.7.2.3 Event Tree Analysis (ETA)

Event Tree Analysis (ETA) is a forward logic technique that is used to analysis the consequences that would accompany the occurrence of an unwanted event (Ferdous *et al.*, 2009). Since the successful introduction of the technique in the WASH 1400 nuclear study in the 1960s, ETA started to be applied in risk assessments research in different areas such as chemical processing, offshore oil and gas production, and transportation (Andrews and Dunnett, 2000). The technique allows for assessment of the frequency of an event, which involves identifying the trigger or initiator of the event and how fatal the event can be (Cigolini and Rossi, 2010). ETA is a largely logical bottom-up diagram that can be applied in the production and process of transporting oil and gas and in order to investigate unknown effects from known causes (Mokhtari *et al.*, 2011; Khakzad *et al.*, 2013a; Ferdous *et al.*, 2011). The logical diagram variables mostly connect by following a series of paths. Therefore, the occurrence of an event gives an assurance of the events that follow within the diagram through its success or failure (Ferdous *et al.*, 2009). ETA is a safety/risk analysis technique used in the risk evaluation phase; in ETA, the probability of each of the unwanted event's possible paths is identified using historical data or expert judgement (Ronza *et al.*, 2003; Mokhtari *et al.*, 2011; Khan *et al.*, 2015). The ETA technique tree can be applied to many different scenarios and gives a true expression of an event's final fatal consequences. The technique analyses the probability of an event's consequences through taking into consideration the accident's probability of existence and the likelihood of failure or success in each path (Khakzad *et al.*, 2013a).

2.7.2.4 Fuzzy Set Theory (FST)

Fuzzy Set Theory (FST) was introduced by Prof. L. Zadeh in the 1960s for uncertainty treatment within the possibility theory bases (Riahi *et al.*, 2012). As the name suggests, fuzzy sets cater not only to ideas that are completely true or completely false but also to those that lie in between. FST is a powerful technique to analyse systems with uncertainty situations due to human or machine actions (Ballı and Korukoğlu, 2009). Unlike the probability theory, in which values are indicated by numbers, the values in the possibility theory are indicated by words, whether in natural or artificial language, such as *high*, *medium*, and *low* for dealing with uncertainty (Riahi *et al.*, 2012). This method consists of a set of objects with a range of grades of membership. The set is represented by a membership (characteristic) function, with each object having a membership degree ranging between 0 and 1 (Rahman, 2012; Ren *et al.*, 2005). The theory also allows mathematical operators and programming to apply to the fuzzy domain. Furthermore, a fuzzy set is an extension of a crisp set.

FST is a powerful tool which has been successfully applied in various risk assessment and risk management studies in several fields due to the technique's ability to deal with vagueness of human judgment. Fuzzy environments that benefit from this technique include engineering, medicine, computer science, and several operational research areas such as the oil and petroleum industries. In the petroleum production and transportation industry, FST uses quantitative information to determine the possibilities of accidents occurring (Elsayed *et al.*, 2009; Mokhtari *et al.*, 2012; Yuhua and Datao, 2005; Shahriar *et al.*, 2012).

2.7.2.5 Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is a well-known multi-criteria decision making tool that was introduced in the 1970s by Thomas L Saaty (Alexander, 2012). According to Varma *et al.* (2008), this powerful technique for analysing complex systems is usually used when choosing from among several alternatives. AHP technique is known for its ability to provide a comparison of a list of considered options according to each option's weight through performing a pairwise comparison of a group of criteria. Moreover, the technique has the ability to deal with large numbers of decision-making criteria of both a quantitative and a qualitative nature, and it also simplifies the decision making process with its hierarchy structure formation (Cheng and Li, 2001). Instead of plainly deciding which decision is the best one, the process helps in making a decision that is best in line with the goals of the organisation, as it allows deep consideration of how the decision makers understand the problem (Liu *et al.*, 2011a). The technique starts by breaking down the problem into a hierarchical structure with different levels. Each level is analysed independently up to the top level (Varma *et al.*, 2008). This method is also useful in analysing the other alternative solutions. Various elements are evaluated by comparing them to other elements one at a time (Cheng *et al.*, 2002). The AHP approach has been widely and successfully used in several fields (Katarne and Negi, 2013; Pecchia *et al.*, 2011; Wickramasinghe and Takano, 2009; Kubler *et al.,* 2016; Dawotola *et al.*, 2009; Zhang *et al.*, 2016)

2.7.2.6 Evidential Reasoning (ER)

Evidential reasoning (ER) theory has been used to deal with multi attribute decision making analysis since the 1990s (Yang and Xu, 2004; Xu, 2012). ER approach addresses problems that involve both quantitative and qualitative measures under uncertainty based on the Dempster–Shafer theory. The Dempster–Shafer theory of evidence or D-S theory allows the aggregation of different pieces of evidence using their Degrees of Belief (DoBs) (Keeney and Raiffa, 1993; Kong *et al*., 2012; Riahi *et al*., 2012). This approach has been used to develop models that are used in assessing risk, the impact of those risks on the environment, the risk of fraud, the level of information security, and the risk of information quality (Wang *et al.*, 2013b). Unlike all other multi-attribute decision-making approaches, ER is capable of handling incomplete, uncertain, and vague data through allowing the decision maker to illustrate a belief degree less than 1 (Li and Liao, 2007; Riahi, 2010). The ER mechanism allows aggregation of the attributes at the same levels of the approach hierarchy up to the system's highest level. The ER approach has been widely and successfully used in several fields for dealing with multi-attribute decision-making problems under uncertainty in a reliable, transparent, and reasonable way (Alyami *et al.*, 2016; Yang *et al*., 2014; Yeo *et al*., 2014; Zhang *et al.*, 2016; John *et al*., 2014a).

2.7.2.7 Bayesian Network (BN)

At Stanford University in the 1970s, the basic Bayesian theory and a networking technique were successfully married into a single technique in order to develop a strong framework for dealing with uncertainty problems. The marriage of these techniques created the technique known as Bayesian Network (BN) (McCabe *et al.*, 1998; Bernardo and Smith, 2009). The first application of BNs, as addressed by Andreassen *et al.* (1989), occurred when Munin first researched using the technique. Since Munin's research, the method has become popular and is now widely applied due to its ability to model many real world problems (Oliver and Smith, 1990; Ottonello *et al.*, 1992; Burnell and Horvitz, 1995; Szolovits and Pauker, 1993; Russell and Norvig, 1995). BN, which is also known as Bayesian Belief Networks (BBNs), is an artificial intelligence technique that aims to provide a decision-support framework for problems involving uncertainty, complexity, and probabilistic reasoning (Ben-Gal, 2007). A set of random variables is represented in the BN probability graphical model. The technique graphical models a set of nodes and links are presented. The nodes represent random variables, and each node is connected to another node. The nodes' relationships (i.e. parent node to child node) are represented by a connection (link) representing the dependencies between these variables (Vinnem *et al.,* 2012). According to Trucco *et al.* (2008), this link starts from the parent node and ends with an arrowhead pointing to the child node. The BN approach has been widely and successfully used in several fields (Riahi *et al.*, 2013; Montewka *et al.*, 2014; Wu *et al.*, 2015; Khakzad *et al.*, 2013a; Khakzad *et al.*, 2013b).

2.7.3 Risk Mitigation Phase

Risk may be described as the chance of occurrence of undesired activities. In the case of petroleum transportation, the consequences of these activities are oil spillage. Oil spillage has the potential to have adverse effects on the surrounding environment, culture, and economic resources. The outcome of spillage might threaten not only the petroleum flow within the system but also human and natural life. In risk analysis, a higher risk reflects a higher probability and more severe consequences of the hazard event. Risk-control/mitigation is a major element in addressing a risk and is required in order to reduce the risks associated with high-risk hazards (Wang, 2001; Wang and Foinikis, 2001; Wang, 2002). Risk mitigation usually involves taking steps to reduce the effects of a risk. Mitigation can be accomplished through two major steps: reducing the probability of occurrence of the likely undesirable result and mitigating the consequences should the unwanted event occur anyway (Lassen, 2008). In other words, these two steps are introduced in order to reduce the frequency of an event or to prevent it from happening altogether. When reducing the consequences, preparation must be made to reduce the impact of the spill on humans and valuable resources. For example, fires should be avoided as well as human contact with the spilled substance (Menoni and Margottini, 2011). All statutory regulations, classification of societies' rules, and the International Maritime Organization's (IMO) conventions and codes are typical examples of strategies used for the purpose of risk mitigation. In this phase, various analysis techniques are usually performed for measuring and selecting the best solution among various strategies for mitigating the risk. The multi-criteria decision-making techniques such as AHP, Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), ER, and VIKOR are the most popular techniques for risk mitigation purposes.

2.7.3.1 Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)

The Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), was generated by Hwang and Yoon in 1981 (Suder *et al.*, 2015; Chang *et al.*, 2014; Zandi and Tavana, 2011; Peng *et al.*, 2011). The developed approach is utilised to deal with multi-attribute decision-making problems. The technique is built around the concept of ranking alternatives based on their distance from the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS), where the preferred alternative has the shortest distance to the PIS and the farthest distance to the NIS (Rahman, 2012; John *et al.*, 2014b; Ertuğrul and Karakaşoğlu, 2009; Behzadian *et al.*, 2012). In other words, TOPSIS is a decision-making tool that takes into account the distance between the PIS and NIS in ranking and deciding between the system alternatives. The PIS maximises the benefit criteria and minimises the cost criteria, but the NIS does the opposite statement (i.e. increases the cost criteria and reduces the benefit criteria). TOPSIS is a powerful technique which has been extensively used in different fields such as in engineering (John *et al*., 2014b; Krohling and Campanharo, 2011), healthcare (Büyüközkan and Çifçi, 2012), finance (Mardani *et al.,* 2015; Ertuğrul and Karakaşoğlu, 2009) and management (Liao and Kao, 2011). It offers simplicity in calculation and the capability to deal with complex systems, which includes selecting the best and the worst solution from several alternatives in a system and presenting them in a ranking order (Behzadian *et al.*, 2012; Rahman, 2012; Suder *et al*., 2015). For example, in the petroleum industry, Wood (2016) used the method to determine which option could be selected by suppliers for development projects across the petroleum industry (Wood, 2016). TOPSIS can be used to identify the best option for a system. For instance, the major petroleum transportation mode for long distances on land is a pipeline system. However, if pipelines cannot be used due to uncertainties such as cracking of the pipes, TOPSIS can be used to calculate the next best mode that can be used in place of pipelines (Ertuğrul and Karakaşoğlu, 2008).

2.7.3.2 VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)

VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), is a multi-attribute decision-making tool that was established by Opricovic in 1998 and developed by Opricovic and Tzeng in 2004 for multi-criteria optimisation problems and compromise solutions (Tzeng and Huang, 2011; Tzeng *et al.*, 2005; Kaya and Kahraman, 2011). The technique was built around the concept of distance from the Ideal Solution for ranking the alternatives (Opricovic and Tzeng, 2004; Rezaie *et al.*, 2014; Ebrahimnejad *et al.*, 2012). Unlike TOPSIS, VIKOR used a formula that fused the ranking index (i.e. the VIKOR index). This index uses all criteria, the relative importance of the criteria, and a balance between total and individual satisfaction in order to determine a compromise solution based on each solution’s distance from the ideal solution (Chu *et al.*, 2007; Tzeng and Huang, 2011). In other words, VIKOR is a decision-making tool that produces a ranked list of solutions after taking into account the distance from the ideal solution. Many researchers have successfully applied the technique in economics, finance, anthropology, communication systems, transport infrastructure, and even in humanities studies (Yazdani-Chamzini *et al*., 2013; Bazzazi *et al*., 2011; Sanayei *et al.*, 2010; Jahan *et al.,* 2011; Rezaie *et al.,* 2014; Yalcin *et al*., 2012).

2.8 Existing Hazards in Petroleum Transportation System

In the past decades, studies have examined the safety of the petroleum industry in different areas within its supply chain such as petroleum production, storage, marine transportation, inland transportation, offshore and onshore terminals refining, system infrastructure etc. Studies on the PTSs chain have commonly been investigating operational risk in a specific segment/local level instead of from a system perspective. Generic PTSs can be categorised into 1) petroleum terminal operation, 2) ship transportation operation, and 3) pipeline transportation operation. Figure 2.1 illustrates the systems within PTSs in a generic picture. In this thesis, the literature review has been used to detect the hazards and the hazard events of petroleum ports, ships, and pipeline systems. According to Hassler (2011), operational risk is one of the driven risk sources in transportation systems, where crude oil spill is one of the driven sources of this hazard. Within this study, a careful identification process (i.e. literature review) has been carried out to identify the driven sources of oil spills in PTSs.

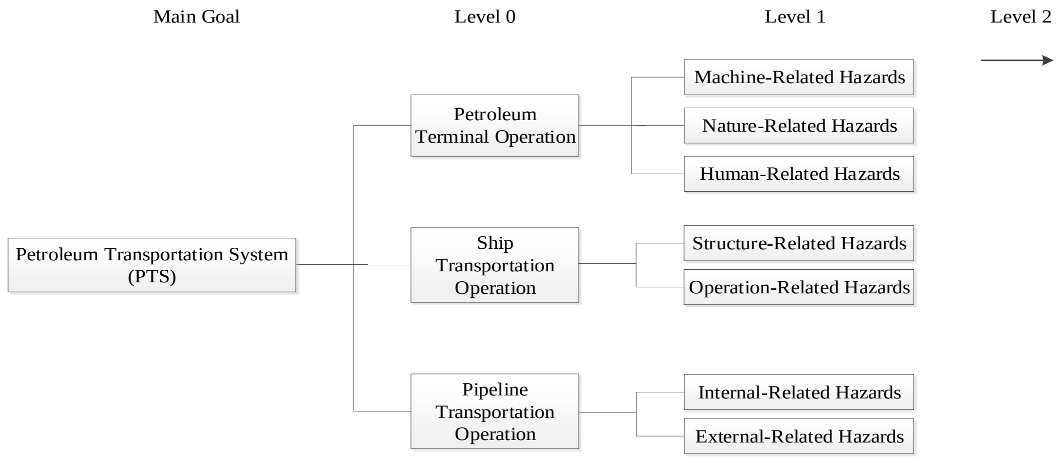

Figure 2.1: Main hierarchical structure if the risk in Petroleum Transportation Systems (PTSs)

2.8.1 Petroleum Port

Operational risk was defined by Chavez-Demoulin (2006) as risk associated with carrying out an operation. With respect to the operational activities that occur in the ports area, oil spill is a widespread hazard associated with marine transportation. According to O'Rourke and Connolly (2003), "*The current separation between the location of oil reserves and the location of oil consumption necessitates that crude oil be transported great distances to refineries and consumer markets*". Consequently, almost 60% of petroleum is transported by sea to reach the final customer (Burgherr, 2007). Therefore, about 60% of all transported petroleum passes through the petroleum port system~~.~~

Diverse activities take place at ports area, such as activities related to oil terminals and port-vessel related activities (e.g., loading/unloading activities) (Ronza *et al.*, 2006). Leaks and spillages may occur during the handling operation of transferring crude oil from the terminal to tankers or vice versa, as this process requires equipment such as pipelines. A crude oil spill not only leads to loss of the product, its impact extends to reach economic and environmental levels (Ventikos and Psaraftis, 2004). Furthermore, continued operational failure may lead to an organisation’s loss of reputation among the public at large and its shareholders. For example, two of the largest marine spills in US history occurred because of well blowouts during ocean drilling (Ronza *et al.*, 2003). According to the International Tanker Owners Pollution Federation Limited (ITOPF) statistics (2015), from 2004 to 2014 there were 132 spills where approximately 102,000 tons of oil were lost as a result of maritime activities. Therefore, with the increase in marine activities, there is the potential for oil spills to occur more regularly with the lack of protective processes.

A single failure or mistake is not the most common reason for an accident to occur. Rather, accidents tend to occur due to the confluence of a whole series of errors. For a spill of petroleum caused during the operational process, accidents are often initiated by errors induced by machinery failures, human failures, or a combination of both. This internal operational failure leads to a crude oil spill and affects the petroleum flow within the Maritime Petroleum Transportation Networks (MPTNs). Therefore, the most important elements that affect the safety of the petroleum terminal are listed as follows (see Figure 2.1):

- Human-Related Hazards
- Machinery-Related Hazards
- Natueral-Related Hazards

These three hazard sources are investigated in the following sections.

2.8.1.1 Human-Related Hazards

Human activities are a prime source of hazards and can contribute to a cause of accidents within PTSs. The International Maritime Organization (IMO) defines the human-related factor in the maritime industry, as follows (IMO, 2008): "*A departure from acceptable or desirable practice on the part of an individual or group of individuals that can result in unacceptable or undesirable results*". There is a growing awareness of the neglect of the human elements in risk education strategies due to the severe consequences that can result from human error that threatens humans and businesses (Rothblum, 2000). Most studies agree that the majority of accidents that occur in crude oil transportation operations are primarily attributable to human activities (Martins and Maturana, 2013; Eleye-Datubo *et al.*, 2006; Ventikos and Psaraftis, 2004; Ren, 2008; Wang *et al.*, 2011; Horck, 2008).

Human Failure can be evaluated by the aggregation of the following four elements (see Table 2.4):

- Organisation/Management Failure
- Terminal/Vessel Personal Error
- Operators' Error
- Ship/Port Interference

Table 2.4: Summary of human-related hazards that affect terminal operation within PTSs

Main criteria	Description	Hazards	Reference
Organisation/ Management Failure	A failure caused by an organisation or management decision that affects the safety of the operation	Company Policies, Company Standards, and Management Procedure.	Mokhtari *et al*. (2012); John *et al*. (2014a); Skogdalen and Vinnem (2011); Grabowski *et al*. (2010); Brattbakk *et al*. (2005); Wang *et al*. (2011)
Personal Error	An individual-related error that affects the safety operations of ports system	Inattention, Skills, Fatigue, and Neglect.	Cai *et al*. (2013); International Safety Guide for Oil Tankers and Terminals (2006); Eleye-Datubo *et al*. (2006); Ren *et al*. (2008); Ventikos and

			Psaraftis (2004); Riahi *et al.* (2012); Vinnem *et al.* (2012); Ceyhun (2014); Uğurlu *et al.* (2015); Wang *et al.* (2011)
Operators’ Error	A failure related to the operator that affects the safety of the operation	Breakdown of Communication, Communication Misunderstanding, Wrong Signals, Overfill, SOPs Not Followed, Overpressure, Release From Loading Arm, and Understaffing.	Trbojevic and Carr (2000); Cai *et al.* (2013); Horck (2008); International Safety Guide for Oil Tankers and Terminals (2006); Wang *et al.* (2011); Rao and Raghavan (1996); Chang and Lin (2006); Eleye-Datubo *et al.* (2006); Ventikos and Psaraftis (2004); Ronza *et al.* (2006); Ronza *et al.* (2003); Riahi *et al.* (2012); Vinnem *et al.* (2012); Grabowski *et al.* (2010)
Ship/Port Interference	Poor or failed interaction at ports area between ports and tankers, e.g., poor operation between ship and port operators, or between moving or immobile objects (ship and berth or a ship with other ships)	Procedural Failure, and Collision between Ship and Other Ship/Berth	Trbojevic and Carr (2000); Christie (2014); Rømer *et al.* (1993); Martins and Maturana (2013); Horck (2008); Ren *et al.* (2008); Ventikos and Psaraftis (2004); Ronza *et al.* (2003); Ronza *et al.* (2006); Rømer *et al.* (1995); Ceyhun (2014); Ismail and Karim (2013); Uğurlu *et al.* (2015).

2.8.1.2 Machinery-Related Hazards

In this context, a machine is a tool used for the operational process that occurs in the ports area. A small failure in a machine’s activity or parts may lead to loss of a large volume of a hazardous cargo, in this case, petroleum. Therefore, operators should not overlook the danger of equipment failure (Shang and Tseng, 2010). According to Chang and Lin (2006), machinery-related hazards have their own share in the failures that occur at oil terminals and lead to oil spills. The ITOPF and Major Hazard Incident Data Service (MHIDAS) databases highlight that oil spillage might occur due to machinery failure. Consequently, engineering skills are required to maintain the equipment in good working order (Darbra and Casal, 2004). Certain researchers (Vinnem *et al.*, 2012; Cai *et al.*, 2013; Rao and Raghavan, 1996; Ronza *et al.*, 2003;

Ronza *et al.*, 2006) have identified that machinery failure should be taken into consideration during the operational process.

Machinery failure can be evaluated by the aggregation of the following two elements (see Table 2.5):

- Maintenance Failure
- Equipment Failure

Table 2.5: Summary of machinery-related hazards that affect terminal operation within PTSs

Main criteria	Description	Hazards	Reference
Maintenance Failure	A failure that occurs after maintenance activities caused by an error or an omission during the maintenance	Maintenance Omission, Lack of Tools/Spare Parts, Inappropriate maintenance, and Use of Inappropriate Tools/Spare Parts	Chang and Lin (2006); Ronza *et al*. (2003); Thorsen and Dalva (1995); Vinnem *et al*. (2012); Liu and Frangopol (2006); International Safety Guide for Oil Tankers and Terminals (2006); Nwaoha *et al.* (2013)
Equipment Failure	Any event in which the equipment cannot accomplish its intended purpose or task	Lack of Communication System, Lack of Lighting System, Lack of Movable Facilities, A/C System Failure, Control System Failure, Instrument Failure, Cathodic Protection Failure, Gasket Failure, Pipeline Failure, Valve Failure, Loading Arm/SBM Failure, Hose/Pump Failure, and Power Failure	Cai *et al*. (2013); Rao and Raghavan (1996); Chang and Lin (2006); Darbra and Casal (2004); Ronza *et al*. (2006); Thorsen and Dalva (1995); Vinnem *et al*. (2012); International Safety Guide for Oil Tankers and Terminals (2006); Nwaoha *et al.* (2013); Soszynska (2010)

2.8.1.3 Natural-Related Hazards

Unpredicted natural events can influence operations at oil terminals. Such events are capable of disrupting maritime business and therefore make this business vulnerable to hazards. A limited amount of research has highlighted the importance and effectiveness of nature in causing accidents. According to Kröger (2008), hydrological, atmospheric, and seismic hazards are the categories for the main natural-related hazards, which are responsible for about 4% of accidents. The effects of these hazards have consistently increased the costs of the oil terminals in the form of annual maintenance, reconstruction, and preparedness. For example, Hurricane Sandy, which struck New York Harbor's oil terminal in 2012, damaged the infrastructure and the environment.

Natural-related hazards can be evaluated by the aggregation of the following three elements (see Table 2.6):

- Hydrologic hazards
- Atmospheric hazards
- Seismic hazards

Table 2.6: Summary of nature-related hazards that affect terminal operation within PTSs

Main criteria	Hazards	Reference
Natural-Related Hazards	Heavy Rainfall, Flood, Snow, Hurricane, Tornadoes, Lightning, Earthquake, and Tsunami	Skogdalen and Vinnem (2011); Ronza *et al*. (2003); Mokhtari *et al*. (2012); John *et al*. (2014a); Kröger (2008); Chang and Lin (2006); Trbojevic and Carr, (2000); Guha-Sapir *et al*. (2012); Ceyhun (2014); Ismail and Karim (2013).

2.8.2 Tanker Transportation

Oil tankers are floating objects classified by different sizes in order to transfer the crude product from point A to point B across the sea. According to Burgherr (2007), almost 60% of petroleum is transported by sea. International maritime authorities have recently been working to improve the safety of shipping transportation (Celik *et al*., 2010; Hetherington *et al*., 2006; Chauvin *et al*., 2013). However, despite significant efforts, shipping accidents are still occurring. The European Maritime Safety Agency (EMSA) (2016) stated that 5,942 marine accidents occurred from 2011 to 2015. This report highlights that accidents involving oil tankers significantly increased in 2015 and that the majority of these accidents took place at ports (EMSA, 2016). Historically, shipping accidents have been the result of human errors, technical and mechanical failures, and environmental factors. In this study, ship accidents are classified based on the type of accident as follows:

- Collision
- Grounding
- Hull Failure
- Equipment Failure
- Fire/Explosion

The mentioned hazard sources are investigated in the following sections.

2.8.2.1 Collision

A collision is an interaction that occurs between two ships, between a ship and a port jetty, or between a ship and another floating or immovable body. In recent years, ship collision was the cause behind two of the largest spills in 2015 and 2017. Both of these spills occurred in January, but in different years and different areas (i.e. near Singapore and Kamarajar Ports) (MPA, 2015; Simhan, 2017). Certain researchers (Soares and Teixeira, 2001; Uğurlu *et al*., 2016; Montewka *et al*., 2011; Zaman *et al*., 2015; Li *et al*., 2012a; Vanem and Skjong, 2004) have identified that collision accidents should not be neglected because of the high risk that follows such accidents. Collision accidents destabilize the individuals, publics, and industries involved. The EMSA (2016) found that collision was also the cause of the most oil tanker accidents between the years of 2011 and 2015. ITOPF (2017) highlighted that ship collision was the major accident category behind crude oil spills, accounting for 26% of the biggest spills between 1970 and 2016.

Collisions can be evaluated by the aggregation of the following two elements (see Table 2.7):

- Internal Factors
- External Factors

Table 2.7: Summary of collision hazards that affect ship operations within PTSs

Main Factors	Description	Hazards	Reference
Internal Factors	Failures related to either machinery or navigational errors that occur due to operational failure on board	Main Engine Failure, Bridge Navigation Equipment Failure, Communication System Failure, Wrong use of Navigation Equipment, Lack of Communication, Failure to Follow Operational Procedure, Action To Avoid Collision, Human Inattention, Human Neglect, Human Fatigue, and Human Skills,	Uğurlu *et al.* (2015); Uğurlu *et al*. (2016); Montewka *et al.* (2011); Zaman *et al*. (2015); Li *et al*. (2012a); Hänninen and Kujala (2009); Gucma and Przywarty (2008); Qu *et al*. (2012).
External Factors	Off-board actions that affect the overall ship operation	Weather Condition, and Third Party Activity	Uğurlu *et al.* (2015); Uğurlu *et al*. (2016); Montewka *et al.* (2011); Zaman *et al*. (2015); Li *et al*. (2012a); Hänninen and Kujala (2009).

2.8.2.2 Grounding

The Exxon Valdes oil spill in 1989, which remains one of the largest crude oil spills in history, was the result of ship grounding. 37,000 tonnes of crude oil spilled due to this accident (ITOPF, 2017). One of the main reasons behind this type of operation failure is failure to account for sea depth. Grounding diminishes the strength of the ship hull and makes the ship in an unfavourable situation for loading conditions (Gill *et al.,* 2012; Piatt *et al.,* 1990; Williams *et al.,* 1994). This operation failure affects the environment and poses a threat to human life and the culpable business (Martins and Maturana, 2010; Uğurlu *et al.,* 2015; Mazaheri *et al.,* 2015; Samuelides *et al.,* 2009; Li *et al.,* 2012a). From 1970 to 2016, a total of 150 accidents took place; ship grounding was considered to be the main accident category among all operational accidents, with the consequences totalling over 700 tonnes of oil spilled (ITOPF, 2017). Within the last few years (from 2011 to 2015), approximately 50 tanker accidents have occurred due to ship grounding (EMSA, 2016).

Grounding can be evaluated by the aggregation of the following two elements (see Table 2.8):

- Internal Factors
- External Factors

Table 2.8: Summary of grounding hazards that affect ship operations within PTSs

Main Factors	Description	Hazards	Reference
Internal Factors	Failures that occur due to operational failure on tanker. This failure is either related to	Main Engine Failure, Bridge Navigation Equipment Failure, Communication System Failure, Wrong use of Navigation Equipment, Lack of	Uğurlu *et al.* (2015); Uğurlu *et al.* (2016); Martins and Maturana (2010); Mazaheri *et al.* (2015); Akhtar and Utne

	machinery or navigational errors	Communication, Rout Selection, Failure to Follow Operational Procedure, Action To Avoid Collision, Human Inattention, Human Neglect, Human Fatigue, and Human Skills.	(2014); Kite-Powell *et al.* (1999); Mohović *et al.* (2013); Cross and Ballesio (2003)
External Factors	Outside actions that affect the safe operation of the ship	Weather Condition, Water Depth, and Third Party Activity.	Uğurlu *et al.* (2015); Uğurlu *et al*. (2016); Montewka *et al*. (2011); Kite-Powell *et al.* (1999); Quy *et al*. (2006); Briggs *et al*. (2003).

2.8.2.3 Hull Failure

The hull of a tanker is, roughly speaking, the body of the ship. In ship design, hulls have passed through several generations, from the single hull of the first generation to the double side, double bottom, and double hulls of subsequent generations. The accident of the Exxon Valdes oil spill played an indirect role in the redesign of hulls from single hulls to the current generations that aim to enhance vessel safety (Gill *et al.*, 2012; Piatt *et al.*, 1990; Williams *et al.*, 1994). These hull generations are a vital safety measure for tankers. Still, despite all this improvement, hull failures are considered as one of the major operation failures for ship operations in recent years. In recent years, no reported ship transportation accidents have been attributed to ship hull failure. Still, looking at the history, hull failure has been the cause of oil spills at anchor areas, in open water, and during loading and unloading operations (ITOPF, 2017; EMSA, 2016).

Hull failure can be evaluated by the aggregation of the following two elements (see Table 2.9):

- Structural Failures
- Procedural Failures

Table 2.9: Summary of hull failure hazards that affect ship operation within PTSs

Main Factors	Hazards	Reference
Structural Failures	Construction Damage, Hull Corrosion, and Maintenance Failure	Wang *et al*. (2002); Hussein and Soares (2009); Kim *et al*. (2014); DeCola (2009); Terhune (2011); Tzannatos and Xirouchakis (2013); Akpan *et al*. (2002);
Procedural Failures	Stowage Planning Failure, Collision, and Grounding	Vanem and Skjong (2004); Kim *et al*. (2013); Akyuz, (2015); Wang *et al*. (2002); Kim *et al*. (2014); DeCola (2009); Terhune (2011); Tzannatos and Xirouchakis (2013)

2.8.2.4 Equipment Failure

Equipment failure is one of the major types of accident that might lead to crude oil spill. Due to the complexity and amount of equipment involved in the operation process of oil tankers, dangerous that tracks the operating equipment failure should not overlook (Shang and Tseng, 2010). Damage to the equipment might harm the operation and environment. Part of operating tankers is maintaining the equipment; failing to maintain equipment might contribute to operational risks (Xie *et al.*, 2010; Lindgren and Sosnowski, 2009). Unlike collision and grounding, equipment failure is a main cause of major, moderate, and minor petroleum spills. The ITOPF and MHIDAS databases state that loading and discharging operations comprise one of the major areas for a crude oil spill due to equipment failure. There are various causes behind this failure (see Table 2.10). The operational process on any ship is a step-by-step process that plays a direct and an indirect role in enhancing the vessel safety. That process includes ensuring that equipment is operating in a safe condition.

Equipment failure can be evaluated by the aggregation of the following two elements (see Table 2.10):

- Machinery-Related Failures
- Man-Related Failures

Table 2.10: Summary of equipment failure hazards that affect ship operations within PTSs

Main Factors	Description	Hazards	Reference
Machinery-Related Failures	Failures that occur due to the ship operational equipment	Pipe Failure, Valve Failure, Pump Failure, Tank Gauging System, Manifold Failure, Power Failure, Heating System Failure, Loading Computer, Maintenance Error, and Maintenance Omission.	Uğurlu *et al.* (2015); Uğurlu *et al.* (2016); Martins and Maturana (2010); Mazaheri *et al.* (2015); Akhtar and Utne (2014); Kite-Powell *et al.* (1999); Mohović *et al.* (2013); Cross and Ballesio (2003)
Man-Related Failures	Human activities that cause failures to occur in the operational equipment	Lack of Communication, Procedural Failure, Human Inattention, Human Neglect, Human Fatigue, and Human Skills.	Uğurlu *et al.* (2015); Uğurlu *et al.* (2016); Montewka *et al.* (2011); Kite-Powell *et al.* (1999); Quy *et al.* (2006); Briggs *et al.* (2003).

2.8.2.5 Fire/Explosion

Fires and/or explosions form another of the accident classifications for crude oil spills. This type of accident might cause tragic results for human life and the environment (Zhang *et al.*, 2013b; Gasparotti and Rusu, 2012; Samuelides *et al.*, 2009). Compared with the other four types of tanker accidents (i.e. collision, grounding, hull failure, and equipment failure), fires/explosions historically from 1975 to 2015 have caused fewer oil spills. Nonetheless this type of accident should be involved when considering the hazards associated with ship transportation. The database of EMSA (2016) recorded that from 2011 to 2015, fewer than 50 ship tanker accidents were due to fire/explosion. One died and four suffered burns after a massive explosion of a petroleum tanker at Al Hamriyah port in 2017 (Aghaddir, 2017).

Fires/explosions can be evaluated by the aggregation of the following two elements (see Table 2.11):

- Internal Factors
- External Factors

Table 2.11: Summary of fires/explosions hazards that affect ship operations within PTSs

Main Factors	Hazards	Reference
Internal Factors	Inert Gas/Ventilation System Failure, Electric Failure, Pumping Room Failure, Main Engine Failure, Heating system Failure, Human Inattention, Human Neglect, and Human Skills.	Cross and Ballesio (2003); Lindgren and Sosnowski (2009); Uğurlu *et al.* (2015); International Safety Guide for Oil Tankers and Terminals (2006); Li *et al.* (2012a); IMO (2008); Trucco *et al.* (2008); Riahi *et al.* (2012); Vinnem *et al.* (2012); Trbojevic and Carr (2000)
External Factors	Spread of Fire From Other Object, Sabotage, and Weather Condition.	Uğurlu *et al.* (2015); International Safety Guide for Oil Tankers and Terminals (2006); Li *et al.* (2012a); IMO (2008); Lehr (2009); Nwaoha *et al.* (2013)

2.8.3 Pipeline Transportation

Pipelines within the petroleum industry are used to transport crude or refined products by pumping the product through the pipes to reach the final destinations. The final destinations might be a port, a refinery, or a storage area (Aroh *et al*., 2010; Papadakis, 1999; Yuhua and Datao, 2005). Pipelines are the most used modes in order to transfer the product by land; pipelines are constructed above or under the ground (Dziubiński *et al*., 2006; Brito and Almeida, 2009). In recent years, the pipeline safety level has significantly improved via changes to pipeline building materials and dimensions (Restrepo *et al*., 2009). Nonetheless, rupture and puncture pipeline accidents, such as with the Shell and Sunoco pipeline leak in 2016, still occur. In addition, the CONCAWE (2017) annual spillage database recorded that 196 spillage incidents were reported from 2011 to 2015. Based on historical data, pipeline failures can be due to internal and external failures (see Figure 2.1).

2.8.3.1 Internal Failures

Internal failures are hazards in the pipeline system that are either related to the system design or to the operator who executes the operation process. According to the Health and Safety Executive (HSE), internal hazards were the main reason for 32% of the system failures (HSE, 1999). For example, in 2014 and 2015, seven accidents were recorded as causing crude oil spills (CONCAWE, 2017). Internal failures have received attention in numerous studies due to the consequences that follow (Mohamed *et al.*, 2011; Simonoff *et al.*, 2010; Rios *et al.*, 2015; Dawotola *et al.*, 2011; Dawotola *et al.*, 2012). Studies show that 14.9% of the total crude oil spills in 2002–2005 in the United States occurred due to the corrosion caused by pipes corrosive (Restrepo *et al.*, 2009).

Internal failures can be evaluated by the aggregation of the following three elements (see Table 2.12):

- Operator Failures
- Structural Failures
- Corrosion

Table 2.12: Summary of internal failure hazards that affect pipeline operations within PTSs

Main Factors	Hazards	Reference
Operator Failures	Failure to Follow Procedure, and Maintenance Failure	Yuhua and Datao (2005); Jo and Ahn (2005); El-Abbasy *et al*. (2015); CONCAWE (2017); HSE (1999)
Structural Failures	Material Failure, and Construction Failure	Yuhua and Datao (2005); Onuoha *et al*. (2008); Jo and Ahn (2005); CONCAWE (2017); HSE (1999); Soszynska (2010)
Corrosion	Internal Corrosion, and External Corrosion	CONCAWE (2017); Yuhua and Datao (2005); El-Abbasy *et al*. (2017); HSE (1999)

2.8.3.2 External Failures

External failures are hazards that are man-made or nature-based hazards. They affect either the operation process or the facility structure of the pipeline. If any external failures accrue, they could lead to crude oil spillage. These failures are dangerous not only to the business but also to the environment. The Health and Safety Executive (1999) highlights that the majority, at 64%, of spills in recent years are due to external hazards. Accidents related to human interaction with pipelines cause the majority of pipeline crude oil spills. For instance, only in 2015 third party activities caused 87 spills (CONCAWE, 2017). This statistic highlights the significant importance of addressing external failures. The causes of external failures have been investigated by several researchers (Girgin and Krausmann *et al*., 2014; Onuoha *et al*., 2008; Anifowose *et al.*, 2012; Yuhua and Datao, 2005).

External failures can be evaluated by the aggregation of the following two elements (see Table 2.13):

- Natural Hazards

- Third Party Activity

Table 2.13: Summary of external failure hazards that affect pipeline operations within PTSs

Main Factors	Hazards	Reference
Natural Hazards	Weather Condition, and Geological Hazards	Yuhua and Datao (2005); Girgin and Krausmann (2014); Girgin and Krausmann (2016); El-Abbasy *et al*. (2015); CONCAWE (2017); HSE (1999)
Third Party Activity	Workers' Actions, and Sabotage	Yuhua and Datao (2005); Onuoha *et al*. (2008); Anifowose *et al.* (2012); CONCAWE (2017); HSE (1999)

2.9 Conclusion

This chapter has reviewed PTSs to exhibit their impact on the petroleum industry. PTSs contain multiple systems, and their operational processes include petroleum tankers, terminal facilities, and pipeline infrastructure. These aspects were described, and a detailed review followed that focused on previous accidents for the systems involved within PTSs. This chapter carefully discussed the theory, practice, and research developed in the risk assessment of petroleum ports, tankers, and pipelines. The chapter also overviewed existing safety/risk analysis techniques such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Analytic Hierarchy Process (AHP), Evidential Reasoning (ER), Bayesian Network (BN), and VIKOR. The links of those techniques to risk assessment were discussed and supported with significant works that can be employed to assess the operational practice of PTSs. The basis of this research is this chapter's comprehensive literature review related to petroleum ports, tankers, and pipeline safety. This review has opened the doors to discover several practices and problems related to PTSs' operational processes and risk factors.

PTSs studies over the last decade, have highlighted the significance of operational practices research in enhancing PTSs. However, most scholars have dealt with operational issues that occur either within the marine ports, ship, or pipeline sectors instead of in petroleum transportation as a complete system. In other words, previous studies have focused on operational aspects of the PTSs and have comprehensively examined system safety in terms of a specific segment/local level, though these studies have failed to address system safety on a global/system level. The absence of safety studies on PTSs as a complete system marks a research gap that must be filled in order to ensure worker and resources protect, as well as increasing efficiency on operational and managerial levels, which will reflect either negatively or positively on revenue.

Chapter 3: Analysing Safety Critical Points within MPTNs using Centrality Measures

3.1 Summary

Centrality theory is a useful measurement tool in identifying the node situation within a system. The aim of this chapter is to apply centrality theory in a petroleum supply chain risk assessment study and thereby highlight the nodes' vulnerability within petroleum transportation systems (PTSs). The chapter adopts two of Freeman's well-known centrality measures: degree centrality and betweenness centrality. The two measures are used to evaluate the centrality of ports and routes within maritime PTSs regarding direct connections between pairs of nodes and strategic positions in the network. An additional tuning parameter is also introduced to the formulas to identify the importance of each node, namely consideration of shipping capacity and connection to other ports or routes. Furthermore, a beta parameter is presented to recognise each node's role within Petroleum Transportation Networks (PTNs). The results of this chapter present powerful decision-making tools to identify nodes' vulnerability within PTSs

3.2 Introduction

Crude oil is one of the world's strategic resources. The petroleum industry has a strategic impact on global, national, and local economies. The logistics network of the petroleum industry faces major challenges in terms of the links in its nodes (Jenkins and Wright, 1998). Those links include production of crude oil and the modes of transportation that are used in the movement of the product (Hussain, 2006).

Transportation systems connect the petroleum industry supply chain nodes. The strategic role of transportation within Petroleum Transportation Systems (PTSs) is based on connecting three major components: upstream, midstream, and downstream components. Upstream refers to exploration and production phases. Midstream refers to refining phases (wherein the petroleum is refined into different products such as fuel, diesel, petrochemicals, etc.). The downstream is distribution and delivery of the refined products to storage terminals for the end users (Ross, 2000; Fernandes *et al.*, 2010, Briggs, 2010). Once a disruption event strikes, it is too late to take emergency action without any preparation or facilities. Disruption will affect the supply chain's desired functions, leading to failure (Baublys, 2007).

Still, PTSs are complex systems that cannot be easily dealt with by classical risk assessment methods. Therefore, social network analysis techniques have been adopted in this transportation system. Social network analysis is a technique that was originally introduced in social systems to analyse the connections between groups of people. Social network analysis has also been used by researchers in order to understand the influence of a person's connections in a social system (Valente and Foreman, 1998). When dealing with a huge and complex network, the critical points must be identified. For determining these points, various network analysis techniques have been established for identifying the importance of nodes within systems.

Centrality is one of the most studied concepts in analysing networks. This old concept was introduced as a tool to analyse the importance of a node through connecting each node to other nodes within the overall network (Benzi and Klymko, 2013). Based on this concept, several studies have adapted centrality measures in fields that involve large and complex networks, including communication systems, transport infrastructure, and social science (Borgatti and Li, 2009; Hagen *et al*., 1997; Cohn and Marriott, 1958; Granovetter, 1995; Holme, 2003; Guimera *et al*., 2005; Valente and

Foreman, 1998; Kaltashov *et al*., 2010). Conversely, there is still a major shortage in centrality studies on PTSs.

When considering the safety of a system, one should take into account the important points in the examined network. To reach the aim of this chapter, centrality theory has been adopted to evaluate maritime PTSs. Following the introduction, a brief review of the concept of centrality measures is given. Degree centrality and betweenness centrality measures, which are two of the most well-known centrality measures, are then adopted for analysing the centrality of ports and routes within maritime PTSs. Finally, a study of a real-life system is displayed.

3.3 Centrality Measures

Centrality is one of the most commonly studied concepts in social network analysis. Developed in the 1950s, centrality aims to deepen understanding of the structure and relationship of a network (Freeman, 1978). Unlike other network analysis techniques (e.g. cohesive sub-groups, cohesion and density), centrality method measure node importance to other nodes within the network (Haythornthwaite, 1996; Benzi and Klymko, 2013). Thus, centrality theory is suitable for describing and analysing networks.

Centrality measures provide powerful tools for analysing networks. The structure of a network consists of collections of nodes, which may or may not be connected to other nodes by links (also known as edges). After the success of the first use of social network analysis, which described the connections between the individuals within a group of people, many researchers have successfully adopted the technique in different fields such as economics, finance, anthropology, communication systems, transportation, and even medicine (Benzi and Klymko, 2013; Barrat *et al*., 2008; Boccaletti *et al*., 2006;

Brandes and Erlebach, 2005; Caldarelli, 2007; Burgess, 1969; Pitts, 1978; Cook *et al*., 2015; Berger and Iyengar, 2009; Park *et al*., 2002; Paul, 2011; Zio and Piccinelli, 2010; Zio and Golea, 2012).

In the transportation sector, Wang *et al.* (2011) adopted centrality measures to examine the complex air transportation network of China. Within this study, various centrality measures were adopted in order to analyse the locational advantage of an airport based on its connection, accessibility and strategic proximity to other airports within the network by employing degree, closeness, and betweenness measures respectively. The results of their model indicated that all centrality outputs were closely aligned with socioeconomic indicators of nodes such as air passenger volume, population, and gross regional domestic product. Derrible (2012) also adopted centrality measures in the transportation sector, specifically to help improve the design of the transit systems of a metro network system. The scholar applied betweenness centrality to 28 of the world’s metro systems. The author studied the emergence of metro trends in terms of network centrality by examining the measurements of several systems.

In maritime transportation, specifically in the container port sector, the centrality concept has already been addressed in various research works (Hall and Jacobs, 2010; Wang and Cullinane, 2008; Wang, 2013). Centrality measures were introduced for identifying the locational advantages of a port and its strategic role within the transportation system (Fleming and Hayuth, 1994). Identifying port centrality helps scholars in analysing the locational advantage of a specific port in the market area which the port serves. For example, when a seaport is positioned in the centre of a large inland market, the port has an advantage in attracting traffic. Hong Kong port versus Singapore port and Hamburg port versus Rotterdam port are good examples in respect to Southeast Asia and European business areas respectively.

Centrality measures have greatly facilitated practical research in port development and the area of inter-port relationship issues. For example, McCalla (2008) applied the betweenness centrality measure in order to determine the possibility of constructing Kingston port as a central port in the Caribbean Basin area. Wang and Cullinane (2008) studied the relationship between the competitiveness and accessibility of a port to overseas markets. In this research the centrality measure within the network was the opportunity or potential for transporting containerised cargo via a port. Furthermore, Laxe *et al.* (2012) provided further evidence for the efficiency of a container port in the containerised sea transportation network through using degree centrality. These studies highlight that researchers studying maritime transportation systems have proved the ability of centrality measures to symbolise the capabilities of a port in attracting cargos from its inland market and shipping services from markets further afield. In other words, centrality measures can be used in order to highlight the advantage of a port within the market area that the port serves. Therefore, the concept is a capable tool to identify a port's importance within a maritime transportation system.

Centrality measures have also been adopted in risk assessment studies to highlight the critical nodes within a network. Cadini *et al.* (2008) applied centrality measures to a complex electrical power transmission system. This type of network is not easily analysed by classical risk assessment approaches. Its complexity thus raises critical concerns regarding safety, reliability, and security. The researchers found that adopting centrality measures to study the electrical power transmission system highlighted the safety strengths and the weaknesses in the network (Cadini *et al.*, 2008). Büttner *et al.* (2013) used network analysis for analysing the risks of disease spread when transporting live animals (pigs) between farmhouses. To identify the centrality of a holding in a directed network in Northern Germany, several methods were applied (i.e.

in-degree, out-degree, ingoing and outgoing infection chain, betweenness centrality, and closeness centrality). Zio and Golea (2012) developed an analysis measurement for analysing the vulnerability of an electrical network. To test the approach of a vulnerability analysis of the most critical links (edges) in a network, an Italian high-voltage electrical transmission network was examined. Moreover, for identifying the importance of a link within the electrical network, betweenness centrality was considered. Furthermore, a multi-objective genetic algorithm was carried out to maximise the importance of these edges in the network.

Based on the flow movement through the network, measuring node centrality developed from binary formation to directed weighted networks in order to identify which node is more central than others in the network (Opsahl *et al.*, 2010). Many methods are available for measuring centrality, which involves ranking and describing the important nodes in the network. Degree centrality and betweenness centrality, are the two most commonly used centrality measures. Unlike other centrality measures, degree centrality and betweenness centrality were built around the concept of assessing nodes importance, regarding its connectivity between pairs of nodes and being in a strategic position in the network (Ergün and Usluel, 2016; Derrible, 2012; Laxe *et al.*, 2012). Degree centrality and betweenness centrality are described in the following sections.

3.3.1 Degree Centrality

Degree centrality, which was introduced by Shaw (1954) and has been generalised by researchers including Garrison (1960) and Nieminen (1973), is the simplest and the most intuitive measure. The measure can be defined by the number of links each node has, which reflects the node’s importance within a network. However, this interpretation does not take into account any indirect links in the same network. Opsahl *et al.* (2010) performed further study in order to improve the capability of measuring nodes within a network. As a result, two measures were developed for measuring the degree centrality in terms of the direction of the link: the first is in-degree, which is defined by the number of links to a node; and the second is out-degree, which is defined by the number of links that go from a node to connect with other nodes (Opsahl *et al.*, 2010; Wang, 2013).

3.3.2 Betweenness Centrality

Unlike other measures, betweenness centrality offers a pragmatic way of highlighting the importance of a node in the network; degree centrality, in contrast, counts only the number of connections. Therefore, in betweenness centrality, the node has a paramount importance to the whole network. The betweenness centrality measure is based on the concept that the node is central when it is strategically located in communication routes for linking between other nodes (Bavelas, 1950; Shaw, 1954). The betweenness centrality measure evaluates the centrality of a particular node that is located between other nodes in a network (Freeman, 1977). If a node is located in a strategic position, namely if a node offers the shortest paths to connect to many other nodes in the network, the node tends to be in a powerful position for connecting or breaking the connections between other nodes.

Freeman (1978) generated both of the above centrality measures (i.e. degree and betweenness). Through transferring from a binary network to a graph, these two centrality measures are expressed as flow: Degree centrality is expressed by the sum of links connected to a node, and betweenness centrality is expressed by the number of times that a node acts as a bridge that allows completion of the connection between other nodes by the shortest path.

Freeman’s (1978) original formula was designed to analyse undirected, unweighted networks. Through adapting the original two centrality measures to deal with directed or weighted network types in particular networks, a number of researchers (e.g. Opsahl *et al.,* 2010) have attempted to overcome the disadvantages of undirected, unweighted network nodes.

3.4 Network Analysis Software

In the last 20 years, a great number of software programs have been developed for network analysis. Some of the most popular software packages that have been used in network analysis are UCINET, NetDraw, R-Software, Pajek, and NetMiner. To meet the objectives of this research, two software packages are used, namely NetDraw and R-Software. NetDraw was used to present the maritime petroleum transportation nodes and their connections, and R-Software was applied to conduct the maritime petroleum transportation network evaluation (R-Software allows for the measuring of the centrality of a node in a weighted network (Batagelj and Mrvar, 2007; Borgatti *et al.*, 2002)).

3.4.1 NetDraw

NetDraw is software developed by Steven Borgatti in 2002 for the purpose of visualising social network data. The software reads UCINET files, operates in Windows, and is used for analysing network data. The objective of the software is to transfer UCINET data in a way that allows researchers to visualise graph formation. NetDraw allows users to organise the output network (e.g. to change the colours of the nodes and the links) and to save these changes (Apostolato, 2013). For the purpose of this study, NetDraw has been adopted to allow easier visualisation of the maritime petroleum transportation network. To utilise NetDraw for the visual representation of nodes within the network, the following steps should be taken:

- The network nodes must be identified.
- The nodes’ connection must be defined.
- The nodes’ data must be presented in UCINET files for visual representation in NetDraw.

3.4.2 R-Software

R-Software is a free statistic computing programming language. This programming language was developed at the University of Auckland, New Zealand by Ross Ihaka and Robert Gentleman for statistical analysis and data visualisation (Ihaka and Gentleman, 1997). R-Software was developed to work on various computer operation systems (e.g. Windows and Mac).

Most network analysis software adopts Freeman’s (1978) two centrality measures. However, R-Software has an advantage for the purpose of this research. Software such as UCINET and Pajek are capable only of analysing node centrality in binary networks; thus they do not allow for measuring the centrality of a node in a weighted network (Batagelj and Mrvar, 2007; Borgatti *et al.*, 2002). Therefore, the present research has adopted R-Software, which is an open source software. Through the introduction of writing packages, the software has been made capable of measuring node degree and betweenness centralities in a weighted network. To apply R-Software in the analysis of the centrality approach, the following steps should be taken (Opsahl, 2009):

- The network nodes must be identified.
- The nodes’ connection data must be defined.

- The nodes’ data must be installed in R-Software tnet form.

3.5 Methodology

Centrality measures have been applied in risk assessment studies of various fields such as engineering, health, and transportation systems to highlight the critical nodes within a network. Still, there is a shortage of studies on adopting centrality measures in PTSs. Therefore, the novelty of this chapter is to adopt centrality measures for the evaluation of PTSs as one complete system.

The Petroleum Transportation Network (PTNs) constitutes a complex transport network within the Petroleum Supply Chain (PSC). This network is influenced by internal and external disruptions. These disruptions could affect a single throughput between two transportation systems or impact the whole network. Therefore, determining the critical points within a complex network, which is a difficult task when working with only classical risk assessment approaches, is an important issue with respect to the protection of PTSs. For the purposes of this study, petroleum ports and the transportation modes within PTSs are analysed. Maritime petroleum transportation networks (MPTNs) comprise one of the systems within petroleum transportation networks (PTNs). To identify the critical ports in the MPTNs, degree and betweenness centrality measures have been applied to analyse ports’ ability to connect two ports via direct connections and ports’ location in terms of strategic advantages.

The steps in analysing the petroleum terminals and shipping routes within the MPTNs are defined as follows (see Figure 3.1):

- **MPTNs development:** Identify the petroleum ports within the MPTNs and present them in a network structure.

- **Data collection:** Identify and collect the petroleum throughput between two ports within the MPTNs.
- **Degree centrality:** Apply degree centrality to identify critical nodes based on network direction.
- **Betweenness centrality:** Apply betweenness centrality to identify critical nodes based on location.

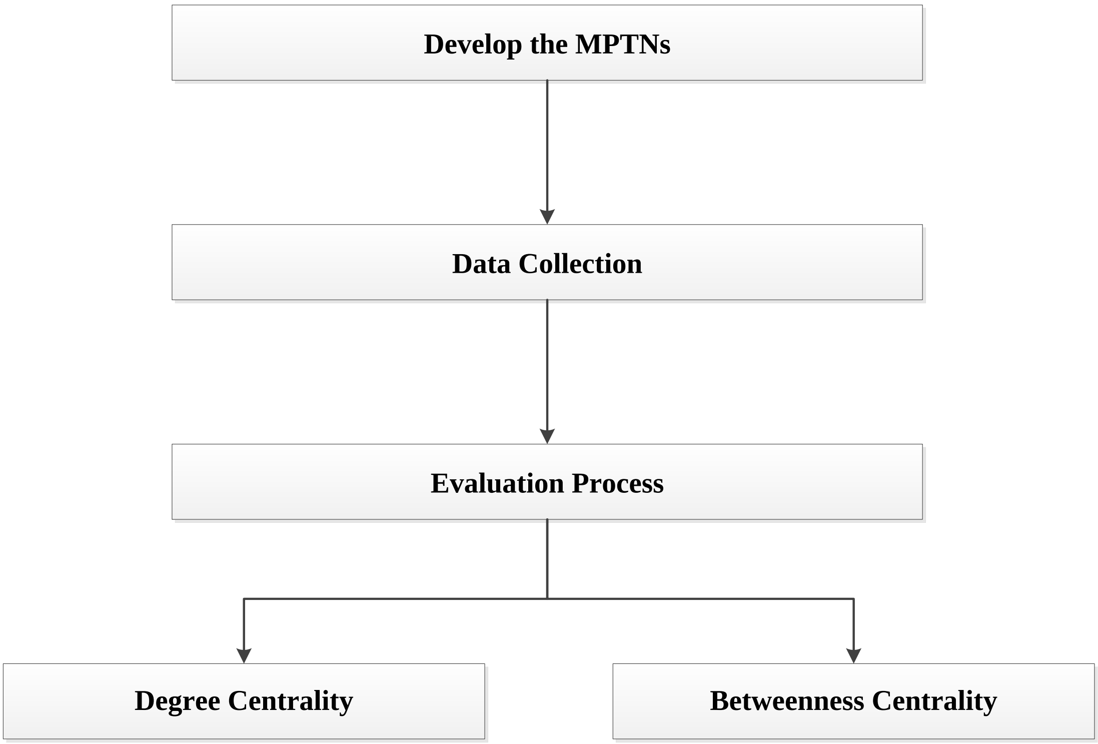

Figure 3.1: The MPTNs assessment model flow chart

3.5.1 MPTNs Development

MPTNs are complex systems that contain ports that are connected with each other by ship transportation routes. The simple structure of this network is a node connected to other nodes by links. In MPTNs, the nodes represent the petroleum terminals, and the links represent the maritime transportation routes (see Figure 3.2).

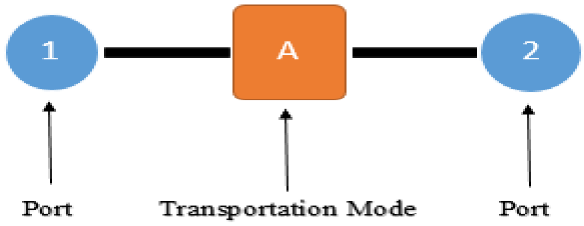

Figure 3.2: A network sample

To evaluate the ports within the crude oil transportation system, firstly, it was important to identify the ports involved within the network. The links between pairs of ports were identified based on whether any trade occurs between the two ports. Therefore, a list of ports and their connections had to be produced by investigating real-life data.

3.5.2 Data Collection

As mentioned previously, pairs of nodes within a network might be connected by links. Presence of links between two nodes was determined based on whether trade exists between the ports. To identify the connection or lack thereof, a set of quantitative data were collected for the evaluated network. These data were collected through contacting individuals, organisations, and trusted maritime sources.

3.5.3 Evaluation Process

Within the context of this research, the process of measuring port centrality in a weighted network was adopted from Opsahl *et al.* (2010), who re-formalised the measures on the basis of Freeman's degree and betweenness centrality measures (1978) to identify the safety critical ports in MPTNs. A tuning parameter (α) was introduced to the centrality formulas to identify the criticality of the node based on both shipping capacity and connection to other ports (Opsahl *et al.,* 2010). A beta parameter (β) was introduced to determine the port importance to inland and sea transportation.

Consider an MPTN composed of a group of nodes (*N*) which represent the petroleum ports and links (L) which represent the maritime transportation abstracted as graph *G (N, L),* in which L is connecting a set of $N = \left\{x_i, x_j, \ldots, x_n\right\}$ if $\left(x_i, x_j\right) \in L$. Centrality measures for the safety criticality of the petroleum transportation network are defined as follows.

3.5.4 Degree Centrality

The concept of degree centrality is based on identifying the port importations within the MPTNs through the port links. In network analysis, the first step of measuring Degree centrality $[C_D(i)]$ is to analyse the binary network of the MPTNs. The measure of binary network was detected by Freeman (1978) as follows:

$$N_i = C_D(i) = \sum_j^P x_{ij} \qquad 3.1$$

where *i* is the focal port, *j* represents all other ports inside the network, *P* is the total number of ports, and x_{ij} is the connection between port *i* and port *j*, in which it is defined by 1 if there is a connection between port *i* and port *j*, or by 0 if this connection does not exist.

In terms of the safety of MPTNs, the formalism of a weighted network is calculated undertaken by $[C_D^W(i)]$. Consequently, the measure of a weighted network has been extended to the sum of weights, in which Equation (3.1) has been formularised (Barrat *et al.*, 2004; Newman, 2004) as follows:

$$N_i = C_D^W(i) = \sum_j^P W_{ij} \qquad 3.2$$

where W_{ij} is similar to x_{ij}, which represents the interaction between port *i* and port *j*. However, W_{ij} is weighted by the throughput strength in terms of its value (i.e. barrel) instead of its link. To simplify, assume that an MPTN consists of a group of ports and seven weighted shipping routes (see Figure 3.3). Ports A and C obtain the same weight in terms of their relative throughputs. However, Port C has more connections compared to Port A.

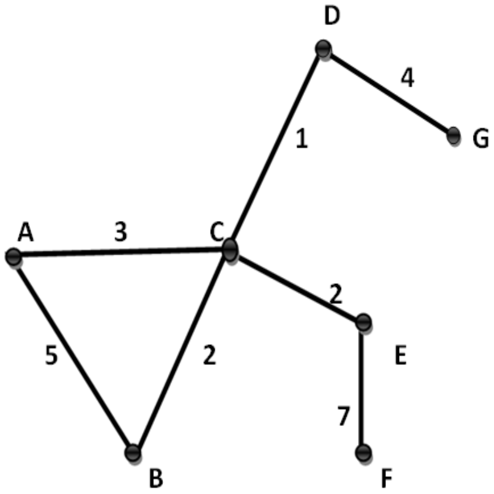

Figure 3.3: A network with seven ports and seven weighted throughputs

Degree centrality has been defined in terms of the number of connected shipping routes or by the total weights (based on throughput) allocated to ports, which can be evaluated by Equations (3.1) and (3.2). However, neither of these definitions is capable of reflecting the safety criticality of a port in weighted MPTNs. To overcome this deficiency, a tuning parameter (α), which was originally introduced by Opsahl *et al.* (2010), is incorporated in order to aggregate Equations (3.1) and (3.2). The degree centrality measuring the safety of a port in weighted MPTNs has thus been formularised as follows (Opsahl *et al.*, 2010):

$$C_D^{w\alpha}(i) = k_i \times \left(\frac{s_i}{k_i}\right)^{\alpha} = k_i^{(1-\alpha)} \times s_i^{\alpha} \qquad 3.3$$

where α is a positive number or is equal to zero, which can be described based on the research setting and data. When α = 0, the port safety degree centrality value is identical to the degree centrality value interpreted in Equation (3.1). Similarly, when α = 1, the port safety degree centrality value is identical to the degree centrality value interpreted in Equation (3.2). Conversely, when 0 < α < 1 and the total port strength is fixed, the safety degree centrality value of the port increases, and the total strength is distributed from the port to further connections. On the other hand, when 1 < α and the total port strength is fixed, a higher number of connections through which the strength is distributed will lead to a lower value of the measure; greater concentration of port strength among only a limited number of ports will be favoured (Opsahl *et al.*, 2010). Table 3.1 exemplifies the effectiveness of the changing α values (i.e. α = 0, 0.5, 1, and 1.5) of the network in Figure 3.3.

Table 3.1: Degree centrality when different values are used for α.

Port	C_D	C_D^W	$C_D^{w\alpha}$ when α =			
			0	0.5	1	1.5
A	2	8	2	4	8	16
B	2	7	2	3.74	7	13.1
C	4	8	4	5.66	8	11.31
D	2	5	2	3.16	5	7.91
E	2	9	2	4.24	9	19.09
F	1	7	1	2.65	7	18.52
G	1	4	1	2	4	8

The direction of the network can be identified as out-degree or in-degree. Values of these measures reflect the criticality of the port, which could be quantified by the amount of throughput from the port (K^{out}) and the amount of throughput that is directed to the port $\left(K^{in}\right)$. The equations are shown below (Opsahl *et al.*, 2010):

$$C_{D-out}^{w\alpha}(i) = k_i^{out} \times \left(\frac{s_i^{out}}{k_i^{out}}\right)^{\alpha} = k_i^{out(1-\alpha)} \times s_i^{out\ \alpha} \qquad 3.4a$$

$$C_{D-in}^{w\alpha}(i) = k_i^{in} \times \left(\frac{s_i^{in}}{k_i^{in}}\right)^{\alpha} = k_i^{in(1-\alpha)} \times s_i^{in\,\alpha} \quad 3.4b$$

Within MPTNs, the out-degree indicates the safety criticality of the port in terms of its influence on other ports, while the in-degree indicates the safety criticality of the port in terms of its link to downstream inland transportation. Therefore, the out- and in-degree are combined in this study as follows:

$$C_D^{w\beta}(i) = [C_{D-out}^{w\alpha}(i)]^{\beta} \times [C_{D-in}^{w\alpha}(i)]^{(1-\beta)} \quad 3.5$$

where $C_D^{w\beta}$ means the safety criticality, and β is the parameter describing the role of *in* and *out* in the MPTNs. For example, if β = 1, the MPTN is a network focusing on sea transportation. If β = 0, the network is focused more on inland transportation. When β = 0, the port safety criticality value is identical to the value interpreted in Equation (3.4b). Similarly, when β = 1, the port safety degree centrality value is identical to the degree centrality value interpreted in Equation (3.4a).

3.5.5 Betweenness Centrality

The concept of betweenness centralities is based on identifying the shortest routes between pairs of ports in MPTNs. Betweenness centrality is defined as the number of steps that a port needs to pass through in order to complete the connection between pairs of ports within a network via the shortest route (Freeman, 1978). In the binary network of MPTNs, the shortest route $[d(i,j)]$ of this measure is simplified by the following equation (Freeman, 1978):

$$d(i,j) = min(x_{ih} + \cdots + x_{hj}) \quad 3.6$$

where h are intermediary ports on pathways between ports i and j when indirect connections are considered. The shortest pathway in a binary network is identified by minimising the number of in-between ports, and the length of that pathway is identified through minimising the number of routes that link between two ports.

Therefore, port betweenness centrality within a binary network of MPTNs has been simplified with reference to Freeman (1978) as follows:

$$C_B(i) = \frac{g_{jk}(i)}{g_{jk}} \qquad 3.7$$

where g_{jk} is the number of binary shortest routes between ports j and k, and $g_{jk}(i)$ is the number of those pathways that pass through port i.

Unfortunately, this type of equation does not work with weighted networks for measuring the safety criticality of a port in weighted MPTNs, where the throughputs are weighted with different values (i.e. barrel). As a result, for defining a network's shortest route, Newman (2001) and Brandes (2001) implemented Dijkstra's (1959) algorithm for network analysis definition of the shortest path in a weighted network [$d^w(i,j)$]. Their approach has been formularised as follows (Opsahl *et al.*, 2010):

$$d^w(i,j) = min\left(\frac{1}{w_{ih}} + \cdots + \frac{1}{w_{hj}}\right) \qquad 3.8$$

where W_{ih} is similar to x_{ih}. However, W_{ij} is weighted by the throughput strength in terms of its value.

Still, none of these equations can reflect the relative importance of paths in weighted MPTNs. Therefore, based on the tuning parameter (α) introduced by Opsahl *et al.* (2010), the safety shortest path has been formularised by the following equation:

$$d^{w\alpha}(i,j) = min\left(\frac{1}{(w_{ih})^\alpha} + \cdots + \frac{1}{(w_{hj})^\alpha}\right) \qquad 3.9$$

α can be described based on the research setting and data where $\alpha \geq 0$. For example, when $\alpha = 0$, the port safety shortest path value is identical to the shortest route value interpreted in Equation (3.6), which was on the basis of a binary network. Similarly, when α = 1, the port safety shortest pathway value is identical to the shortest route value interpreted in Equation (3.8). However, when 0 < α < 1 and the total route strength is fixed, the safety shortest pathway value of the ports increases as more intermediary ports become involved. On the other hand, when 1 < α and the total pathway strength is fixed, the impact of an additional intermediary port is relatively unimportant, as the strength of the links and routes with more intermediaries are favoured (Opsahl *et al.*, 2010). To simplify, the network in Figure 3.4 shows four routes between ports A and B, each of which contains a different number of in-between ports with different weighted routes. Table 3.2 further illustrates the binary and weighted distance between ports A and B as shown in Figure 3.4, as well as different values of tuning parameters (i.e. the last four columns in Table 3.2).

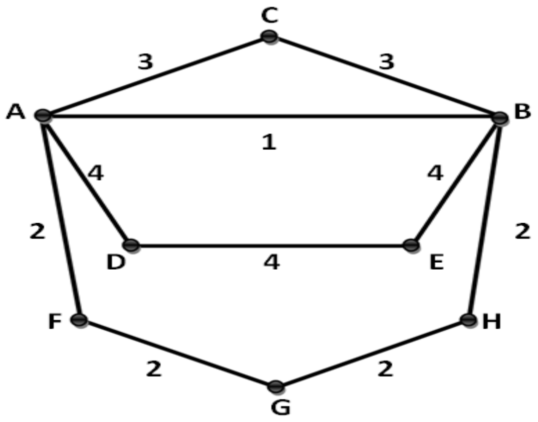

Figure 3.4: A network with three weighted paths between ports A and B

As a result, both the number of intermediary ports and weighted links took into account the betweenness centrality measures through applying the proposed shortest route algorithm. Therefore, to identify the safety critical ports in weighted MPTNs, Equations (3.7) and (3.9) are combined as follows (Opsahl *et al.*, 2010):

$$C_B^{w\alpha}(i) = \frac{g_{jk}^{w\alpha}(i)}{g_{jk}^{w\alpha}} \qquad 3.10$$

where $g_{jk}^{w\alpha}$ is the sum of all shortest routes between ports j and k, and $g_{jk}^{w\alpha}(i)$ is the number of these shortest pathways that go through port *i*.

Table 3.2: Lengths of paths when defined by binary and weight as well as when different values of α are used

Path	$d(A,B)$	$d^{w}(A,B)$	$d^{w\alpha}(A,B)$ when α =			
			0	0.5	1	1.5
(A,B)	1	1	1	1	1	1
(A,C,B)	2	0.67	2	1.15	0.67	0.38
(A,D,E,B)	3	0.75	3	1.5	0.75	0.37
(A,F,G,H,B)	4	2	4	2.83	2	1.41
Min	1	0.67	1	1	0.67	0.37

As the results from the degree and betweenness centralities are in absolute values, the outcomes are not easy to compare. Therefore, the values are normalised with min-max normalisation by the following equation:

$$\text{Min} - \text{Max}\ a_i = \frac{a_i - A_{min}}{A_{max} - A_{min}} \qquad 3.11$$

where *i* is the focal port, A_{min} is the minimum centrality results, and A_{max} captures the maximum centrality results.

The sum of the normalised values is going to be greater than 1 ($\sum a_i < 1$). This result needed to be equal to 1 ($\sum a_i = 1$). Therefore, the values are normalised as follows:

$$\text{Normalised}\ a_i = \frac{a_i}{\sum a_i} \qquad 3.12$$

where *i* is the focal port, and *N* is the number of ports within the network.

3.6 Case Study and Results Analysis

To identify the safety critical points within the crude oil transportation system, a case study is conducted in this chapter in order to demonstrate how the methodology can be employed to evaluate a real-life MPTN within a PTN. The steps of this evaluation process are listed as follows:

3.6.1 MPTN Development and Data Collection

Maritime crude oil transportation is undertaken by a combination of various shipping companies and worldwide petroleum terminals. This highly interconnected system runs with a typical network feature, which could be abstracted to a graph where petroleum terminals constitute the nodes and shipping services provide the links. Thus the maritime crude oil transportation network provides an excellent fundamental basis for accomplishing network analysis of the petroleum transportation structure.

Crude oil is among the most strategic natural resources for all industries. In the annual 2013 report, the Organization of the Petroleum Exporting Countries (OPEC) announced that worldwide growth in crude oil demand was 1.05 million barrels per day. The importance of crude oil is rooted in the refined products of this resource, which are applied in many businesses for generating heat, fuelling vehicles and airplanes, and manufacturing nearly all chemical products (e.g. plastics, detergents, paints, and even medicines). Therefore, transporting this resource plays a strategic role in the world economic growth cycle.

Maritime crude oil transportation networks contain a group of nodes (ports) that are connected to each other through links (shipping companies). The nature of this network contains two types of ports:

1) Exporting ports: Used for transporting the crude oil out of an origin country after the production phase.
2) Importing ports: Used for importing the crude oil that is shipped from the origin country to the refineries.

For the purpose of this research, the maritime crude oil transportation network is going to be built based on a major petroleum exporter and on the world's major crude oil importers (see Figure 3.5).

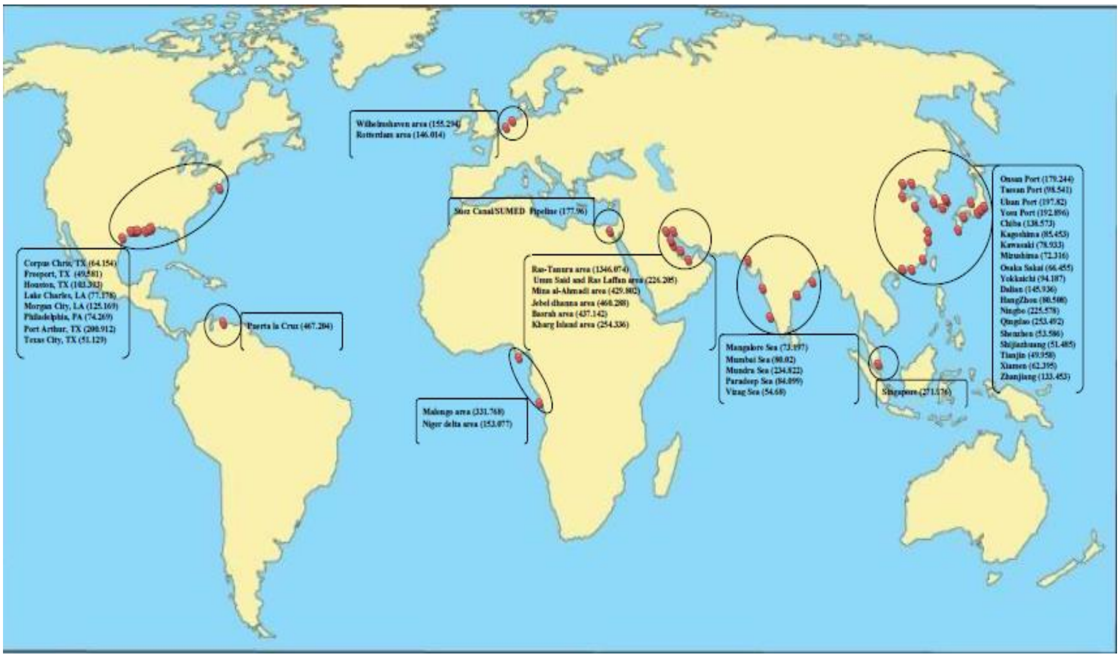

Figure 3.5: Sample network ports and their throughputs in 2013 (million barrels)

Due to the lack of actual crude oil traffic statistics, links within the network are weighted with the crude oil transportation capacity (in barrels) deployed between the ports of major OPEC members and the ports of major crude oil importers for the year in 2013. The reason for accounting only for capacity from OPEC members is that about 81% of the world's crude oil reserve is handled by these members (OPEC, 2014a). Moreover, they contributed more than 60% of the world's total crude oil exports in the year 2013 (OPEC, 2014a). The OPEC members that are adopted in this network are counted in the world's top 10 crude oil exporters according to U.S. Energy Information Administration (EIA, 2014): Angola, Islamic Republic of Iran, Iraq, Nigeria, Kuwait, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela. Directions of capacity flow movement are considered as well in this network. Therefore, this research covers all major crude oil trading markets on the East-West route, which includes the North

American, Latin American, European, Asia and Pacific, Middle-East, and African areas.

The data in this research have been collected from annual reports, countries' customs, and companies' statistics. As aforementioned, the MPTN in this case study covers major crude oil trading markets, and the connections between ports have been weighted based on these statistics. Therefore, this evaluated maritime network will consist of 45 of the world's major ports in the PTN, where the links between these ports are weighted with barrels through 2013 (see Figure 3.5).

In the collected data, each port was using different units for measuring the throughput (e.g. Houston port measures by barrel, while Chiba port uses kilolitres). According to British Petroleum (BP) (2010), there are several different units for measuring the crude oil throughput: tonnes (metric), kilolitres, barrels, and US gallons. For the purpose of this study, and before starting to analyse the port centrality in a weighted network, firstly it was important to convert different units to one unit (i.e. barrel). The OPEC annual report (2014a) delivers simple mathematical matrixes to convert the units, which are shown in Table 3.3.

Table 3.3: Conversion factors for crude oil adopted from OPEC's annual statistical in 2014 (OPEC, 2014a)

From	To				
	Tonnes (metric)	Kilolitres	Barrels	US gallons	Tonnes per year
	Multiply by				
Tonnes (metric)	1	1.165	7.33	307.86	-
Kilolitres	0.8581	1	62898	264.17	-
Barrels	0.1364	0.159	1	42	-
US gallons	0.00325	0.0038	0.0238	1	-
Tonnes per year	-	-	-	-	49.8

3.6.2 Evaluation Process

In this section, the safety critical ports within the MPTN are identified by applying degree and betweenness centrality measures. This section identifies the safety critical ports and choke points within the MPTN. Therefore, in case 1, the safety critical ports within the maritime PTS are identified. In case 2, through adding crude oil choke points (i.e. Strait of Hormuz, Strait of Malacca, Suez Canal and SUMED Pipeline, Bab el-Mandab, and Cape of Good Hope), the central points within the MPTN are identified.

3.6.2.1 Case 1

First, port safety criticality was analysed with Freeman's degree and betweenness centrality measures without adding world choke points (see Figure 3.6). The analysed results were further normalised with min-max normalisation (see Appendixes 1.5, 1.6, and 1.7) to ensure the identification. The results were finally examined through comparing correlations between port centrality and throughputs via Microsoft Excel.

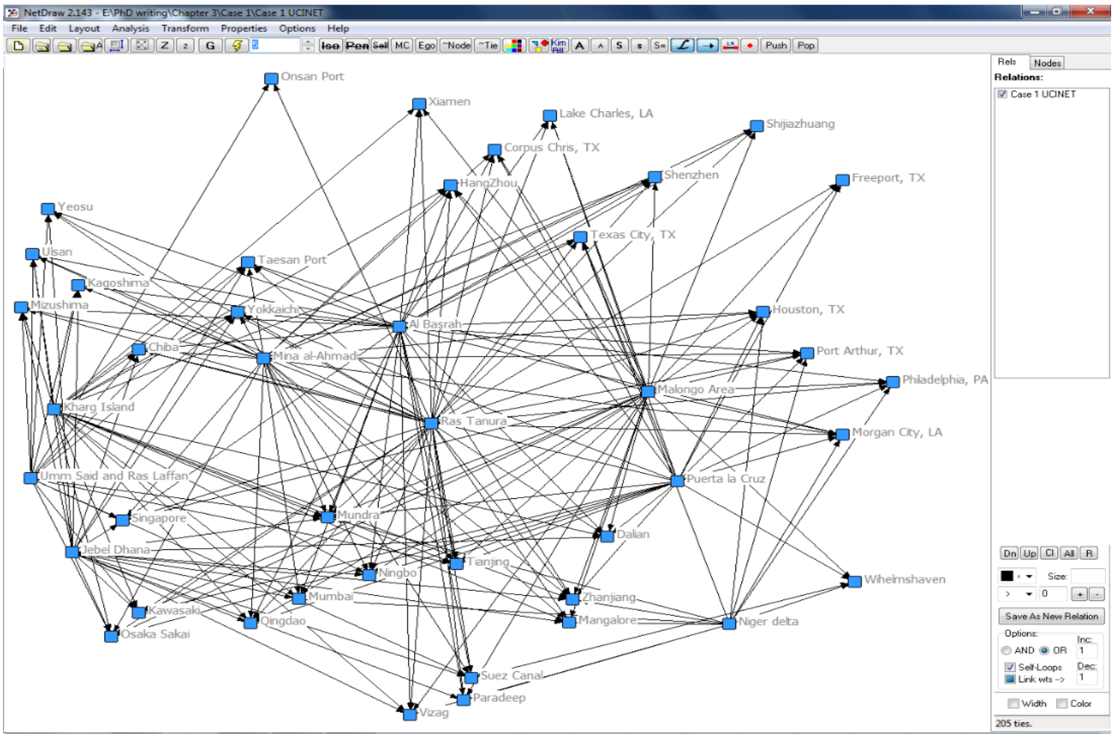

Figure 3.6: Visualisation of ports through using NetDraw software

Port degree centrality

To identify the safety critical ports within the MPTN, port centrality has been examined from the perspective of its direct connectivity (i.e. degree, in-degree, and out-degree centrality). Through assigning different values to the tuning parameter (α) (i.e. 0, 0.5, 1, and 1.5), Equation (3.5) illustrated the safety criticality of the ports within the crude oil transportation network. To calculate that equation, the collected data of the petroleum transported between ports were calculated through R-software (see Tables 3.4 and 3.5 and Appendixes 1.2, 1.3, and 1.4). The following section first exemplifies the steps for measuring the safety criticality of a port in the weighted MPTN. The section then demonstrates the normalisation of the values with min-max normalisation.

For measuring the safety criticality of a node in the weighted MPTN, the Suez Canal/SUMED Pipeline (S) is used as an example (see Appendix 1.1).

Through applying Equation 3.1, the degree centrality of $C_D(S)$ is equal to 7.Based on Equation 3.1, the Suez Canal/SUMED Pipeline links to seven ports (i.e. Ras-Tanura port, Mina al-Ahmadi, Basrah Oil Terminal, Umm Said and Ras-Laffan Terminal, Jebel Dhanna port, Wilhelmshaven port, and Rotterdam port).

In terms of safety network, Equation 3.2 measures the degree centrality of $C_D^W(S)$ (i.e. weighted by throughput in terms of barrels instead of the number of links) as 355.92.

Through introducing a tuning parameter (α) to aggregate the values of Equations (3.1) and (3.2), Equation (3.3) analyses the centrality of (S) in the weighted MPTN $C_D^{w\alpha}(S)$. With respect to the direction of the network, Equations (3.4a) and (3.4b) analyse the in, and out-degree safety centrality of (S) in the weighted MPTN (see Tables 3.4 and 3.5 and Appendixes 1.3, and 1.4).

Table 3.4: Out-degree centrality scores sample with different values of tuning parameter

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	34	213.9311	1346.074	8469.6204
Jebel Dhanna port	20	95.9467	460.288	2208.1546
Puerta la Cruz	21	99.0519	467.204	2203.6884

Table 3.5: In-degree centrality scores sample with different values of tuning parameter

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Corpus Chris port	5	17.9101	64.154	229.8003
Singapore port	6	40.3368	271.176	1823.0612
Zhanjiang port	8	32.6745	133.453	545.064

Based on the result of Equations (3.4a) and (3.4b), Equation (3.5) introduced a parameter (β) to aggregate the in and out values (see Appendixes 1.3, and 1.4).

In terms of normalisation, Equation (3.11) normalised the safety criticality values when $\beta = 0$ as follows:

$$\text{Normalised } C_D^w(S) = \frac{C_D^{w\beta}(S) - C_{D-\text{min}}^{w\beta}}{C_{D-\text{max}}^{w\beta} - C_{D-\text{min}}^{w\beta}} = \frac{5-0}{9-0} = 0.5556$$

$$\text{Normalised } C_{D-\text{in}}^{w\alpha}(S) = \frac{C_{D-\text{in}}^{w\alpha}(S) - C_{D-\text{in}_{\text{min}}}^{w\alpha}}{C_{D-\text{in}_{\text{max}}}^{w\alpha} - C_{D-\text{in}_{\text{min}}}^{w\alpha}} = \frac{29.83-0}{45.972-0} = 0.6489$$

$$\text{Normalised } C_{D-\text{in}}^{w\alpha}(S) = \frac{C_{D-\text{in}}^{w\alpha}(S) - C_{D-\text{in}_{\text{min}}}^{w\alpha}}{C_{D-\text{in}_{\text{max}}}^{w\alpha} - C_{D-\text{in}_{\text{min}}}^{w\alpha}} = \frac{177.96-0}{271.176-0} = 0.6563$$

$$\text{Normalised } C_{D-\text{in}}^{w\alpha}(S) = \frac{C_{D-\text{in}}^{w\alpha}(S) - C_{D-\text{in}_{\text{min}}}^{w\alpha}}{C_{D-\text{in}_{\text{max}}}^{w\alpha} - C_{D-\text{in}_{\text{min}}}^{w\alpha}} = \frac{1061.692-0}{1823.061-0} = 0.5824$$

Appendix 1.5 shows the resulting normalised scores of the petroleum ports with respect to ports' safety criticality when $\beta = 1$ with different assumptions of tuning parameters.

With respect to the change of the tuning parameters' values, Ras-Tanura port is the most critical port (1). This importance is mainly attributed to the port's dominant role in petroleum transportation; in other words, Ras-Tanura port attracts significant shipping capacity. Therefore, any major incident/accident in Ras-Tanura port leading to a disruption would affect the petroleum throughput within the MPTN. On the opposite side, ports such as Wilhelmshaven port and other ports from different regions have low centrality scores (0) within the evaluated MPTN (see Figure 3.7). Umm Said and Ras-Laffan terminal maintains a relatively stable position, ranking as eighth across the changes of parameter.

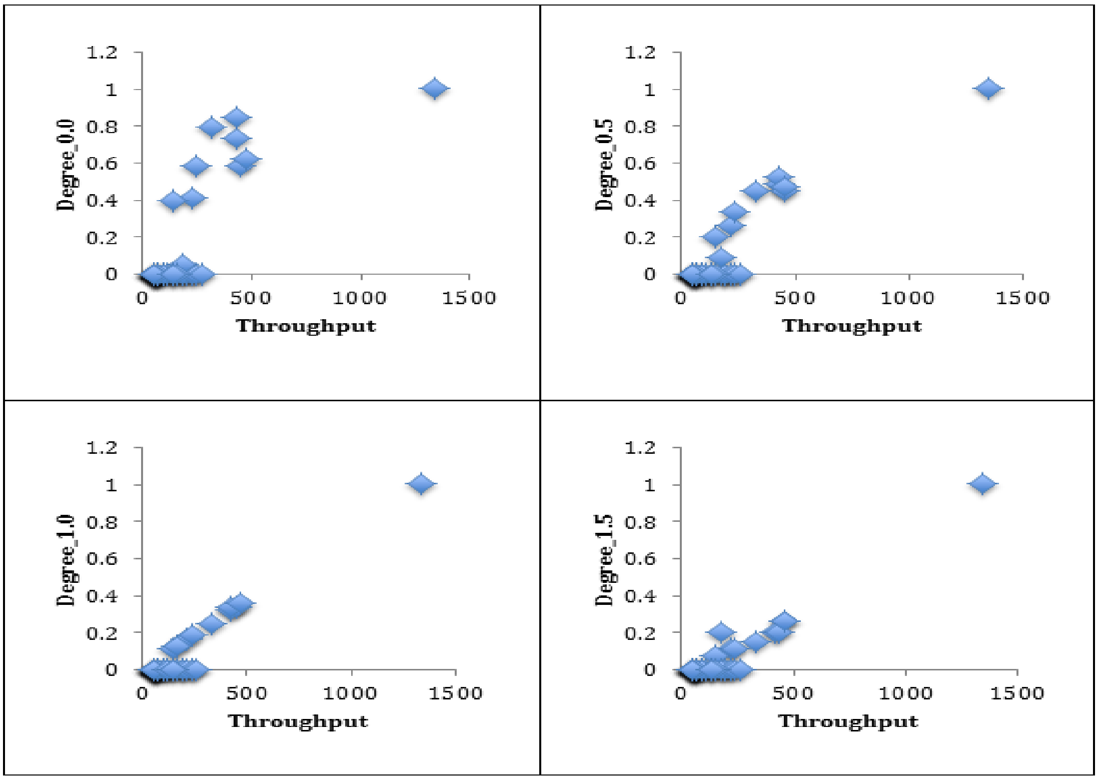

Figure 3.7: Correlations between throughputs and degree centrality when β=1

Mina al-Ahmadi (0.484) and Basrah Oil Terminal (0.526) score high safety levels when the parameter is set as 0 and 0 < α < 1. However, when the network is weighted with shipping capacity (i.e. 1 < α), Jebel Dhanna port (0.261) and Puerta la Cruz port (0.26) become ports with higher safety criticality within the MPTN in comparison with Mina al-Ahmadi (0.21) and Basrah Oil Terminal (0.2).

Turning to the ports' effect on inland transportation, which is represented in Appendix 1.6, in terms of incoming service, Mundra seaport (1) is the most central port. However, when the network is weighted for the safety of the MPTN, the port loses this importance to other ports (i.e. α ≤ 1). Conversely, the port of Singapore has a low level of importance (0.667 and 0.877). However, when α ≤ 1, the port of Singapore has a high level of criticality in the crude oil transportation network. Therefore, based on safety criticality, any risk factor that should strike Singapore port would have a significant impact on the petroleum throughput within the MPTN in terms of port connection to the downstream supply chain (see Figure 3.8).

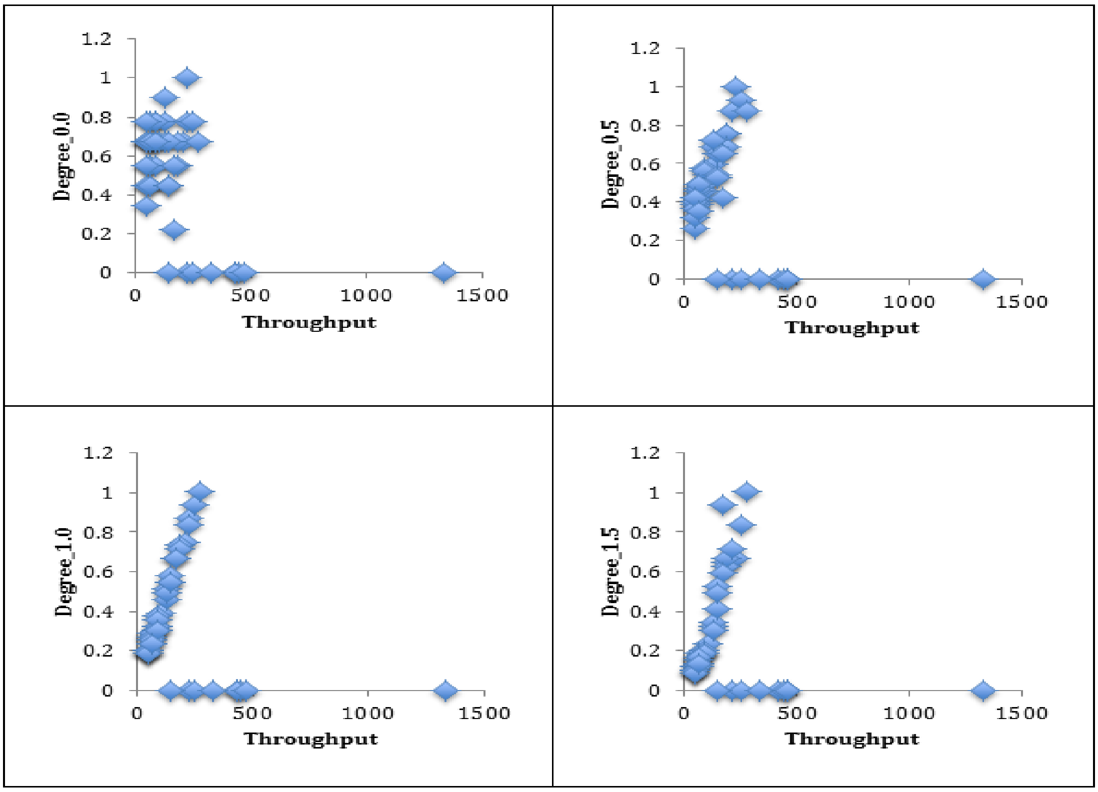

Figure 3.8: Correlations between throughputs and degree centrality when β=0

Therefore, the safety criticality degree centrality of a specific port within the network is affected by the change of the parameters' values as well as by the shipping capacity of the port. The number of connections in and out of a port within the MPTN also affects the degree centrality.

Port Betweenness Centrality

Through assigning different values to the tuning parameter (α), Equation (3.10) illustrates the safety critical ports within the crude oil transportation network. To generate this equation, the collected data of petroleum transported between ports were calculated by R-software (see Table 3.6).

Table 3.6: Betweenness centrality scores sample with different values of tuning parameter

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	0	0	0	0
Yokkaichi port	0	0	0	0
Suez Canal/SUMED Pipeline	10	10	10	10

Appendix 1.7 shows that, with the changes of the parameter, the Suez Canal/SUMED Pipeline counts as the most critical point within the network (1) (i.e. it is the location for exporting and/or importing petroleum to ensure the ability of ships to pass through the Suez Canal) (see Figure 3.9). This critical point gains its importance based on the nature of this network. The world choke points were then added to identify the safety critical ports and routes in the MPTN.

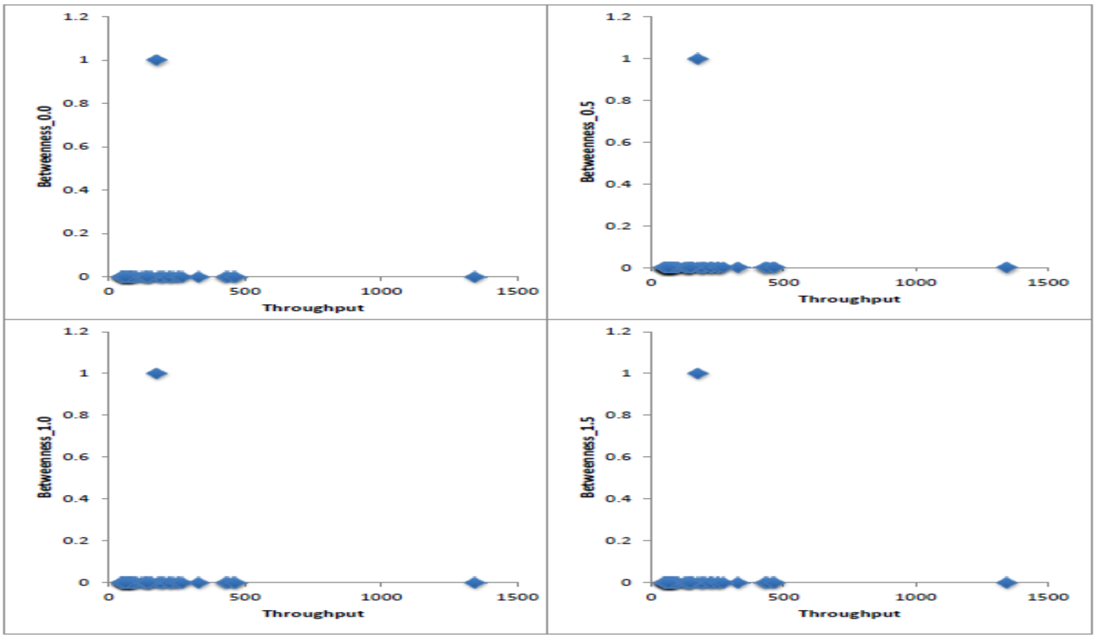

Figure 3.9: Correlations between throughputs and betweenness centrality

3.6.2.2 Case 2

Port safety criticality was identified by using Freeman's degree and betweenness centrality measures and adding world choke points to the network (see Figure 3.10). The results were normalised with min-max normalisation to ensure the identification. The results were then examined through comparing correlations between port criticality and throughputs via Microsoft Excel (see Appendixes 1.10, 1.11, and 1.12).

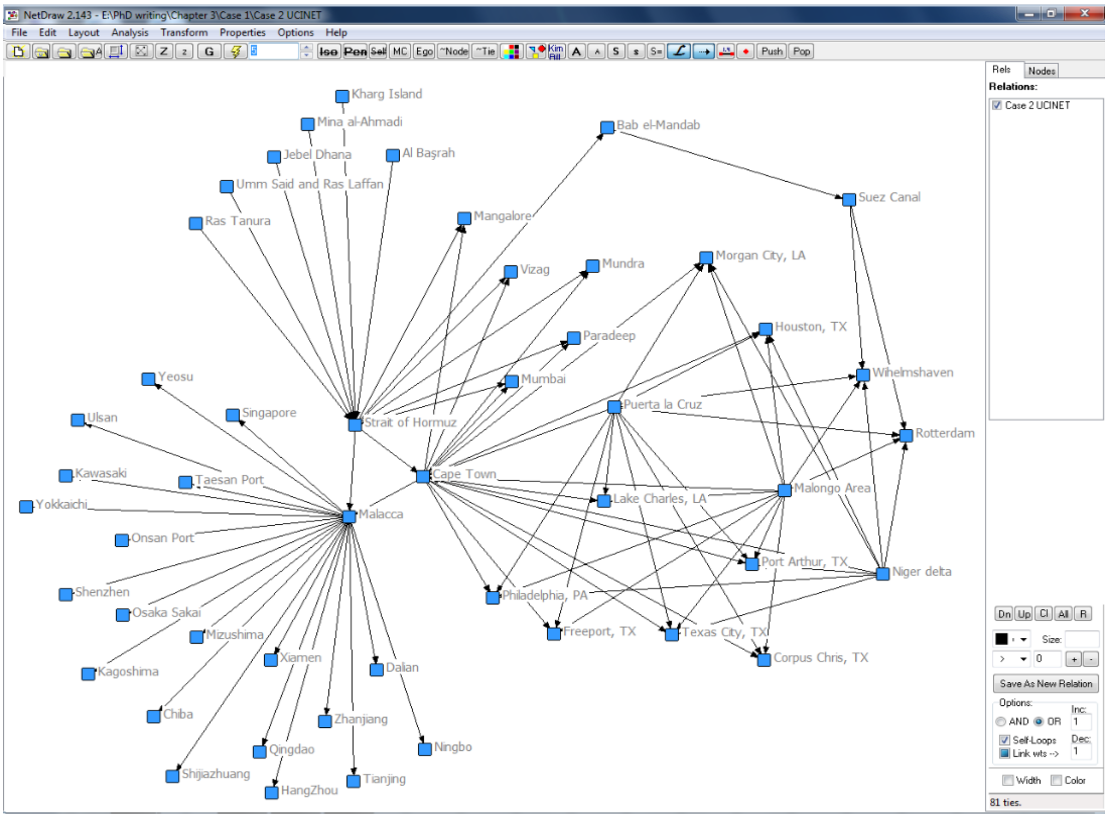

Figure 3.10: Visualisation of ports through using NetDraw software

Port Degree Centrality

To identify the safety critical petroleum ports and routes within the MPTN, different values (namely 0, 0.5, 1, and 1.5) were assigned to the tuning parameter (α) in Equations (3.4a) and (3.4b). The results illustrate the relative importance of the ports and routes within the crude oil transportation network (see Tables 3.7 and 3.8 and Appendixes 1.8, and 1.9).

Table 3.7: Out-degree centrality scores sample with different values of tuning parameter

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	1	1	1346.074	49385.949
Niger Delta area	8	8	153.077	669.6069
Strait of Malacca	20	20	2531.985	28488.9665

Table 3.8: In-degree centrality scores sample with different values of tuning parameter

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Strait of Hormuz	6	137.5612	3153.847	72307.8263
Port Arthur port	4	28.3487	200.912	1423.8978
Singapore port	1	16.4674	271.176	4465.5697

The degree centrality is measuring the safety criticality of a node in the weighted MPTN, which contains ports and choke points, assumed by different parameters (see Appendix 1.10). The Strait of Malacca (1) and Cape of Good Hope route (0.7) are important routes in respect of outflow; also, the Malongo port (0.55) and Puerta la Cruz port (0.55) are important ports within the MPTN. When the network is weighted for the safety of the ports and routes within the MPTN, these ports and routes still have high safety criticality levels. However, their levels are not the most critical points. In terms of binary networks, the Strait of Hormuz (0.4) and Ras-Tanura port (0.05) have less advantage in terms of direct connections to other routes and ports. Conversely, when considering the connection and the strength of these connections with respect to the change of the tuning parameters' values, the Strait of Hormuz (1) and Ras-Tanura port (0.789) become the most critical choke point and port, respectively, in the MPTN. This result is mainly attributed to their role in the petroleum transportation routes (see Figure 3.11). Therefore, any major incident/accident in Ras-Tanura port and the Strait of Hormuz will significantly impact the petroleum throughput within the MPTN.

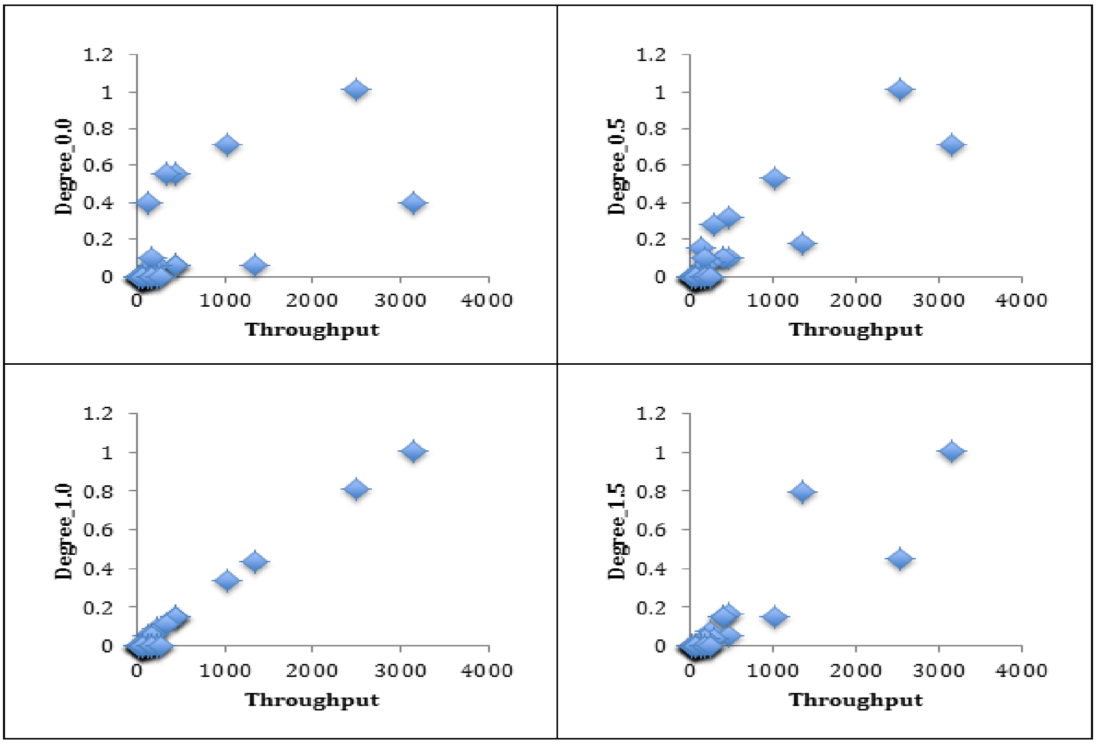

Figure 3.11: Correlations between throughputs and degree centrality when β=1

Appendix 1.11 shows the normalised values with respect to safety criticality when $\beta = 0$ with different assumptions of tuning parameters. The Strait of Hormuz (1) and Cape of Good Hope route (0.667) are the two most critical routes. Despite overtaking the Strait of Malacca in terms of the safety of the routes within the MPTN, these two routes still rank as the second and third when α = 1.5. In the ports sector, the Rotterdam (0.667) and Arthur (0.667) ports have a high centrality level across the network. When the network is weighted for the safety of the MPTN, they still hold this importance in their regions. Conversely, Singapore port (0.167) has a low centrality level when (α) = 0, but when α < 1, the port becomes the most safety critical port in the MPTN (see Figure 3.12).

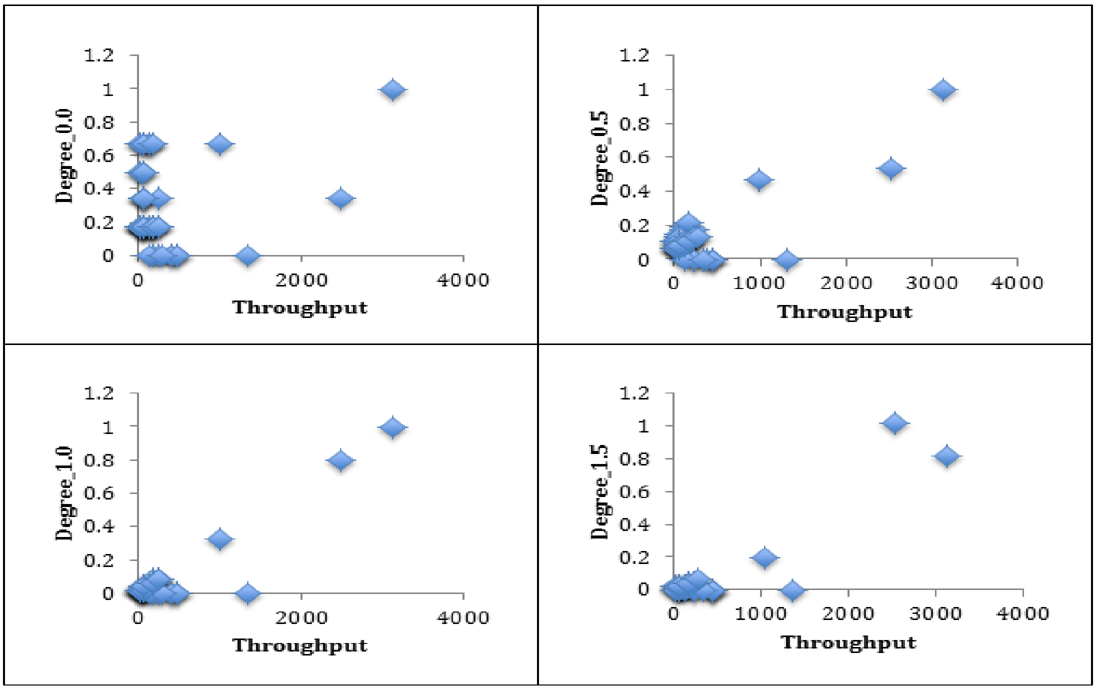

Figure 3.12: Correlations between throughputs and degree centrality when β=0

Port Betweenness Centrality

To identify the petroleum ports and route criticality within the MPTN, centrality has been examined from the potential perspective of being intermediary between ports. Betweenness centrality represents the likelihood of ports and routes being applied as intermediary points in the MPTN within petroleum transportation network. Ports and routes with high centrality values are likely to have extra traffic if they are favoured by transportation carriers as important points in the network. Through assigning different values to the tuning parameter (α), the safety critical ports and routes within the MPTN have been evaluated by Equation (3.10) (see Table 3.9).

Table 3.9: Betweenness centrality scores sample with different values of tuning parameter

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Suez Canal/SUMED Pipeline	16	16	16	16
Cape of Good Hope	137	153	162	162
Strait of Hormuz	234	234	234	234

According to the results (see Appendix 1.12), when α = 0, traditional choke points like the Strait of Hormuz (1) and Strait of Malacca (0.94) are the two central routes in the PTS. When the network is weighted (i.e. α = 0.5, 1, and 1.5), the Strait of Hormuz and Strait of Malacca retain their importance in the network. Therefore, with respect to the change of the tuning parameters' values, the Strait of Hormuz and Strait of Malacca are the safest and most strategic routes in the network. This result is mainly attributed to their dominant role in the petroleum network, in which they connect many other ports (see Figure 3.13). Therefore, any major incident/accident in these two routes (e.g. piracy) leading to a disruption would affect the petroleum throughput within the MPTN.

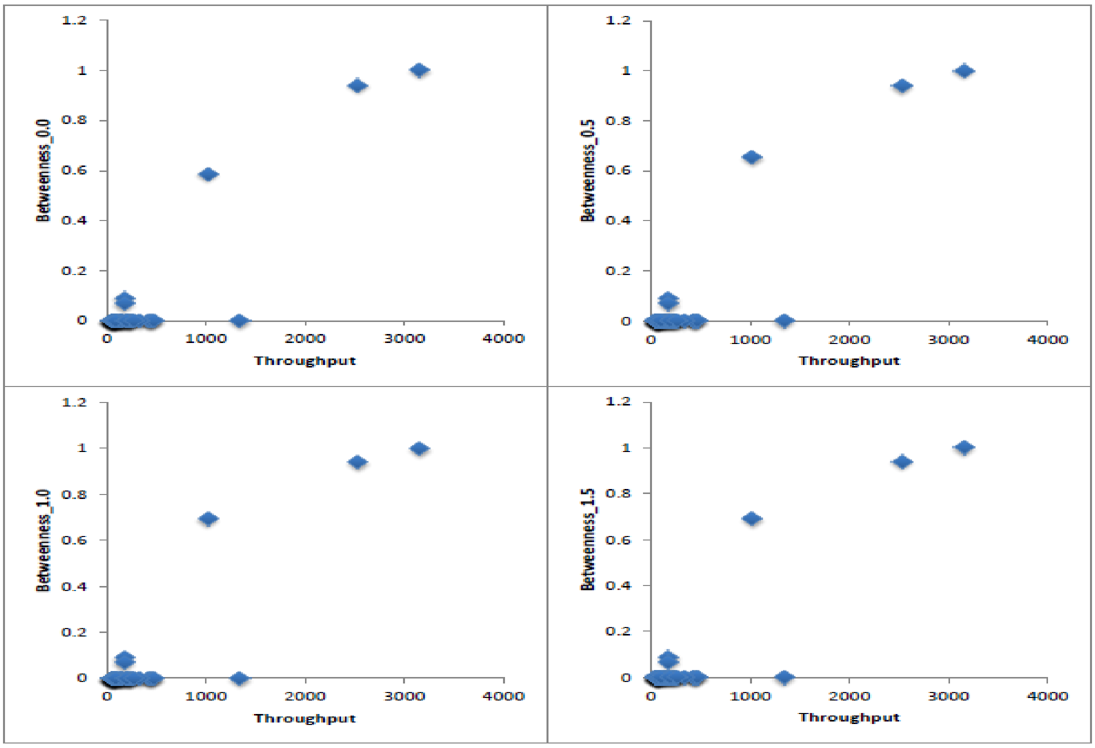

Figure 3.13: Correlations between throughputs and betweenness centrality

3.7 Conclusion

This chapter was motivated by the need to develop a quantitative analysis framework for safety analysis of ports and transportation modes within PTSs. This chapter established the basis for evaluating PTSs as complete systems. Thus, the result of this chapter helps to identify the safety critical ports and routes within MPTNs. This result could be analysed in further research by applying risk assessment techniques. In this study, the most popular centrality measures developed in social network analysis have been categorised and reviewed. To apply centrality measures to a maritime PTS, a set of criteria was identified based on the characteristics of shipping flow through a network. Hence, the criteria were the ability to connect two ports via direct connections and the strategic position (i.e. status as an intermediary) in the network. The degree and betweenness centrality measures were selected in order to analyse the safety criticality of ports and routes.

For measuring the critical ports and routes in weighted MPTNs, Freeman's degree and betweenness centrality measures were adopted. A tuning parameter with different values (i.e. 0, 0.5, 1, and 1.5) was added to measure the importance of the port and route through considering both the weight and the number of connections.

The formulas of Freeman's degree and betweenness measures were adopted to meet the needs of examining a weighted and directed network. In case 1 and case 2, a parameter with a set of results generated by adopting the two measures shows the following:

- Centrality measures are capable of identifying the safety critical ports and routes of maritime PTSs at both regional and global levels.
- Shipping capacity has a direct effect on the port centrality results based on the available inflow and outflow.
- Ras-Tanura port and Singapore port are safety critical ports regarding their degree centrality measure.
- Routes and ports with high betweenness centrality are in critical positions, as they affect the flow of cargo (i.e. the Strait of Hormuz and Suez Canal/SUMED

Pipeline).

Centrality measures present a useful tool for analysing and identifying the safety critical ports and routes within the MPTN. Based on the degree and betweenness centrality measures, Ras-Tanura port, Singapore port, and the Strait of Hormuz are identified as the critical ports and routes in the analysed MPTN.

This chapter mainly focused on evaluating the global level of PTSs. However, ensuring PTSs operation in a safe condition, is a significant element for the safety of PTNs. In the following chapters, the global level of PTNs will be evaluated (chapter 5). While the network analysis technique was used to assess the global level of the PTSs, a hybrid Fuzzy Rule-Based Bayesian Reasoning (FRBBR) approach is going to be applied, to identify and evaluate the operational hazards associated with PTSs (chapter 4). Moreover, other techniques, such as Analytical Hierarchy Process (AHP) and Evidential Reasoning (ER), will be used as to evaluate the petroleum transportation as one complete system.

Chapter 4: A New Quantitative Hybrid Fuzzy Rule Based Bayesian Reasoning for PTSs Operations

Petroleum transportation systems (PTSs) play an important role in the movement of the crude product from its production to the end user. To ensure an effective transportation system, port and transportation mode safety must not be neglected. A hybrid Fuzzy Rule-Based Bayesian Reasoning (FRBBR) model is introduced in order to perform risk ranking due to the high level of uncertainty in petroleum transportation operations. This method combines the Fuzzy Rule-Based (FRB) approach and Bayesian Networks (BNs) to compensate for the disadvantages of each technique and benefit from each one's advantages. The resulting technique can be used by decision makers to measure and improve PTSs safety.

4.1 Introduction

PTSs play a major role in global and local supply chain systems. Pipelines and tankers are used for inland and sea transportation, and ports link these transportation modes in the flow of crude oil from its production sites to the final customer. According to the U.S. Energy Information Administration (EIA) (2014), 56.5 million barrels per day from the total worldwide production of crude oil, which is about 90.1 million barrels per day, was transported by sea in 2013. Therefore, about 63% of the transported crude oil passed through PTSs during its journey from the producer to the customer. Risk assessment is an important subject in the safe transportation of crude oil to ensure the safety and reliability of the petroleum industry as a whole.

Petroleum ports and transportation modes operate in a dynamic environment. This environment raises a prime concern with regard to the hazards that might lead to accidents. Mokhtari *et al.* (2011) mentioned that an effective safety analysis and risk management programme offers the possibility of avoiding all major accidents and loss of lives and resources. Therefore, risk assessment could provide a suitable and effective method of safety analysis. However, in several situations, it is better not to apply the traditional techniques because the output might be inaccurate due to non-existent data and the high level of uncertainty (Ren *et al.,* 2009).

Many methods have been developed to deal with uncertainty. These developed techniques are used to enhance the performance of Failure Modes and Effects Analysis (FMEA) in situations that deal with uncertainty (Yang *et al.,* 2008). Fuzzy logic is one of the techniques that have been widely applied to enhance the performance of FMEA in situations of uncertainty. The technique of fuzzy logic has been applied to and involved in creating new techniques such as fuzzy TOPSIS, fuzzy rule-based Min-Max, and fuzzy evidential reasoning. However, criticisms of fuzzy logic relate to the complex calculation and the insufficient ability to express the real risk that each situation involves.

This chapter aims to apply an advanced risk assessment technique for evaluating PTSs' operational hazards. Therefore, in this chapter a method known by the name of Fuzzy Rule-Based Bayesian Reasoning (FRBBR) is investigated for developing risk analysis techniques that support decision-makers in circumstances of uncertainty. Based on earlier studies (Yang *et al.,* 2008; Liu *et al.,* 2013; Alyami *et al.,* 2014), FRBBR is a hybrid technique that utilises a combination of Fuzzy Rule-Based (FRB) approach and Bayesian Networks (BNs) to compensate for each respective method's disadvantages. For example, a known disadvantage in BNs is that the methodology requires an amount of information that is commonly difficult or impossible to obtain in risk assessment; the relevant information is required to be presented in the form of prior probability (Alyami *et al.,* 2014; Yang *et al.,* 2008). By using the FRB approach, the FMEA parameters (i.e. likelihood of the existence of failure, consequence severity, and probability of a failure going undetected) can be defined and evaluated. Additionally, by using a BN, all the FRB results of a failure can be aggregated to produce values that assist decision-makers in circumstances of vagueness. The proposed methodology is demonstrated by investigating a real PTSs.

4.2 Background of Failure Modes and Effects Analysis

According to Liu *et al.* (2013), Failure Modes and Effects Analysis (FMEA) is a step-by-step procedure applicable to various businesses for evaluating safety and reliability failure modes and effects. FMEA is among the most widely used and effective analysis methods to define, identify, and eliminate expected and/or potential failure from a system.

The aerospace industry in the1960s was the first field to adopt the method for increasing the safety and reliability level of a system (Ravi Sankar and Prabju, 2001). The FMEA has since been practically used to ensure the safety and reliability of production in many industries, such as the aerospace, automotive, nuclear, and medical industries.

Traditional FMEA considers three factors (Yang *et al.*, 2008):

- Likelihood of failure existence (L)
- Consequent severity of the failure (C)
- Probability of a failure going undetected (P)

These three factors determine the safety level of each failure mode and are used to calculate the Risk Priority Number (RPN) (Chin *et al.*, 2009). The RPN, which determines the rank of the risks, is obtained by multiplying the Likelihood (L), Consequence (C), and Probability (P) scores (Chin *et al.*, 2009). A high RPN for a failure mode means that the failure mode is more risky and should take priority over other failure modes with a lower RPN. The RPN is formulated as follows (Chin *et al.*, 2009; Yang *et al.*, 2008):

$$RPN = L \times C \times P \qquad 4.1$$

This clear and simple methodology has gained wide acceptance for hazard identification and risk analysis (Braglia *et al.*, 2003). Moreover, FMEA can be extended for criticality analysis, specifically for identifying the critical components where failure might lead to an accident. This extension is known as Failure Modes and Effects Criticality Analysis (FMECA) (Yang *et al.*, 2008).

Over the years, several variations of the traditional FMEA have been developed. For example, in the automotive industry, FMEA has been divided into two processes: FMEA design and FMEA process (Aldridge *et al.*, 1991).

- FMEA design is a procedure used during design to ensure that the right materials are being used to conform to customer satisfaction and that the regulations set by the government are being met.
- FMEA process deals with manufacturing and assembly processes.

Studies such as Price *et al.*'s (1992) research, which was the first and major step in automation of the FMEA process, describe the use of functional reasoning as a basis to perform failure mode analysis. Russomanno *et al.* (1992) discussed the use of an expert system for the automation of numeric and symbolic reasoning in the FMEA process. Bell *et al.* (1992) developed an automation tool built around a causal reasoning model for FMEA in the FMEA process. Price *et al.* (1995) described the use of a flame system which aimed to deliver a knowledge-based system for the automation of the FMEA process. Kara-Zaitri *et al.* (1992) presented an improved FMEA methodology. This improved method was derived from the combination of an FMEA matrix and RPN technique and hence captured the benefits of these techniques in a single matrix, providing an organised and traceable analysis model from the component level to system-level failure effects.

4.2.1 Drawbacks of Failure Modes and Effects Analysis

Although extensively used in safety analysis, traditional FMEA suffered from some critical drawbacks. One of the critical problems is associated with the use of the RPN. The technique of using RPN has been widely criticised for the following reasons (Wang *et al.,* 2009; Pillay and Wang, 2003; Chin *et al.,* 2009).

- The mathematical formula of the RPN may produce the same value in analysing different risks while using different sets for rating the L, C, and P. However, the risk implication of these similar RPNs might be very different. For example, consider two different events (i.e. $RPN_1 \ and \ RPN_2$). The L, C, and P values of the first and second events are 2, 4, 3 and 4, 1, 6 respectively. By using Equation 4.1, the total value of these two events is the same, at 24 ($RPN_1 = 2 \times 4 \times 3 = 24$ and $RPN_2 = 4 \times 1 \times 6 = 24$). However, the risk implication of these events might differ from each other with respect to the consequent severity of the failure differences. In some situations, this difference might lead to the high-risk event going unnoticed or to a waste of resources and time.
- The RPN only considers the L, C, and P factors. It neglects and does not consider other important risk factors and information such as the associated weights of these three parameters.
- Information in FMEA can be expressed in linguistic variables such as remote, moderate, or very high. In contrast, the RPN only deals with numerical

evaluation. Therefore, the values of the factors may be inaccurate; moreover, it may be difficult to assign intangible quantities.

To overcome these setbacks, many methods have been proposed to enhance the performance of FMEA. These incorporated methods are based on uncertainty modelling techniques such as fuzzy sets (Xu *et al.,* 2002), Dempster–Shafer theory (Liu *et al.,* 2005), grey theory (Pillay and Wang, 2003), evidential reasoning (Yang, 2001), Monte Carlo simulation (Bevilacqua *et al.,* 2000), and artificial neural network (Keskin and Özkan, 2009). The enhanced FMEA has been used to assist its practical application in several fields such as in maritime and offshore engineering safety (Sii *et al.,* 2001), system reliability and failure mode analysis (Braglia *et al.,* 2003), engineering system safety (Garcia and Schirru, 2005), and maritime and port security (Yang *et al.*, 2009b).

4.2.2 Fuzzy Failure Modes and Effects Analysis

At the University of California in 1965, Prof. L Zadeh (1965) introduced fuzzy logic by extending possibility theory where its basis was formed from a fuzzy set (Riahi *et al.,* 2012). Zadeh designed the theory to deal with the fuzziness of human judgment. Fuzzy logic allowed a mathematical approach to be applied for identifying fuzzy information, knowledge, and concepts (Riahi *et al.*, 2012). In other words, in probability theory the values are indicated by numbers; however, in possibility theory the values are indicated by words, in natural or artificial language, to deal with uncertainty. Thus probability theory and possibility theory are distinct. Negligible, moderately likely, and highly unlikely are a sample of description variables that may be used for defining situations (Pillay and Wang, 2003; Sii, *et al.*, 2001). These linguistic variables allow imprecise possibility statements to be mathematically described within fuzzy algorithms. From the beneficial characteristics of the linguistic variables to the possibility theory, the technique developed in the 1960s (i.e. fuzzy logic) became one of the most widely known approaches in expert knowledge.

According to Liu *et al.* (2004), fuzzy knowledge base/rule base is the core fuzzy logic structure. A fuzzy knowledge base/rule base is constructed by using experts' knowledge and expertise about the failure in the form of fuzzy IF-THEN rules (Yang *et al.*, 2008). A simple example of a fuzzy IF-THEN rule is as follows (Liu *et al.*, 2004):

$$IF\ x\ is\ A\ Then\ y\ is\ B \tag{4.2}$$

where A and B represent the linguistic grades for rules x and y respectively. The first part of the fuzzy IF-THEN rule (i.e. the IF part) is known as the antecedent or premise, whilst the second part of the rule (i.e. the THEN part) is known as the consequence or conclusion (Liu *et al.*, 2004).

In a fuzzy rule base FMEA, the L, C, and P are represented in the IF, whilst the THEN represents the risk. An example of a fuzzy IF-THEN rule for safety analysis is as follows (Liu *et al.*, 2004):

Rule: *IF the Failure Rate (FR) is frequent and the Consequence Severity (CS) is catastrophic and the Failure Consequence Probability (FRP) is likely, THEN the Safety Level (S) is poor*

Incompleteness is another type of uncertainty. This type of uncertainty occurs when the experts are incapable of creating a strong correlation between the IF and the THEN. In other words, it occurs when there is not enough available evidence, or when the experts' belief in a particular hypothesis is not 100% certain, but only to a certain degree of belief (Liu *et al.*, 2004). An example of a fuzzy IF-THEN rule with degree of belief for multiple possible consequence terms is as follows (Yang *et al.*, 2008):

Rule: *IF Likelihood (L) is Very Low, Consequence severity (C) is Negligible and chance of failure being undetected (P) is Reasonably Unlikely, THEN S is Good with 0.91, Average with 0.09, Fair with 0 and Poor with 0*

where [(Good 0.91), (Average 0.09), (Fair 0), and (Poor 0)] is the expert degree of belief, which means that the experts are 91% sure that the safety level is Good, and 9% sure that the safety level is Average.

The representation of knowledge and reasoning with rules-based structures is widely used in risk assessment due to the following factors (Rahman, 2012; Liu *et al.*, 2004; John *et al.* 2014a):

- The modularity of each rule, which can be seen as one unit of knowledge
- The expressed knowledge in the rule, which is represented with the same formation
- The natural formation of the rules in knowledge expression
- The easiness and clarity of the expressed knowledge

The incorporation of fuzzy logic and FMEA for enhancing the performance of FMEA has been widely applied. For example, an alternative multi-attribute decision-making method was proposed by Braglia *et al.* (2003), who termed the method the fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. This decision-making method considers the three risk attributes (i.e. L, C, and P) as criteria, and the failure mode as an alternative.

A fuzzy method and grey theory were proposed by Chang *et al.* (1999). To evaluate the risk attributes L, C, and P, the researchers applied fuzzy linguistic variables. However, the grey theory was used for determining the risk priority of potential failure. Pillay and

Wang (2003) developed a fuzzy rule-based approach that does not require a utility function for defining the risk factors and avoids using the traditional use of RPN. The linguistic variables in Pillay and Wang's (2003) study that represented the three FMEA attributes were directly evaluated within this method. Other studies have assigned relative weighting coefficients using the grey theory to achieve an RPN. Similar studies, such as Sharma *et al.* (2008, 2007) and Chang *et al.* (2001), applied the fuzzy method and grey theory for ranking the failure mode in FMEA.

A critical risk assessment approach was presented by Puente *et al.* (2002). The approach is qualitative rule-based, which provides a risk ranking for potential failures. Depending on the presented knowledge about the three risk factors (failure detection, frequency, and severity), a risk priority ranking is assigned to each failure cause in an FMEA. A total of 125 rules are then structured by using the IF-THEN rule formation in FMEA. All the rules are presented in a three-dimensional graph. Liu *et al.* (2015) combined interval 2-tuple linguistic variables with grey relational analysis to improve the effectiveness of the traditional FMEA in medical services. Jiang *et al.* (2017) developed an advance risk ranking method based on fuzzy evidential theory in a Micro-Electro-Mechanical System (MEMS). Tazi *et al.* (2017) integrated cost factors to traditional FMEA to improve system design reliability of wind turbine systems.

Among the developments in FMEA, a fuzzy rule-based Bayesian reasoning (FuRBaR) approach was developed by Yang *et al.* (2008) to prioritise failures in FMEA without compromising the simplicity of the traditional RPN approach. The researchers developed this hybrid technique to deal with some of the FMEA drawbacks regarding the use of conventional fuzzy rule-based methods. The connection between the L, C, and P parameters is established in a fuzzy IF-THEN rule with the degree of belief structure in FuRBaR defined by using domain experts' knowledge. The approach applies the mechanism of Bayesian reasoning to rank the potential failure modes through aggregating the relevant rules.

For the purpose of this research, the technique of fuzzy rule-based Bayesian reasoning (FRBBR) is adopted. This hybrid technique analyses the risks associated with PTSs and provides a risk-ranking technique that is useful for decision-makers in uncertain situations. Therefore, it is important to understand the Bayesian Network (BN) mechanism for applying the FRBBR technique.

4.3 Background of the Bayesian Network Method

Bayesian Network (BN) which is also known as Bayesian Belief Networks (BBNs), was developed based on the marriage of the basic Bayesian theory (i.e. which was developed by Bayes and later developed into a more applicable level in the late 1960s) and a networking technique. Therefore, BN was firstly developed at Stanford University in the 1970s (McCabe *et al.*, 1998; Bernardo and Smith, 2009). The merging of these two techniques provides a strong framework for dealing with uncertainty problems (Yang *et al.*, 2008). The BN presents the fundamental concepts of probabilistic graphical models, or probabilistic networks in a new picture. Probabilistic networks have become popular and are widely applied due to their ability to deal with decisions under uncertainty (Khakzad *et al.*, 2013a; Montewka *et al.*, 2014; Wu *et al.*, 2015; Riahi *et al.*, 2013;)

The BN have been defined by Eleye-Datubo *et al.* (2006), Khakzad *et al.* (2013a), Khakzad *et al.* (2013b), and Li *et al.* (2014) as sets of random variables represented in a probability graphical model that consists of two parts:

- Conditional Probability Distribution (CPD), which specifies the relationship between the parent and child node quantitatively.

- Directed Acyclic Graph (DAG), which is the directed representation of the network structure.

The BN Directed Acyclic Graph (DAG), consisting of a set of nodes (also known as vertices) and directed links (also known as edges). Nodes, which are usually drawn as circles, represent random variables, and connected arcs (edges or links) between a pair of nodes represent dependencies between these variables (Vinnem *et al.*, 2012). According to Trucco *et al.* (2008), the relationship of each node to another node (i.e. the relationship between a parent node and a child node) is represented by an edge that connects the two nodes, where this edge starts from the parent node and ends with an arrowhead pointing to the child node.

The BN technique has been widely used due to the following advantages (Ben-Gal, 2007; Eleye-Datubo *et al.,* 2006; Riahi *et al.*, 2013; Rahman, 2012):

- The output of the method is clearly understood.
- Over time, the model has been continuously improved as new knowledge emerges.
- The model makes it easy to pinpoint whether a specific piece of information has actually been taken into consideration.
- The visual representation of the model provides a clear visualisation of the relationship between the nodes.
- The graphical model enables direct representation of the relationship between the parent node and the child nodes.
- Both qualitative and quantitative data can be analysed using the technique, which allows an easy understanding of the relationships among the factors.

The BN belongs to the family of probabilistic graphical models. Such models aim to provide a decision-support framework for problems involving uncertainty, complexity, and probabilistic reasoning (Ben-Gal, 2007). The BN technique is characterised as being naturally flexible in its network modelling. For dealing with uncertain knowledge, the technique has been extensively and successfully applied in various areas such as medical diagnosis (Spiegelhalter *et al.,* 2013), image recognition (Booker and Hota, 2013), language understanding (Charniak and Goldman, 1989; 2013), and search algorithms (Hansson and Mayer, 2013). Korb and Nicholson (2010) and Heckerman *et al.* (1995) provided a list of BN computer software applications to deal with BNs. Each of these computer tools has a unique interface. Analytica, BayesiaLab, Bayes Net Toolbox, GeNIe, Netica, HUGIN, JavaBayes, and MS*BN*x, are examples of computer software that deal with BNs.

4.3.1 Definition and Characteristics of Bayesian Network

Jordan (1998) defined BNs as

> "*Graphical models are a marriage between probability theory and graph theory. They provide a natural tool for dealing with two problems that occur throughout applied mathematics and engineering "uncertainty and complexity" and in particular they are playing an increasingly important role in the design and analysis of machine learning algorithms. Fundamental to the idea of a graphical model is the notion of modularity; a complex system is built by combining simpler parts. Probability theory provides the glue whereby the parts are combined, ensuring that the system as a whole is consistent, and providing ways to*

> *interface models to data. The graph theoretic side of graphical models provides both an intuitively appealing interface by which humans can model highly-interacting sets of variables as well as a data structure that lends itself naturally to the design of efficient general-purpose algorithms*".

The BN approach produces a graph which contains nodes connected by links at the structural level. The network nodes are divided into four categories, which are listed as follows (Friis-Hansen, 2000; Ben-Gal, 2007) (see Figure 4.1):

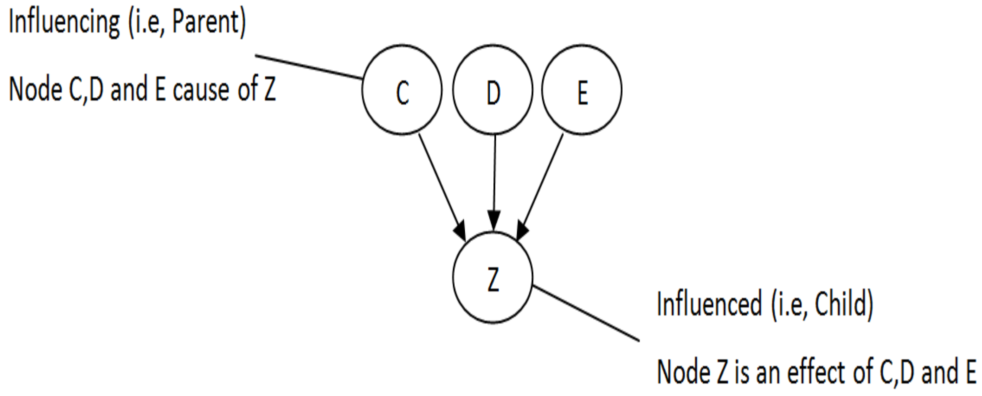

Figure 4.1: A BN sample

- Parent nodes, which are the influencing nodes
- Child nodes, which are the nodes influenced by the parent nodes
- Root nodes, which are nodes that are not linked to any parent nodes
- Leaf nodes, which are nodes that are not linked to any child nodes

The BN variables are represented by the nodes, and the relationships between these variables are represented by the links (Ben-Gal, 2007). A complete set of events, which are also known as states, levels, values, choices, and options (Kjærulff and Madsen, 2005), is represented in each node. This set of values is referred to as the variable domain, where the domain can be disconnected or continuous. For example, a node Z contains three values, which are C, D, and E. Based on the technical information obtained from personal knowledge, reading materials, and experts' knowledge, the names of the values can be determined (see Figure 4.1).

Probability, which could be defined as the likelihood of an event taking place, is another characteristic of a node in a network. Conditional and unconditional (marginal) are two ways to describe the probability distribution of a node. If a node has parents, it is described as having conditional probability; otherwise it is unconditional (Friis-Hansen, 2000; Ben-Gal, 2007; Riahi *et al.*, 2013). An example for the probability distribution of Figure 4.1 is as follows (Figure 4.2):

$$\mathrm{P}(C)$$
$$\mathrm{P}(D)$$
$$\mathrm{P}(E)$$

$$\mathrm{P}(Z|C, D, E)$$

Figure 4.2: Conditional and unconditional probabilities of Figure 4.1

4.3.2 HUGIN Expert Software

HUGIN software is an advanced decision-supporting software package which was established by a group of researchers in 1989 based on BN technology (HUGIN expert, n.d.). An easy-to-use graphical user interface is provided with the software. In addition, HUGIN (which stands for Handling Uncertainty In General Inference Network) software provides an applicable programmer interface. The software provides a graphical representation for each node within the network and simplifies the method of inputting the data and reading the outputs. In this chapter, the software is used to compute the probability values of each node. To construct a network using HUGIN software, the following steps should be taken (Riahi, 2010; Andersen *et al.*, 2013):

- The BN nodes must be mapped out.
- The node states must be defined.
- The probability of each state must be determined.

4.4 Methodology

For the purposes of this study, a model was constructed. An amalgamation of FRB approach and the belief structure in FMEA and BN was used to analyse the risks associated with the petroleum ports and transportation modes within PTSs. The analysis procedure is presented in Figure 4.3.

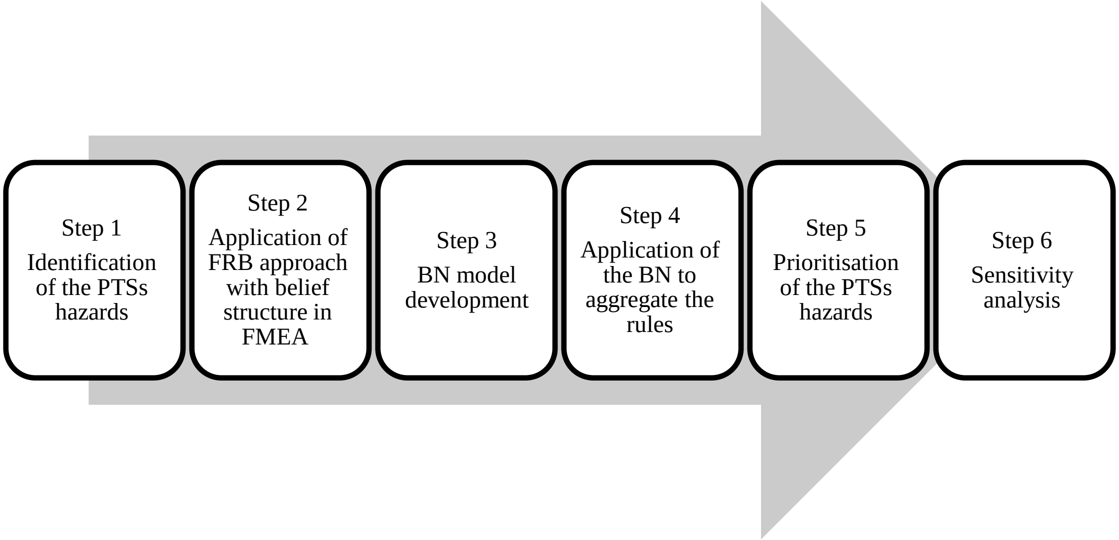

Figure 4.3: The PTSs operational hazards assessment model flow chart

An FRB approach was employed to formulate the conditional statements comprising the complete knowledge base. Moreover, a BN was used to provide a decision-supporting framework for evaluation of the petroleum ports' and transportation modes' operation within PTSs through the use of probabilistic reasoning. The steps in analysing the risks in a petroleum terminal, petroleum ship, and petroleum pipeline within the PTSs are listed as follows:

- Identification of the PTSs Hazards
- Application of FRB approach with belief structure in FMEA
- BN model development
- Application of the BN to aggregate the rules
- Prioritisation of the failure factors
- Sensitivity analysis

4.4.1 Step I: Identify the PTSs Hazards

In the construction process of a model, causality plays an important role. For example, consider the nodes *germs* and *sickness*. Common sense tells us that germs are a cause of sickness, not the other way around. Therefore, to determine the hazards that affect the safe operation of a PTS, a cause and effect analysis technique has been used (Chang and Lin, 2006). This technique has great potential to address the aims and objectives of this study. In addition, the technique can be applied in a multidisciplinary way to stimulate systematic thinking, especially in the engineering field (Chang and Lin, 2006). Therefore, the analysis technique of cause and effect has the potential to address the requirements of this study.

The hazards in PTSs operations that can lead to a crude oil spill were identified through conducting an extensive literature review (i.e. Section 2.8) (Ceyhun, 2014; Vinnem *et al.*, 2012; Ismail and Karim, 2013; Cai *et al.*, 2013). This hazard identification process helps decision makers in identifying any risk scenarios that affect the safety of PTSs operations. The literature review allowed the author to identify the hazards events that affect the safe operation of crude oil terminals, pipelines, and ships. As there are limited studies on operational risks in petroleum terminals, the author extended the literature review to include studies on operational risks in general supply chains as well (Thorsen and Dalva, 1995; Ronza *et al.*, 2006; Rømer *et al.*, 1993; Rømer *et al.*, 1995; Trbojevic and Carr, 2000).

By using a brainstorming technique, the literature review identified hazards that have been validated by experts. It was then determined whether the identified hazards related to PTSs operations and whether any other unidentified hazards exist in real-life practices that should be included in the study. To validate these results, face-to-face interviews were conducted. The advantage of using face-to-face meetings is that they can help the researcher to achieve deeper and clearer understanding of the issue of risk from experts' perspectives. It is reasonable to believe that any discoveries gained from face-to-face interviews with experts are more relevant and reliable for research. In this study, the experts were selected based on their active working experience in petroleum or refined petroleum products' terminals, in pipeline and ship operation, and/or in research on petroleum transportation. Each expert was required to have at least 20 years' relevant experience. These meetings took place in 2015. In the meetings, open questions were used. The interviewees were asked to give their comments on the list of hazards that had already been found through the literature review. The interviewees were also questioned about the hazards that they had faced in real-life practice and that they believed should be included in the list. Based on the results of these meetings, Figures 4.4, 4.5, and 4.6 present a hierarchical structure of the hazards identified and those hazards' effects on the operation of PTSs.

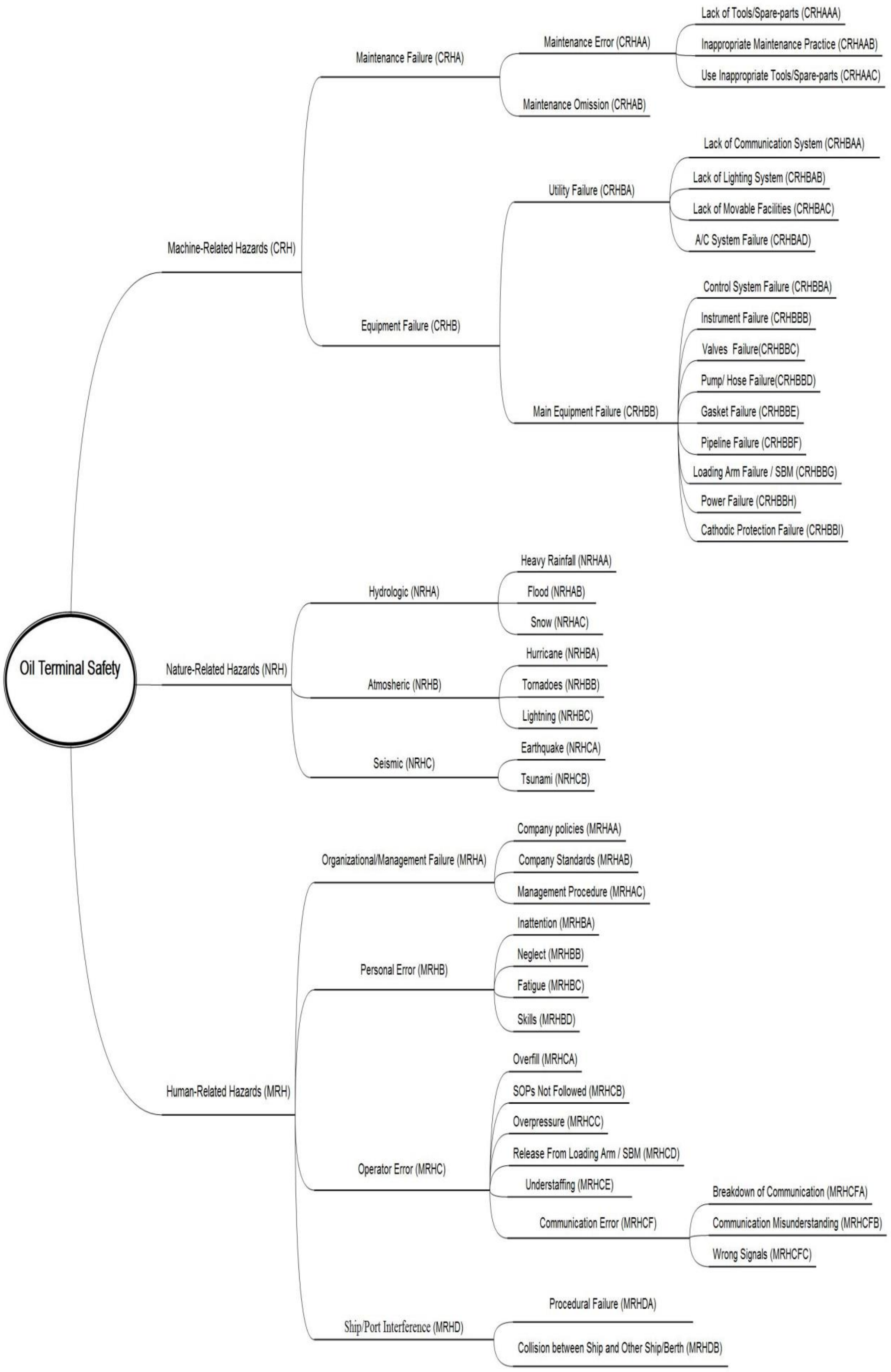

Figure 4.4: Hierarchical structure of hazards associated with the operation of petroleum terminals

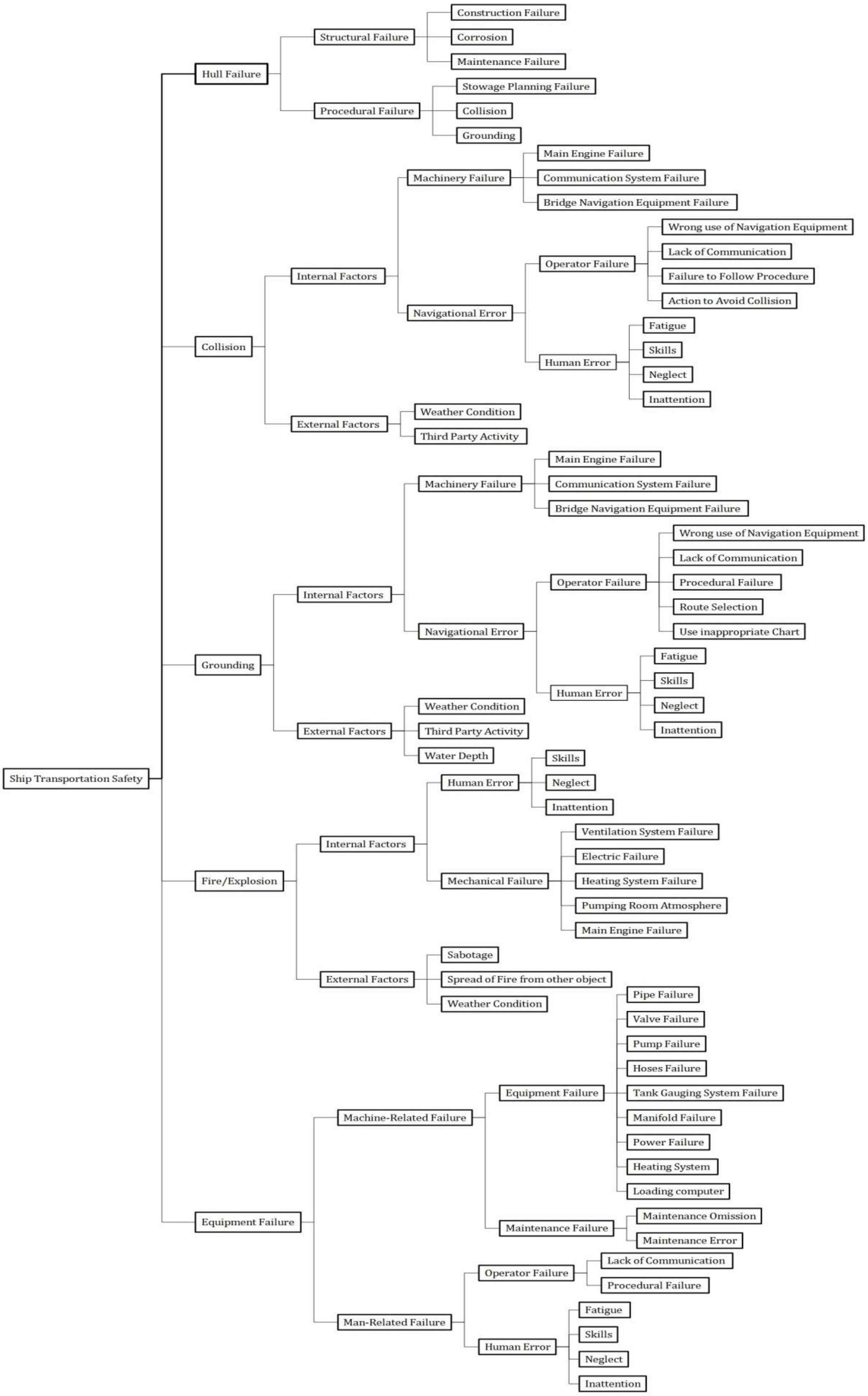

Figure 4.5: Hierarchical structure of hazards associated with the ship transportation operation

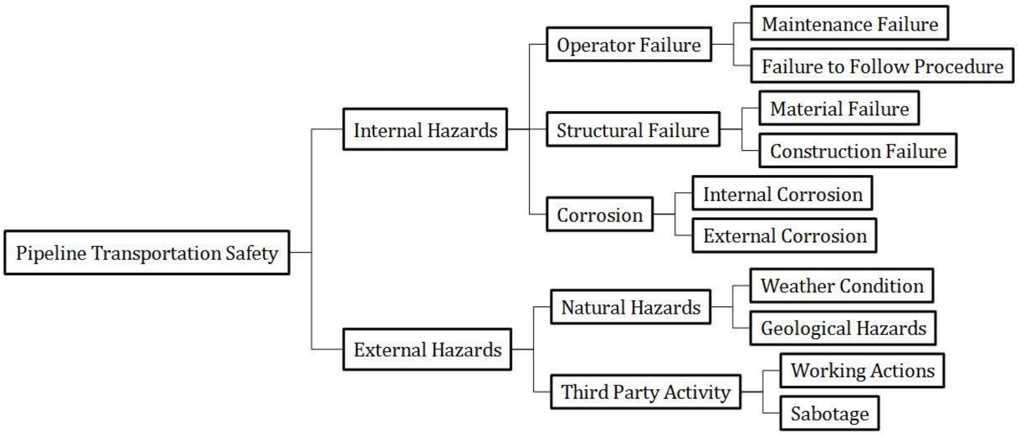

Figure 4.6: Hierarchical structure of hazards associated with the pipeline operation

4.4.2 Step II: Establish an FRB with Belief Structure in FMEA

As mentioned earlier in Section 4.3, L, C, and P are the three risk parameters that are used to evaluate the safety level of the failure mode in the traditional FMEA. For constructing a fuzzy IF-THEN rule with a belief structure for PTSs, the occurrence probability of a risk event during the process of oil transport (P_l), the consequence severity that the risk event would cause if it occurs (S_c), and the probability that the risk event cannot be detected before it occurs (D_p) were employed as the FMEA factors. P_l, S_c, and D_p are the three risk parameters that were used in the IF part. The risk level (R) represented the THEN part. For describing P_l, S_c, D_p, and R, a set of linguistic grades (i.e. Very High, High, Medium, Low, and Very Low) was employed (Mokhtari *et al.*, 2012; John *et al.*, 2014a; Liu *et al.*, 2011b; Pillay and Wang, 2003; Alghanmi *et al.*, 2017). These grades describe the linguistic variables of each attribute associated with the PTSs' hazards (see Tables 4.1, 4.2, and 4.3) (Pillay and Wang, 2003; Sii *et al.*, 2001; Liu *et al.*, 2011b; Yang *et al.*, 2008; Zaman *et al.*, 2015). Through considering the experts' judgments, the degree of each parameter has been valued for each hazard, such that each parameter is defined based on knowledge accrued from PTSs' historical PTSs' events (see Tables 4.1, 4.2, and 4.3).

Table 4.1: Linguistic grades for the likelihood parameter for each hazard in the IF part

Occurrence Probability of a Hazard	Description
Very Low	The probability of occurrence is unlikely to occur but possible
Low	The probability of occurrence is likely once per year
Medium	The probability of occurrence is likely once per quarter
High	The probability of occurrence is likely once per month
Very High	The probability of occurrence is expected once per month

Table 4.2: Linguistic grades for the consequence parameter for each hazard in the IF part

Consequence Severity of a Hazard	Description
Very Low	At most minor injury involved and negligible damage to the system; no damage to the environment
Low	Minor medical treatment required; slight equipment or system damage but still fully functional and serviceable; minor environmental damage
Medium	Minor injury; moderate incapacity of systems, equipment, or facilities that disrupts operations; moderate damage to the environment
High	Permanent total disability; damage to major facilities; severe environmental damage
Very High	Death; loss of major facilities; major environmental damage

Table 4.3: Linguistic grades for the probability parameter for each hazard in the IF part

Probability of a Hazard being Undetected	Description
Very Low	Possible to detect without checks or maintenance
Low	Possible to detect through regular checks or maintenance
Medium	Possible to detect through intensive checks or maintenance
High	Difficult to detect through intensive or regular checks or maintenance
Very High	Impossible to detect even through intensive or regular checks or maintenance

In the FRB approach, a belief structure was utilised to model the THEN part in the IF-THEN rule as shown in the following example (Alyami *et al*., 2014):

- Rule 1: *IF* P_l *is Very High,* S_c *is Very High and* D_p *is Very High, THEN R is Very High with 100%, High with 0%, Medium with 0%, Low with 0% and Very Low with 0%.*
- Rule 2: *IF* P_l *is Very High,* S_c *is Very High and* D_p *is High, THEN R is Very High with 67%, High with 33%, Medium with 0%, Low with 0% and Very Low with 0%.*
- Rule 3: *IF* P_l *is Very High,* S_c *is Very High and* D_p *is Medium, THEN R is Very High with 67%, High with 0%, Medium with 33%, Low with 0% and Very Low with 0%.*
- Rule 4: *IF* P_l *is Very High,* S_c *is Very High and* D_p *is Low, THEN* R_s *is Very High with 67%, High with 0%, Medium with 0%, Low with 33% and Very Low with 0%.*

As is clear from the above four rules, a proportion method has been used to assign the belief degree in the THEN part for each of the linguistic variables (Alyami *et al*., 2014). To simplify this method, the risk factors that receive similar grades in the IF part are divided by the total number of parameters. This process identifies the degree of belief belonging to a particular grade in the THEN part for each rule and uses the following equation (Alyami *et al*., 2014):

$$D(x) = \frac{\sum_{i=1}^{n} a_i(x)}{n} \qquad 4.3$$

where $D(x)$ is the belief degree for Very High, High, Medium, Low, or Very Low in the THEN part, n is the total number of risk parameters in the IF part, and $a_i(x)$ describes the grades of a specific linguistic variable of each attribute associated with the hazards. For example, three risk parameters receive the Very High grade in the IF part for Rule 1. Therefore, the belief degree for Very High in the THEN part is calculated as 100% (3/3 = 100%). Conversely, for Rule 2, two risk parameters get the Very High grade and one gets the High grade in the IF part. Therefore, the belief degrees belonging to Very High and High in the THEN part are 67% (2/3 = 67%) and 33% (1/3 = 33%) respectively. For risk evaluation of a petroleum port, pipeline, and ship, 125 rules (5 × 5 × 5) with their belief degrees have been established (Alyami *et al*., 2014) (see Table 4.4 and Appendix 2.1).

4.4.3 Step III: Develop a BN Model

After identifying the PTSs' hazards and establishing the FRB model with belief structure in FMEA, the relationship between the hazards was confirmed, and a qualitative network was built to represent all the hazards and their dependencies (i.e. the three risk parameters). The BN graphical model enables a clear and direct statement of the relationships between the parent (i.e. P_l, S_c, and D_p) and child (i.e. hazard) nodes. An example of the BN model is shown in Figure 4.1.

4.4.4 Step IV: Aggregate the Rules by using a BN

BNs are known for their ability to capture non-linear causal relationships and model the degree of belief in the THEN part of FRB models (Yang *et al.*, 2008; Alyami *et al.*, 2014). In this step, various BN models were developed. Each model represents one of the PTSs' hazard events identified in the first step.

Table 4.4: The established IF-THEN rules with belief structure for PTSs risk evaluation

Rule No	**Risk Parameters in the IF Part**			**Belief Degree in the THEN Part**				
	P_l	S_c	D_P	VH	H	M	L	VL
1	VH(P_1)	VH(S_1)	VH(D_1)	1	0	0	0	0
2	VH(P_1)	VH(S_1)	H(D_2)	0.67	0.33	0	0	0
3	VH(P_1)	VH(S_1)	M(D_3)	0.67	0	0.33	0	0
4	VH(P_1)	VH(S_1)	L(D_4)	0.67	0	0	0.33	0
5	VH(P_1)	VH(S_1)	VL(D_5)	0.67	0	0	0	0.33
....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....
121	VL(P_5)	VL(S_5)	VH(D_1)	0.33	0	0	0	0.67
122	VL(P_5)	VL(S_5)	H(D_2)	0	0.33	0	0	0.67
123	VL(P_5)	VL(S_5)	M(D_3)	0	0	0.33	0	0.67
124	VL(P_5)	VL(S_5)	L(D_4)	0	0	0	0.33	0.67
125	VL(P_5)	VL(S_5)	VL(D_5)	0	0	0	0	1

To aggregate the rules by using a BN, firstly the rule bases developed in Step 2 had to be represented in the form of conditional probabilities. For example, the established Rule 2 in Table 4.4 was presented in an IF-THEN rule as follows:

R2*: IF Very High (P_1), Very High (S_1) and High (D_2), THEN {(0.67, Very High (R_1)), (0.33, High (R_2)), (0, Medium (R_3)), (0, Low (R_4)), (0, Very Low (R_5)),}.*

From that, the conditional probability of R2 could be expressed as follows:

Given P_1, S_1, and D_2, the probability of R_h ($h = 1,\dots,5$) is (0.67, 0.33, 0, 0, 0) or

$$\text{Ƥ}(R_h|P_1, S_1, D_2) = (0.67, 0.33, 0, 0, 0), \qquad 4.4$$

where " | " symbolises conditional probability.

The established IF-THEN rules within FMEA for evaluation of the risks associated with PTSs were modelled and transferred by using the BN technique in four nodes. Three parent nodes were included, namely the P_l, S_c and D_p of each hazard; these three parent nodes each connected to one child node (Node R), which in turn represented one of the PTSs' hazard. Once the overall rule base was converted into a customised BN model, the marginal probability of the H (i.e. child node) was then computed by simplifying the risk inference mechanism of the rule-base failure criticality evaluation. Through Appendix 2.1 and Equation 4.4, the needed conditional probability table of Node R, $P(R_h|P_l, S_c, D_p)$, was achieved (see Appendix 2.2). That table symbolises a 5 × 5 × 5 × 5 table containing values $P(R_h|P_l, S_c, D_p)$ ($h, l, c, p = 1,\dots,5$) (Yang *et al.*, 2008; Alyami *et al.*, 2014).

Through using subjective judgments based on real comments, each of the PTSs' hazards can be evaluated by risk analysts through considering the hazards' P_l, S_c, and D_p and the hazards' related linguistic ratings, which have already been defined in Tables 4.2, 4.3, and 4.4. Moreover, to support the calculation of the prior probabilities [i.e. $P(P_l)$, $P(S_c)$, and $P(D_p)$] of the three parent nodes P_l, S_c, and D_p, the views of multiple experts were applied in the evaluation, and the averaging technique described above was used for assigning the belief degree of the linguistic grades of each individual parameter. Therefore, the marginal probability of H (R_h) can be detected as follows (Yang *et al.*, 2008; Alyami *et al.*, 2014):

$$\mathrm{P}(R_h) = \sum_{l=1}^{5} \sum_{c=1}^{5} \sum_{p=1}^{5} \mathrm{P}(R_h \mid P_l, S_c, D_p) \mathrm{P}(P_l) \mathrm{P}(S_c) \mathrm{P}(D_p) \qquad 4.5$$

$$(h = 1, \ldots, 5)$$

4.4.5 Step V: Prioritise the PTSs Hazards

The results from the rules aggregated by using the BN are presented in the form of five linguistic variables (i.e. Very High, High, Medium, Low, and Very Low). For a decision maker, it is more useful that these results are presented in single value for ranking the failures and for comparison purposes. To accomplish that, it was necessary to assign appropriate utility values to prioritise the failures R_h $(h = 1, \ldots, 5)$. Therefore, utility values of each linguistic term are symbolised by U_{Rh} , which was determined by using decision makers' preference (Riahi *et al.*, 2012; Yang, 2001; Yang *et al.*, 2008; John *et al.*, 2014a). Still, due to the unavailability of the preference information, the utility value of each linguistic term was presumed equidistantly distributed in a normalised utility space and calculated as follows (Riahi *et al.*, 2012):

$$U_{Rh} = \frac{(R_h - R_{min})}{(R_{max} - R_{min})} \qquad 4.6$$

where R_h is the ranking value of the selected linguistic term, R_{max} is the ranking value of the highest linguistic term, and R_{min} is the ranking value of the lowest linguistic term. Consequently, the hazards can be ranked through calculating the utility as follows (Riahi *et al.*, 2012; Yang, 2001):

$$RH = \sum_{h=1}^{5} \mathrm{P}(\beta_h)\, U_{Rh} \qquad 4.7$$

where the larger the value of *RH*, the more significant the risk level of a hazard.

4.4.6 Step VI: Sensitivity Analysis

Sensitivity analysis is a widely used validation method (Riahi *et al.*, 2012; Alyami *et al.*, 2014; John *et al.*, 2014a). According to Forrester *et al*. (2001), sensitivity analysis is usually performed by a series of tests analysing how sensitive the model is to different parameter values. Forrester *et al*. (2001) noted that sensitivity analysis studies the uncertainties that are often associated with the model parameters in order to increase confidence in the model. Conducting sensitivity analysis of the present model thus allowed determination of the accuracy level of the parameters, making the model sufficiently useful and valid. Literature such as that from Pearl (1986, 2014), Lauritzen and Spiegelhalter (1988), and Castillo *et al.* (2012) provides additional details and explanation about sensitivity analysis.

4.5 Case Study and Results Analysis

For the purpose of this research, a case study has been carried out to demonstrate how the methodology can be employed to evaluate the hazards associated with PTSs. The case study has been conducted based on the analysis procedure presented in Figure 4.3. The petroleum ports' operational hazards have been selected as a sample to present the following evaluation steps.

4.5.1 Identification of the PTSs Hazards

The risk scenarios that affect the safety of PTSs operations were identified. First, an extensive literature review was conducted to identify the hazards that are connected with PTSs operations. Then the identified hazards were discussed with selected experts who are involved in the operation practices of PTSs in several leading petroleum companies. These consultation meetings took place in UK and Saudi Arabia in 2015 and 2016 with nineteen petroleum/refined petroleum products' terminal managers, pipeline and ship operators, and scholars. The experts added or recommended dropping hazard events based on at least two decades of experience. The final result yielded 42, 61, and 10 operation hazards within port, ship, and pipeline sub-systems respectively (see Table 4.5).

Table 4.5: Hazards associated with the operation of each system within PTSs

	Seaport System	Ship Transportation System	Pipeline Transportation System
H 1	Company Policies	Ship Collision due to Main Engine Failure	Sabotage
H 2	Company Standards	Ship Collision due to Bridge Navigation Equipment Failure	Workers Actions
H 3	Management Procedure	Ship Collision due to Communication System Failure	Weather Condition
H 4	Inattention	Ship Collision due to Wrong use of Navigation Equipment	Geological Hazards
H 5	Neglect	Ship Collision due to Lack of Communication	Material Failure
H 6	Fatigue	Ship Collision due to Failure to Follow Operational Procedure	Construction Failure
H 7	Skills	Action To Avoid Collision	Maintenance Failure
H 8	Overfill	Ship Collision due to Human Inattention	Failure to Follow Procedure
H 9	SOPs (Standard Operating Procedures) Not Followed	Ship Collision due to Human Neglect	Internal Corrosion
H 10	Overpressure	Ship Collision due to Human Fatigue	External Corrosion
H 11	Release From Loading Arm/SBM	Ship Collision due to Human Skills	
H 12	Understaffing	Ship Collision due to Weather Condition	
H 13	Breakdown of Communication	Ship Collision due to Third Party Activity	
H 14	Communication Misunderstanding	Ship Grounding due to Main Engine Failure	
H 15	Wrong Signals	Ship Grounding due to Communication System Failure	
H 16	Procedural Failure	Ship Grounding due to Bridge Navigation Equipment Failure	
H 17	Collision between Ship and Other Ship/Berth	Ship Grounding due to Wrong use of Navigation Equipment	
H 18	Lack of Tools/Spare Parts	Ship Grounding due to Lack of Communication	

H 19	Inappropriate maintenance practice	Ship Grounding due to Failure to Follow Operational Procedure	
H 20	Use of Inappropriate Tools/Spare Parts	Ship Grounding due to Route Selection	
H 21	Maintenance Omission	Ship Grounding due to Using Inappropriate Chart	
H 22	Lack of Communication System	Ship Grounding due to Human Inattention	
H 23	Lack of Lighting System	Ship Grounding due to Human Neglect	
H 24	Lack of Movable Facilities	Ship Grounding due to Human Fatigue	
H 25	A/C System Failure	Ship Grounding due to Human Skills	
H 26	Control System Failure	Ship Grounding due to Weather Condition	
H 27	Instrument Failure	Ship Grounding due to Third Party Activity	
H 28	Valve Failure	Ship Grounding due to Water Depth	
H 29	Hose/Pump Failure	Hull Failure due to Construction Damage	
H 30	Gasket Failure	Hull Failure due to Hull Corrosion	
H 31	Pipeline Failure	Hull Failure due to Maintenance Failure	
H 32	Loading Arm/SBM Failure	Hull Failure due to Stowage Planning Failure	
H 33	Power Failure	Hull Failure due to Collision	
H 34	Cathodic Protection Failure	Hull Failure due to Grounding	
H 35	Heavy Rainfall	Fire/Explosion due to Human Inattention	
H 36	Flood	Fire/Explosion due to Human Neglect	
H 37	Snow	Fire/Explosion due to Human Skills	
H 38	Hurricane	Fire/Explosion due to Inert Gas/Ventilation System Failure	
H 39	Tornadoes	Fire/Explosion due to Electric Failure	
H 40	Lightning	Fire/Explosion due to Pumping Room Failure	
H 41	Earthquake	Fire/Explosion due to Main Engine Failure	
H 42	Tsunami	Fire/Explosion due to Heating system Failure	
H 43		Fire/Explosion due to Spread of Fire From Other Object	
H 44		Fire/Explosion due to Sabotage	
H 45		Fire/Explosion due to Weather Condition	
H 46		Equipment Failure due to Pipe Failure	
H 47		Equipment Failure due to Valve Failure	

H 48		Equipment Failure due to Pump Failure	
H 49		Equipment Failure due to Tank Gauging System	
H 50		Equipment Failure due to Manifold Failure	
H 51		Equipment Failure due to Power Failure	
H 52		Equipment Failure due to Heating System Failure	
H 53		Equipment Failure due to Loading Computer	
H 54		Equipment Failure due to Maintenance Error	
H 55		Equipment Failure due to Maintenance Omission	
H 56		Equipment Failure due to Lack of Communication	
H 57		Equipment Failure due to Procedural Failure	
H 58		Equipment Failure due to Human Inattention	
H 59		Equipment Failure due to Human Neglect	
H 60		Equipment Failure due to Human Fatigue	
H 61		Equipment Failure due to Human Skills	

4.5.2 Application of FRB Approach with Belief Structure in FMEA

In this step, the established FRB table in Section 4.6.2 was used. Moreover, a questionnaire was constructed and introduced to twenty-seven experts (nine from each operational sector) with the aim of collecting the failure information from their evaluation of hazards in petroleum ports, ships, and pipelines. The following three points were considered when building the questionnaire (Burgess, 2001; Taylor-Powell, 1998; Oppenheim, 2000):

- The questionnaire questions had to be simple and clear for the experts.
- The survey had to be constructed in various sections that each assisted in reaching the research goals.

- The information, such as years of experience and education of each participant, had to be kept in mind, as this information may have affected each participant's way of thinking.

The questionnaire was constructed in four sections. The first section asked about the experts' personal information with the aim of evaluating each participant's expertise. The questions concerned the experts' experiences, academic knowledge, and industrial background. The second section of the questionnaire provided a description of the hazard events' attributes (i.e. P_l, S_c, and D_p). The experts responded to each attribute based on their knowledge of similar past events through using the proportion technique. Namely, each attribute was defined by five linguistic terms (i.e. Very High, High, Medium, Low, and Very Low) based on past events. The same proportion technique, based on a description of each attribute, was applied in the final two sections of the questionnaire as well. An example of how to fill in the questionnaire is contained in every questionnaire, which is represented in section three, so the expert has a clear understanding of the measurement used in this study. The fourth section of the questionnaire contained three parts, each one referring to one of the hazards in each system (see Figures 4.4, 4.5 and 4.6). Each part of this section contained a matrix to be filled out. The questionnaire was piloted with people from both university and industry sectors and then refined before being sent to the experts. Three academics, two engineers, and one ship captain helped to refine the questionnaire.

All participants are experts with at least a Bachelor's degree (i.e. BSc) in a petroleum industry-related field. Each expert has over 20 years' experience in the operation of tankers, pipelines, and/or inshore and offshore terminals and petroleum ports (Abubakar, 2014). In addition, the twenty seven selected experts (i.e. nine experts for port transportation systems and nine experts for ship and pipeline transportation systems) are still actively working and holding different positions in different operational fields in PTSs (see Table 4.6). Based on these criteria, the experts have equal weights.

Table 4.6: PTSs experts' experience

Expert	Pipeline Transportation System	Port Transportation System	Ship Transportation System
A	Operation superintendent who has been primarily involved in crude and refined pipeline system safety operation for over 20 years	With over 20 years of experience, head of Safety department who has been involved in crude and refined petroleum system safety operation for several crude/refined petroleum terminals	Ship Captain who has been involved in transporting crude and refined petroleum products for several shipping lines for over 20 years
B	Operation foreman who worked in several crude oil pipeline systems safety operation for over 20 years	Worked in several crude oil terminals as a safety officer with a working experience over 20 years	Captain of an oil tanker with an extended working experience over 20 years serving on board for several shipping lines
C	Operation foreman who has been primarily involved in crude oil pipeline system safety operation for over 20 years	Senior safety engineer who has worked in crude oil safety operation for several petroleum terminals for over 20 years	Ship Captain with over 20 years work on board for several shipping lines for transporting crude and refined petroleum products
D	Worked for several petroleum pipeline transportation systems as a control room engineer with a working experience over 20 years	Safety officer who has been involved in crude and refined petroleum system safety operation for several crude/refined petroleum terminals for over 20 years	With over 20 years of experience, Ship Captain who has worked on board for several shipping lines for transporting crude and refined petroleum products
E	Operation foreman with over 20 years work for several companies for transporting crude and refined petroleum products via pipeline systems	Senior safety engineer with over 20 years work for several crude oil terminals	An oil tanker Captain has been involved in transporting crude and refined petroleum products for several shipping lines for over 20 years
F	Control room engineer with an extended working experience over 20 years worked for several companies for transporting crude oil via pipeline systems	Senior safety engineer of crude oil terminals with an extended working experience over 20 years for several petroleum terminals	Ship Captain with over 20 years worked on board for several shipping lines for transporting crude and refined petroleum products
G	With over 20 years of experience, Operation superintendent who has been primarily involved in crude and refined pipeline system safety operation for over 20 years	Safety officer with over 20 years work for several petroleum terminals for transporting crude and refined petroleum products	Worked for several shipping lines as a Captain of an oil tanker with a working experience over 20 years
H	Operation foreman who worked in several crude and refined pipeline systems safety operation for over 20 years	Worked in several leading crude oil terminals as a safety officer with a working experience over 20 years	Ship Captain who has been involved in transporting crude and refined petroleum products for several shipping lines for over 20 years
I	Control room engineer who has been primarily involved in crude and refined pipeline system safety operation for over 20 years	Safety officer who has been primarily involved in crude oil terminal system safety operation with a working experience over 20 years	Captain of an oil tanker with an extended working experience over 20 years serving on board for several shipping lines

After the researcher received the completed questionnaires from all the participants, the arithmetic mean of each risk parameter was calculated. By using the arithmetic mean, the responses from the received questionnaires from all participants were calculated. The resulting values were then used further in the form of prior probabilities (step 4). An example of the combination of the nine experts' judgments by using the arithmetic averaging technique for the hazard of Company Policies (MRHAA) is presented in Table 4.7. The parameter P_l is one example for calculating the average of the nine experts as follows:

$$L_{Very\ High} = \frac{\sum_{E=1}^{9} Very\ High}{E} = \frac{5+10+10+20+5+10+5+10+5}{9}$$

$$= \underline{8.8889}$$

Each of the nine values for each parameter reflect the expert belief degree of the identified hazard. These experts are still actively working and holding different operational positions in different petroleum ports around the world within the PTNs (see Table 4.6). Similarly, the values of the three parameters for MRHAA are shown in Table 4.7 and were calculated as follows:

Table 4.7: Prior Probability of P_l, S_c and D_p when evaluating the MRHAA

Risk Parameters		Experts									Average degree of belief in %
		A	B	C	D	E	F	G	H	I	
P_l	Very High	5	10	10	20	5	10	5	10	5	8.8889
	High	15	20	10	10	10	10	15	10	10	12.2222
	Medium	20	30	20	10	25	20	20	20	25	21. 1111
	Low	35	30	40	30	30	40	40	30	30	33. 8889
	Very Low	25	10	20	30	30	20	20	30	30	23.8889
S_c	Very High	0	10	10	20	15	10	5	10	10	10
	High	10	20	10	20	10	10	15	10	10	12. 7778
	Medium	20	20	30	20	25	30	30	20	10	22. 7778
	Low	30	30	30	20	35	30	30	30	30	29.4444
	Very Low	40	20	20	20	15	20	20	30	40	25

D_p	Very High	0	10	0	3	10	0	0	10	20	5.8889
	High	10	10	20	25	10	20	20	10	20	16.1111
	Medium	10	10	30	32	20	30	30	30	30	24.6667
	Low	30	30	30	15	30	30	30	30	20	27.2222
	Very Low	50	40	20	25	30	20	20	20	10	26.1111

The same technique was applied to calculate the combined belief degree for each of the 113 hazards (i.e. 42 (port) + 61 (ship) + 10 (pipeline)), as shown in Table 4.8 and Appendices 2.3 – 2.8.

Table 4.8: Prior Probability of P_l, S_c and D_p for the petroleum port hazards

	Hs	Degree of Belief (VH, H, M, L, VL)		
		Likelihood	Consequences	Probability
H1	MRHAA	8.8889,12.2222,21.1111,33.8889,23.8889	10,12.7778,22.7778,29.4444,25	5.8889,16.1111,24.6667,27.2222,26.1111
H2	MRHAB	13.8889,20,26.6667,26.1111,13.3333	15,16.6667,31.1111,22.2222,15	10.5556,18.3333,27.2222,23.8889,20
H3	MRHAC	11.6667,19.4444,23.8889,31.1111,13.8889	13.3333,20.5556,27.7778,20.5556,17.7778	13.3333,18.3333,27.7778,28.3333,12.2222
H4	MRHBA	10.5556,28.3333,24.4444,25,11.6667	15,15,26.6667,30.5556,12.7778	10,18.3333,26.1111,34.4444,11.1111
H5	MRHBB	11.6667,16.6667,29.4444,30.5556,11.6667	13.3333,20.5556,28.8889,27.2222,10	10.5556,13.8889,34.4444,30.5556,10.5556
H6	MRHBC	10.5556,10.5556,25,28.3333,25.5556	12.7778,14.4444,28.3333,30,14.4444	10.5556,16.1111,33.8889,27.7778,11.6667
H7	MRHBD	14.4444,18.3333,27.7778,26.1111,13.3333	13.8889,19.4444,28.8889,22.7778,15	13.3333,12.7778,27.7778,32.7778,13.3333
H8	MRHCA	10.5556,16.6667,23.3333,34.4444,15	12.7778,14.4444,26.1111,28.8889,17.7778	8.3333,10,31.6667,31.1111,18.8889
H9	MRHCB	12.7778,18.3333,23.3333,33.8889,11.6667	13.8889,22.7778,25.5556,23.8889,13.8889	10.5556,17.2222,25,31.1111,16.1111
H10	MRHCC	10,11.6667,28.8889,34.4444,15	12.2222,19.4444,26.6667,23.8889,17.7778	16.6667,17.2222,27.2222,26.1111,12.7778
H11	MRHCD	11.1111,15,30,28.3333,15.5556	8.3333,15.5556,28.3333,27.7778,20	10,8.8889,28.3333,37.7778,15
H12	MRHCE	13.3333,13.3333,28.3333,33.3333,11.6667	12.2222,20,30.5556,26.6667,10.5556	11.6667,17.7778,30,28.3333,12.2222
H13	MRHCFA	22.7778,27.7778,24.4444,21.1111,3.8889	10.5556,19.4444,28.8889,27.7778,13.3333	10,11.6667,27.7778,35.5556,15
H14	MRHCFB	16.1111,26.1111,23.8889,22.2222,11.6667	11.1111,27.2222,25,26.6667,10	11.6667,18.8889,28.8889,28.3333,12.2222

H15	MRHCFC	14.4444,20.5556,27.7778,22.7778,14.4444	11.1111,20,31.1111,27.7778,10	10.5556,18.8889,25,32.2222,13.3333
H16	MRHDA	11.6667,12.7778,17.7778,20,37.7778	29.4444,28.8889,19.4444,12.2222,10	30,31.1111,16.1111,11.6667,11.1111
H17	MRHDB	12.2222,12.2222,16.6667,20.5556,38.3333	27.2222,28.8889,21.6667,11.6667,10.5556	30.5556,30,14.4444,13.8889,11.1111
H18	CRHAAC	13.3333,18.3333,20.5556,26.1111,21.6667	11.6667,25.5556,21.6667,30,11.1111	11.1111,18.3333,29.4444,28.8889,12.2222
H19	CRHAAB	13.8889,18.3333,20.5556,31.1111,16.1111	11.6667,17.7778,30,30.5556,10	11.1111,18.3333,28.8889,30,11.6667
H20	CRHAAA	17.7778,23.8889,19.4444,22.7778,16.1111	11.6667,26.6667,23.8889,27.7778,10	12.2222,18.3333,30,29.4444,10
H21	CRHAB	10.5556,15,25,28.8889,20.5556	11.6667,18.8889,29.4444,28.8889,11.1111	12.2222,12.7778,35.5556,28.8889,10.5556
H22	CRHBAA	22.2222,24.4444,20.5556,21.6667,11.1111	12.2222,20,22.7778,32.7778,12.2222	14.4444,15,32.7778,26.6667,11.1111
H23	CRHBAB	3.8889,4.4444,21.1111,33.8889,36.6667	18.8889,20,28.3333,21.1111,11.6667	22.7778,26.1111,23.3333,20.5556,7.2222
H24	CRHBAC	6.1111,8.3333,20.5556,35.5556,29.4444	15,14.4444,28.3333,25,17.2222	11.1111,18.3333,25.5556,29.4444,15.5556
H25	CRHBAD	12.7778,11.1111,25,22.7778,28.3333	4.4444,7.2222,28.3333,34.4444,25.5556	11.6667,25.5556,35.5556,17.2222,10
H26	CRHBBA	23.8889,25,18.8889,17.7778,14.4444	13.8889,18.8889,29.4444,27.2222,10.5556	10.5556,12.2222,27.7778,37.7778,11.6667
H27	CRHBBB	11.1111,16.1111,25,27.7778,20	32.7778,28.3333,15.5556,13.3333,10	5.5556,12.7778,22.7778,53.3333,5.5556
H28	CRHBBC	10,11.1111,25.5556,33.3333,20	19.4444,17.7778,27.7778,26.6667,8.3333	6.2222,13.2222,28.3333,36.6667,15.5556
H29	CRHBBD	8.8889,15,22.7778,30,23.3333	5.5556,10,20,22.2222,42.2222	2.2222,5.5556,22.2222,38.3333,31.6667
H30	CRHBBE	11.1111,16.1111,25.5556,26.1111,21.1111	19.4444,26.1111,28.3333,14.4444,11.6667	28.3333,24.4444,16.1111,18.3333,12.7778
H31	CRHBBF	6.1111,11.6667,16.6667,28.3333,37.2222	13.8889,20.5556,46.1111,11.1111,8.3333	18.8889,18.3333,28.3333,28.3333,6.1111
H32	CRHBBG	8.3333,9.4444,19.4444,42.2222,20.5556	33.3333,36.6667,13.3333,10.5556,6.1111	5,8.3333,26.6667,41.6667,18.3333
H33	CRHBBH	9.4444,14.4444,26.1111,26.6667,23.3333	13.3333,33.8889,31.6667,15,6.1111	35,21.1111,16.6667,20.5556,6.6667
H34	CRHBBI	10.5556,16.6667,25,25,22.7778	13.8889,18.8889,29.4444,27.7778,10	10,13.3333,35,30.5556,11.1111
H35	NRHAA	8.3333,10.5556,21.6667,23.3333,36.1111	5,11.1111,23.8889,30,30	12.2222,35,36.1111,10,6.6667
H36	NRHAB	0,2.2222,7.2222,18.3333,72.2222	8.8889,18.8889,25.5556,25,21.6667	10.5556,33.3333,35.5556,10,10.5556
H37	NRHAC	0.5556,0.5556,3.3333,8.8889,86.6667	3.3333,4.4444,7.2222,8.3333,76.6667	11.1111,33.3333,37.2222,10,7.7778

H38	NRHBA	2.2222,2.7778,18.3333,34.4444,42.2222	5.5556,12.2222,24.4444,30,27.7778	10,15.5556,28.8889,33.8889,11.6667
H39	NRHBC	2.7778,6.6667,20,43.8889,26.6667	10.5556,18.3333,30,32.7778,8.3333	3.8889,9.4444,33.3333,43.3333,10
H40	NRHBB	0,0.5556,1.1111,10,88.3333	47.2222,23.3333,13.8889,9.4444,6.1111	4.4444,8.3333,36.1111,39.4444,11.6667
H41	NRHCA	0.3333,0.5556,6.1111,13,80	47.7778,26.6667,13.8889,8.3333,3.3333	2.7778,3.3333,40,42.7778,11.1111
H42	NRHCB	0.3333,0.5556,1.6667,9.6667,87.7778	48.8889,25.5556,13.8889,7.7778,3.8889	2.7778,3.3333,40,42.7778,11.1111

4.5.3 BN Model Development

In this step, various BN models were developed. Each model represents one of the hazard events that were identified in the first step. Each hazard (child node) is connected to three parent nodes (i.e. three risk parameters); the states of the nodes were identified in the second step. The BN models were developed to represent PTSs' hazards and their dependencies in order to analyse these hazards. For example, the node MRHAA is influenced by three parent nodes, which are the occurrence probability of a risk event during the process of oil transport (P_l), the consequence severity should the risk event cause if it were to occur (S_c), and the probability that the risk event would not be detected before it occurred (D_p). Each of the parent nodes is independent: There is no direct connection between the P_l, S_c, and D_p. For instance, if P_l = Very High, node S_c could be Very High, High, Medium, Low, or Very Low. The same applies to node D_p.

4.5.4 Application of the BN to Aggregate the Rules

To demonstrate the calculation process for aggregating the rules by BN, the hazard (MRHAA) was examined (see Figure 4.7).

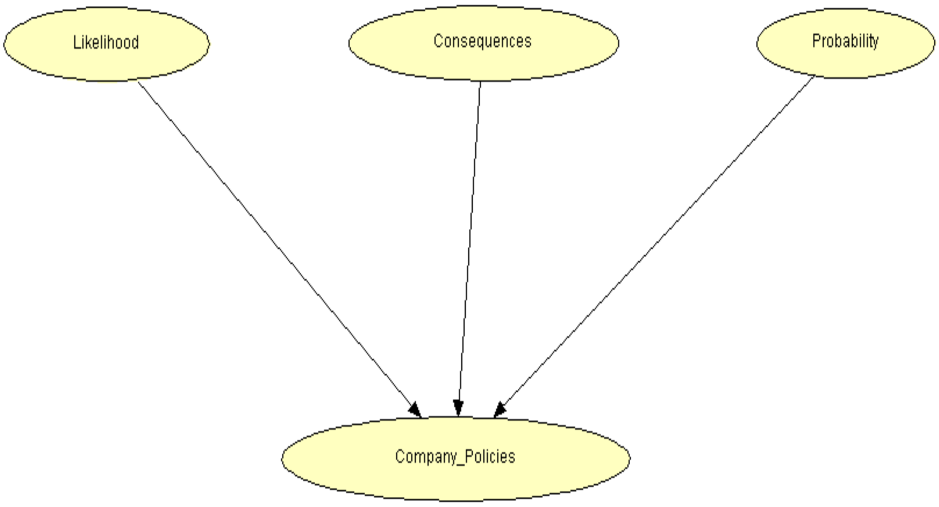

Figure 4.7: BN model of the MRHAA hazard

The degree of belief table for likelihood (without conditions) is shown below:

Likelihood	
Very High	8.8889
High	12.2222
Medium	21. 1111
Low	33. 8889
Very Low	23.8889

For example, $\text{Ƥ}(Likelihood = Very\ High) = 8.8889$

The degree of belief table for consequences (without conditions):

Consequences	
Very High	10
High	12.7778
Medium	22.7778
Low	29.4444
Very Low	25

For example, $\text{Ƥ}(\text{Consequences} = Very\ High) = 10$

The degree of belief table for probability (without conditions):

Probability	
Very High	5.8889
High	16.1111
Medium	24.6667
Low	27.2222
Very Low	26.1111

For example, $\mathcal{P}(\text{Probability} = \mathit{Very\ High}) = 5.8889$

The degree of belief table for MRHAA (without conditions) (see Appendix 2.2 for the full table):

Probability	Very High								Very Low
Consequences	Very High					High		…	Very Low
Likelihood	Very High	High	Medium	Low	Very Low	Very High	High	…	Very Low
Very High	1	0.6667	0.6667	0.6667	0.6667	0.6667	0.3333	…	0
High	0	0.3333	0	0	0	0.3333	0.6667	…	0
Medium	0	0	0.3333	0	0	0	0	…	0
Low	0	0	0	0.3333	0	0	0	…	0
Very Low	0	0	0	0	0.3333	0	0	…	1

$$\mathcal{P}(\text{MRHAA} = \mathit{Very\ High} \mid \mathit{Likelihood} = \mathit{Very\ High}, \text{Consequences} \\ = \mathit{Very\ High}, \text{Probability} = \mathit{Very\ High}) = 1$$

Using the *prior probabilities* values of each node, the *marginal probability* of MRHAA can be calculated with Equation 4.5. MRHAA $= \mathit{Very\ High}$ is used as an example. It is calculated as follows (see Figure 4.8):

The same technique could be applied to calculate $\mathcal{P}(\text{MRHAA}_{High})$, $\mathcal{P}(\text{MRHAA}_{Medium})$, $\mathcal{P}(\text{MRHAA}_{Low})$ and $\mathcal{P}(\text{MRHAA}_{Very\ Low})$. For an easier and faster way to perform this calculation, a computer software tool (i.e. HUGIN software) is used to compute this hazard BN model. As a result, the risk analysis value of MRHAA is as follows (see Figure 4.8):

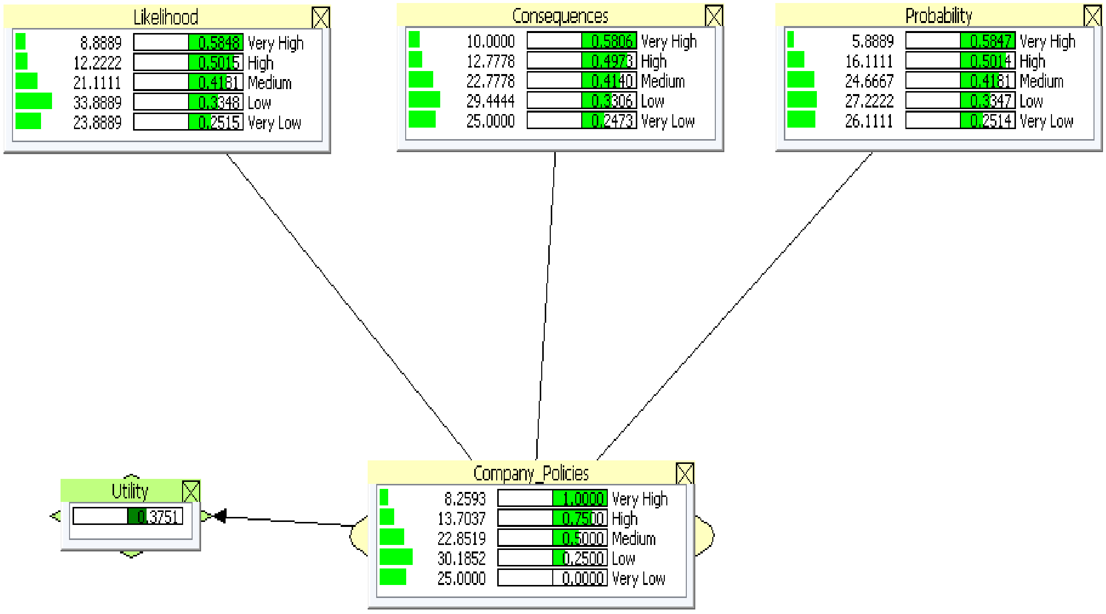

Figure 4.8: The analysis of MRHAA by HUGIN software

As a result, the analysis values of MRHAA can be expressed by using Equation 4.4 as follows:

$$\mathrm{P}(R|L, C, P) = (8.2593, 13.7037, 22.8519, 30.1852, 25)$$

The risk evaluation of the failure MRHAA can be explained as follows:

$$(8.2593\ \text{Very High}, 13.7037\ \text{High}, 22.8519\ \text{Medium}\ , 30.1852\ \text{Low}, 25\ \text{Very Low})$$

By using the same technique, the risk analysis values for all the hazards are identified in Table 4.10 and Appendices 2.9 – 2.10.

4.5.5 Prioritisation of the Failure Factors

For a decision-maker, it is much easier and more practical to prioritise the hazards based on a single value. Therefore, the utility value technique has been applied to obtain a single value for ranking the PTSs' hazards.

The output values of MRHAA were presented by five linguistic terms (i.e. Very High, High, Medium, Low, and Very Low). "Very High" is the highest preference linguistic term (i.e. equal to five), and "Very Low" is the lowest preference linguistic term (i.e. equal to one). By using Equations (4.6) and (4.7), the utility value of MRHAA is calculated as follows (see Table 4.9):

Table 4.9: The steps for calculating the utility value of MRHAA

Rh	Very High	High	Medium	Low	Very Low
V_h	5	4	3	2	1
U_{Rh}	$\frac{5-1}{5-1}=1$	$\frac{4-1}{5-1}=0.75$	$\frac{3-1}{5-1}=0.5$	$\frac{2-1}{5-1}=0.25$	$\frac{1-1}{5-1}=0$
$\text{Ƥ}(R_h)$	8.2593%	13.7037%	22.8519%	30.1851%	25%
$\sum_{h=1}^{5} \text{Ƥ}(R_h) = 8.2593\% + 13.7037\% + 22.8519\% + 30.1851\% + 25\% = 100\%$					
$\text{Ƥ}(R_h)\, U_{rh}$	8.2593%	10.2778%	11.4260%	7.5463%	0
$RH_{\text{MRHAA}} = \sum_{h=1}^{5} \text{Ƥ}(R_h)\, U_{rh} = 37.5093$					

By using the same technique, the utility value for the petroleum terminal, ship, and pipeline hazards are identified and ranked in Table 4.10, Appendix 2.11, and Appendix 2.12 respectively.

Table 4.10: Analysis values of the 42 hazards by HUGIN software

	Hs	Degree of Belief (VH, H, M, L, VL)					Utility value	Ranking
		VH	H	M	L	VL		
H1	Company Policies (MRHAA)	8.2593	13.7037	22.8519	30.1852	25	37.5093	38
H2	Company Standards (MRHAB)	13.1482	18.3333	28.3333	24.0741	16.1111	47.0833	17
H3	Management Procedure (MRHAC)	12.7778	19.4444	26.4815	26.6667	14.6296	47.2685	16
H4	Inattention (MRHBA)	11.8519	20.5555	25.7407	30	11.8519	47.6389	12
H5	Neglect (MRHBB)	11.8519	17.0371	30.9259	29.4444	10.7408	47.4537	13
H6	Fatigue (MRHBC)	11.2963	13.7037	29.0741	28.7037	17.2222	43.2870	28
H7	Skills (MRHBD)	13.8889	16.8518	28.1482	27.2222	13.8889	47.4074	14
H8	Overfill (MRHCA)	10.5556	13.7037	27.0370	31.4815	17.2222	42.2222	29
H9	SOPs Not Followed (MRHCB)	12.4074	19.4444	24.6296	29.6296	13.8889	46.7130	19
H10	Overpressure (MRHCC)	12.9630	16.1111	27.5926	28.1481	15.1852	45.8796	24
H11	Release From Loading Arm/SBM (MRHCD)	9.8148	13.1482	28.8889	31.2963	16.8519	41.9444	30
H12	Understaffing (MRHCE)	12.4074	17.0370	29.6296	29.4444	11.4815	47.3611	15
H13	Breakdown of Communication (MRHCFA)	14.4445	19.6296	27.0370	28.1482	10.7407	49.7222	8
H14	Communication Misunderstanding (MRHCFB)	12.9630	24.0741	25.9259	25.7407	11.2963	50.4167	6
H15	Wrong Signals (MRHCFC)	12.0370	19.8148	27.9630	27.5926	12.5926	47.7778	11
H16	Procedural Failure (MRHDA)	23.7037	24.2593	17.7778	14.6296	19.6296	54.4444	1
H17	Collision between Ship and Other Ship/Berth (MRHDB)	23.3333	23.7037	17.5926	15.3704	20	53.7500	3
H18	Lack of Tools/Spare Parts(CRHAAA)	13.8889	22.9630	24.4444	26.6667	12.0370	50	7
H19	Inappropriate Maintenance Practice (CRHAAB)	12.2222	18.1481	26.4815	30.5556	12.5926	46.7130	19
H20	Use Inappropriate Tools/Spare Parts (CRHAAC)	12.0370	20.7407	23.8889	28.3333	15	46.6204	21
H21	Maintenance Omission (CRHAB)	11.4815	15.5556	30	28.8889	14.0741	45.3704	26
H22	Lack of Communication System (CRHBAA)	16.2963	19.8148	25.3704	27.0371	11.4815	50.6019	5
H23	Lack of Lighting System (CRHBAB)	15.1852	16.8518	24.2592	25.1852	18.5185	46.2500	23
H24	Lack of Movable Facilities (CRHBAC)	10.7407	13.7037	24.8148	30	20.7407	40.9259	33
H25	A/C System Failure (CRHBAD)	9.6296	14.6296	29.6296	24.8148	21.2963	41.6204	31
H26	Control System Failure (CRHBBA)	16.1111	18.7037	25.3704	27.5926	12.2222	49.7222	8

H27	Instrument Failure (CRHBBB)	16.4815	19.0741	21.1111	31.4815	11.8519	49.2130	10
H28	Valve Failure (CRHBBC)	11.8889	14.0370	27.2222	32.2222	14.6296	44.0833	27
H29	Hose/Pump Failure (CRHBBD)	5.5556	10.1852	21.6667	30.1852	32.4074	31.5741	41
H30	Gasket Failure (CRHBBE)	19.6296	22.2222	23.3333	19.6296	15.1852	52.8704	4
H31	Pipeline Failure (CRHBBF)	12.9630	16.8519	30.3704	22.5926	17.2222	46.4352	22
H32	Loading Arm/SBM Failure (CRHBBG)	15.5555	18.1482	19.8148	31.4815	15	46.9444	18
H33	Power Failure (CRHBBH)	19.2592	23.1481	24.8148	20.7408	12.0370	54.2130	2
H34	Cathodic Protection Failure (CRHBBI)	11.4815	16.2963	29.8148	27.7778	14.6296	45.5556	25
H35	Heavy Rainfall (NRHAA)	8.5185	18.8889	27.2222	21.1111	24.2593	41.5741	32
H36	Flood (NRHAB)	6.4815	18.1481	22.7778	17.7778	34.8148	35.9259	39
H37	Snow (NRHAC)	5	12.9630	15.9259	9.0741	57.0371	24.9537	42
H38	Hurricane (NRHBA)	5.9259	10.1852	23.8889	32.7778	27.2222	33.7037	40
H39	Tornadoes (NRHBB)	17.2222	10.7407	17.0370	19.6296	35.3704	38.7037	36
H40	Lightning (NRHBC)	5.7408	11.4815	27.7778	40	15	38.2407	37
H41	Earthquake (NRHCA)	16.9630	10.1852	20	21.3704	31.4815	39.9444	34
H42	Tsunami (NRHCB)	17.3333	9.8148	18.5185	20.0741	34.2593	38.9722	35

Within the port transportation system, based on the results in Table 4.10 and Figure 4.9, the hazard Procedural Failure (MRHDA) is the most important hazard in the port sector, followed by Power Failure (CRHBBH), Collision between Ship and Other Ship/Berth (MRHDB), Gasket Failure (CRHBBE), and Lack of Communication System (CRHBAA). After applying the same technique to each of the hazards within ship and pipeline transportation systems, the belief degree of the five linguistics grades were combined into one crisp number. Ship Collision due to Human Fatigue (SCHF), Action to Avoid Collision (SCAAC), and Ship Collision due to Main Engine Failure (SCMEF), were the top ranked hazards within ship transportation systems (see Appendix 2.11). On the other hand, Geological Hazards (PTGH), followed by Sabotage (PTSH) and Construction Failure (PTCF), were the most important hazards within the pipeline transportation sector (see Appendix 2.12). After utilising the belief degree of the hazards associated with PTSs (i.e. port and transportation modes hazards) to achieve one value, namely a crisp value of 54.44, the hazard MRHDA was identified as the most significant hazard within PTSs (see Appendixes 2.11 and 2.12, Table 4.10 and Table 4.11).

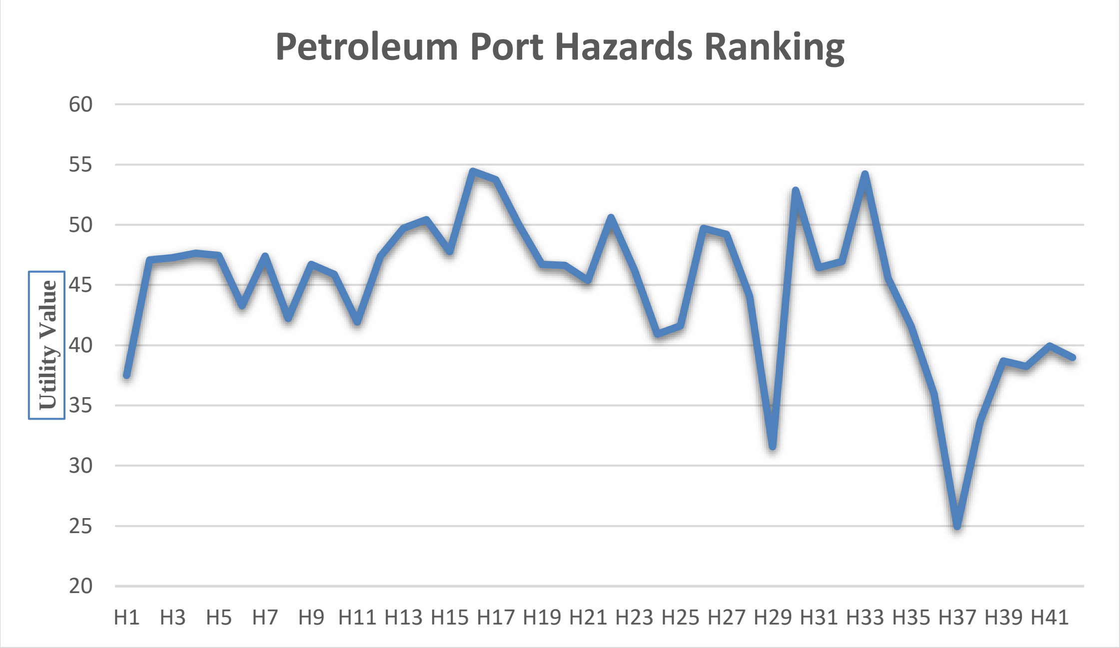

Figure 4.9: Utility Value of the 42 petroleum port hazards

Table 4.11: Utility Value of the most significant hazards in each operational system within the PTSs

	Hs	Utility Value	Ranking
H16	Procedural Failure (port system)	54.44	1
H 33	Power Failure (port system)	54.21	2
H 17	Collision between Ship and Other Ship/Berth (port system)	53.75	3
H 10	Human Fatigue (Collision) (ship system)	50.05	4
H 7	Action To Avoid Collision (Collision) (ship system)	49.26	5
H 1	Main Engine Failure (Collision) (ship system)	48.75	6
H 4	Geological Hazards (pipeline system)	38.96	7
H 1	Sabotage (pipeline system)	38.89	8
H 6	Construction Failure (pipeline system)	34.48	9

4.5.6 Sensitivity Analysis

To partially validate the developed approach, sensitivity analysis was carried out. To test the sensitivity of the model, two axioms were conducted. These two axioms tested the sensitivity of the model in terms of the changes that happened to the output of the risk evaluation when the prior probability changed. The model of MRHAA was examined as follows:

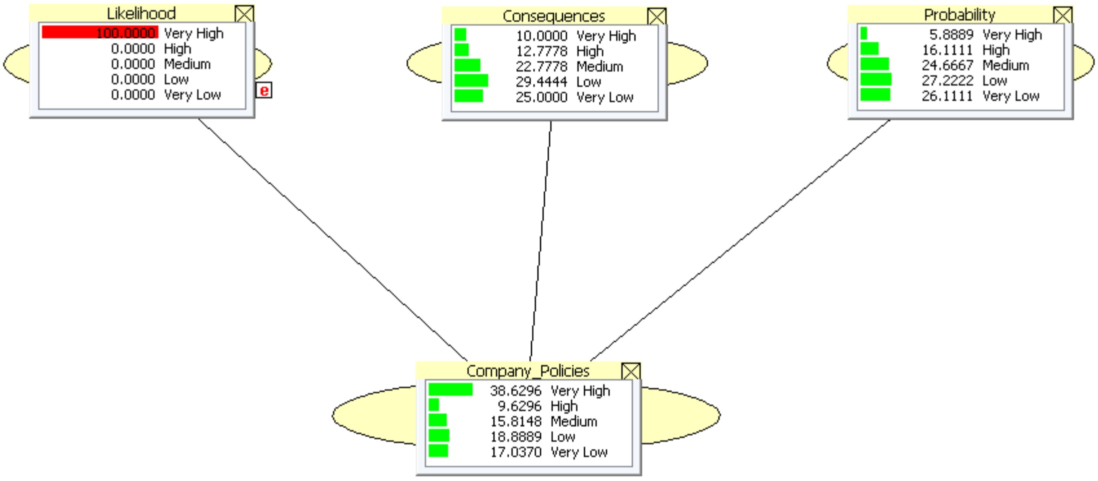

Figure 4.10: The analysis of MRHAA by HUGIN software given the evidence for node “$Likelihood_{Very\ High} = 100\%$"

The prior probability value of the node "likelihood" was updated to 100% “Very High” (see Figures 4.10). As a result, the output value of the node MRHAA$_{Very\ High}$ increased from 8.26% to 38.63%. The response indicates that a slight change in the prior probability value of each input node affects the value of the output node, causing a relative increase/decrease of the output value (axiom 1) (see Figures 4.8 and 4.10).

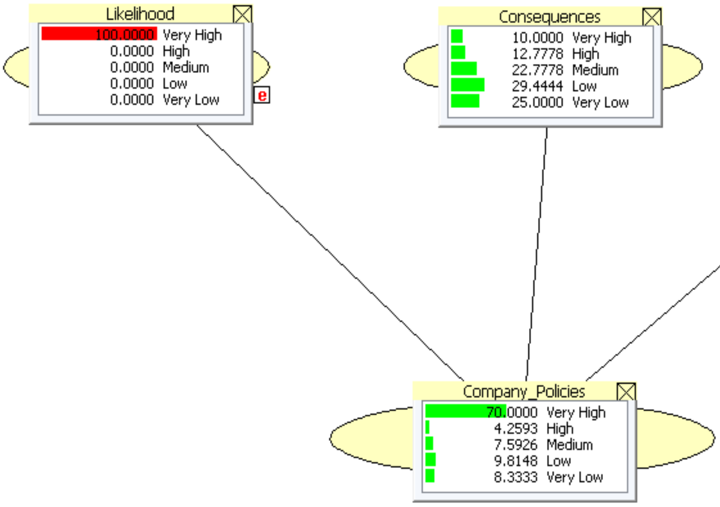

Figure 4.11: The analysis of MRHAA by HUGIN software given the evidence for node "$\boldsymbol{Likelihood_{Very\ High}} = \mathbf{100\%}$" and "$\boldsymbol{Probability_{Very\ High}} = \mathbf{100\%}$"

Changing the prior probability value of the node "Probability" and the node "Likelihood" to be set at 100% "Very High", led to a change in the posterior probability value of the output "$\mathrm{MRHAA}_{Very\ High}$" (see Figure 4.11). This change resulted in a further increase of the posterior probability value of the output "$\mathrm{MRHAA}_{Very\ High}$" from 8.26 % to 70%, as shown in Figures 4.8 and 4.11. Therefore, the output value of "$\mathrm{MRHAA}_{Very\ High}$" in Figure 4.11 is higher than the output value in both Figures 4.8 and 4.10. This result means that the total influence magnitude of the combination of the probability variation, namely the influence of both attributes at once on the values, is always greater than that of any single attribute (axiom 2).

By performing axiom 1 (i.e. increasing the belief degree of $\mathrm{Likelihood}_{Very\ High} = 100\%$") and axiom 2 (i.e. increasing the belief degree for both "$\mathrm{Likelihood}_{Very\ High}$ and "$\mathrm{Probability}_{Very\ High} = 100\%$") for all the hazards, the results of these axioms showed the sensitivity of the models (see Figure 4.12). For example, the posterior probability value of the output H13 (i.e. Breakdown of

Communication (MRHCFA)) increased from 14.44% to 40.19% when the prior probability value of the node "Likelihood" was changed to be set at 100%, “Very High”. Moreover, by changing the prior probability value of the nodes "Likelihood" and "Probability" to be set at 100%, “Very High”, the output value of H13 increased from 14.44% to 70.19%, as shown in Figure 4.12.

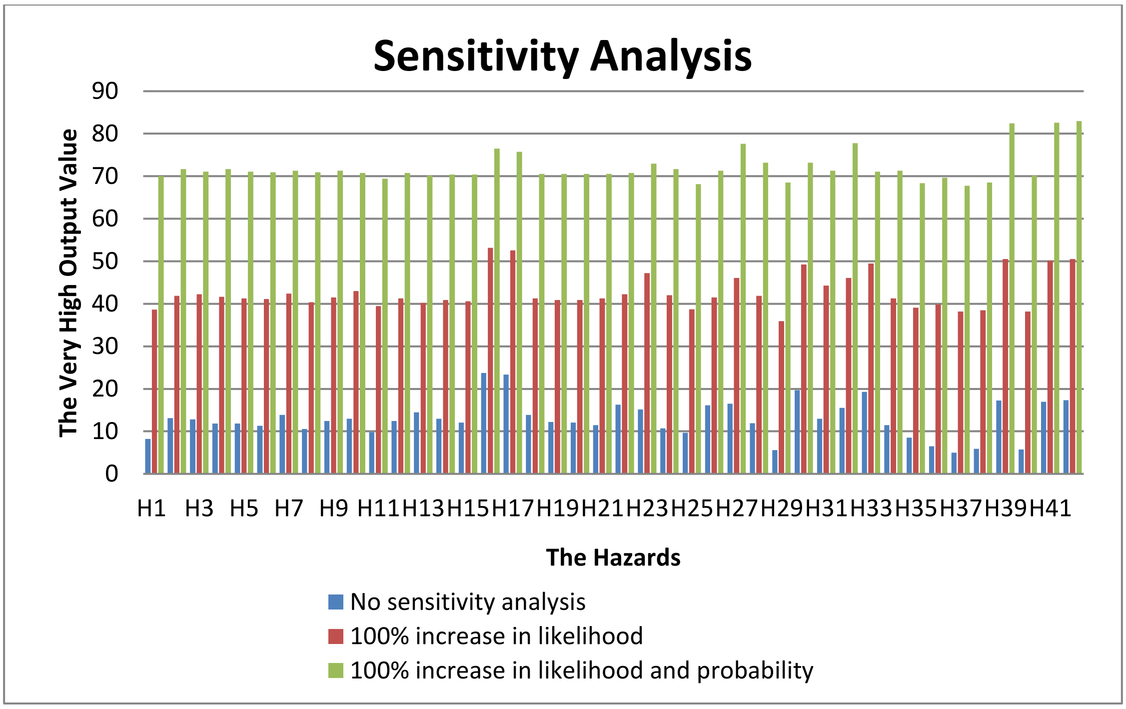

Figure 4.12: The sensitivity analysis of the 42 hazards

4.6 Conclusion

This is one of the first studies that deals with data uncertainty problems in PTSs through developing a new integrated model. This new model integrates fuzzy rule-based (FRB) approach and Bayesian Network (BN) to analyse petroleum ports and transportation modes failures. The fuzzy rule-based Bayesian reasoning (FRBBR) method uses domain expert knowledge in the form of fuzzy IF-THEN rules. Output degree (i.e. belief degree) of the FMEA parameters was integrated by using a BN for risk ranking to provide a supporting system for decision-makers in analysing the failures. After utilising the belief degree of the hazards associated with PTSs (i.e. port and transportation modes hazards), Procedural Failure (MRHDA), Ship Collision due to Human Fatigue (SCHF) and Geological Hazards (PTGH), were the most important hazards in port, ship and pipeline transportation systems. Based on the ranked outputs of this method, the most significant hazard within the PTSs was recognised (i.e. Procedural Failure (54.44)). The output of this technique may be changed based on 1) experts' backgrounds and 2) number of participant experts (i.e. more or less than nine), and different inputs can be included.

The proposed assessment methodology highlights the issues associated with PTSs. The proposed method shows more realistic and flexible results by describing the failure information based on real-life situations. Additionally, the proposed method provides a decision-support system for enhancing the safety practices of petroleum ports and other engineering and management systems through providing decision-makers with a reliable risk-ranking technique.

This chapter mainly focused on evaluating the local levels of PTSs. In addition, a brief discussion of Chapter 4 is presented in Chapter 7. However, controlling the operational risk at the local level may not ensure the safety of PTSs. In the following chapters, the global level of PTSs will be evaluated. While the FRBN technique was used to assess the local level of the PTSs, the Evidential Reasoning (ER) approach is going to be applied to accomplish the PTSs evaluation, due to the approach's capability in synthesising the risk from the local level to the system level. Moreover, other techniques, such as Analytical Hierarchy Process (AHP) and network analysis technique, will be used as well.

Chapter 5: An Advanced Risk Assessment Framework for PTNs using Evidential Reasoning Approach

Petroleum transportation systems (PTSs) play an important role in the flow of crude product from its place of production to the customer. In order to ensure an effective port-to-port transportation system, safety of the PTSs is a key element that must not be neglected for the successful petroleum transportation networks (PTNs). This chapter proposes a novel mathematical model that assesses PTSs locally and globally. An Evidential Reasoning (ER) approach is introduced due to the technique's ability to combine the local/internal and global/external levels of PTSs. This chapter's novel approach starts with the identification of the petroleum transportation hazards and finishes with the model validation process. Whilst the hybrid Fuzzy Rule-Based Bayesian Reasoning (FRBBR), Analytic Hierarchy Process (AHP), and Evidential Reasoning (ER) approaches are used at the internal level, the network analysis technique is used for the external level. The results gained from using these techniques can be used by decision makers to measure and improve PTSs safety.

5.1 Introduction

In the previous chapter, Fuzzy Rule-Based Bayesian Reasoning (FRBBR) was used to evaluate the identified hazards in order to enhance the safety practices of petroleum transportation systems (PTSs). However, the phrase 'PTSs' clarifies that there is more than just one system. PTSs contain two focal points that are linked to each other in order to complete the product transportation cycle. These focal points are ports and transportation modes.

PTSs play an important role in the flow of petroleum product from the production phase to the refinery or customer. If there is no preparation built into the system, or if the system lacks facilities, it might be too late to take emergency actions if a failure strikes. A disruption in a PTS will affect the overall supply chain's desired functions, which can result in various failures (Baublys, 2007). For example, factors such as planning and scheduling may influence the operation of the supply chain and may cause a breakdown in the fluency of the product's movement (Ding and Tseng, 2013; Grossmann, 2005; Shah *et al.*, 2010). Safety in design and operation is a prime concern for operating companies because the hazards could have a high economical and financial impact apart from causing other failures (Elsayed *et al.*, 2009). With regard to the safety of petroleum transportation as a complete system, risk assessment is an important tool for maintaining the safety and reliability of the petroleum industry.

Therefore, this chapter proposes a novel risk evaluation model in order to enhance the safety of the PTSs and applies that model in a real transportation system. To reach this goal, this chapter is organised as follows: the second sub-section provides a literature review for the approaches introduced in this chapter, Evidential Reasoning (ER) and Analytical Hierarchy Process, (AHP). The third sub-section is a step-by-step explanation of the techniques that have been used to evaluate PTSs. This section begins by identifying the petroleum transportation hazards and finishes with the validation process. A real-life case study is presented in the fourth sub-section to demonstrate the methodology proposed in this chapter. Finally, the conclusion is presented in the fifth sub-section.

5.2 Evidential Reasoning (ER) Background and Approach

The ER approach, which is often referred to as the Dempster–Shafer theory of evidence or D–S theory, was firstly generated by Dempster in 1967 and extended and refined by Shafer in 1976 (Rahman, 2012; Riahi *et al.*, 2012). The approach was developed in the

1990s to deal with Multi Attribute Decision Analysis (MADA) problems that have both qualitative and quantitative data under uncertainty based on the D-S theory. This revised approach has been widely applied in recent years for its ability to deal with Multi Attribute Decision Making (MADM) problems qualitatively and quantitatively under uncertainties (Keeney and Raiffa, 1993). The approach is particularly useful for dealing with both qualitative and quantitative criteria under uncertainty, as it utilises individuals' knowledge, expertise, and experience in the form of belief structures (Kong *et al.*, 2012).

The development of the ER approach has passed through several stages. These stages are highlighted as follows (Yang and Xu, 2004; Xu, 2012):

- The ER algorithm was first generated and published in the early 1990s by Yang and Singh (1994). This version of ER employed the evidence combination rule of the D–S theory for criteria aggregation and introduced criteria weight.
- The algorithm was next updated by Yang (2001) and further modified by Yang and Xu (2002). This newer version of ER employed a new evidence combination rule established by reversing the evidence combination rule of the D–S theory.
- Finally, a computer software program known by the name *IDS* (Intelligent Decision System) was developed to assist ER approach calculations.

As mentioned earlier, the ER approach deals with Multi Attribute Decision Making (MADM) for qualitative and quantitative problems under uncertainties (Keeney and Raiffa, 1993). The ER approach algorithm was created on the basis of the multi-attribute problem analysis framework and on the evidence combination rule of the D–S theory (Liu *et al.,* 2004; Yang, 2001). The approach is unlike the majority of MADM techniques. The following advantages distinguish the ER approach from other MADM techniques (Li and Liao, 2007; Riahi, 2010):

- ER offers greater flexibility to its users as it enables them to express their judgements subjectively and quantitatively.
- In addition to handling complete and precise data, ER, unlike all other MADM approaches, is capable of handling incomplete, uncertain and vague data through allowing the decision maker to illustrate a belief degree less than 1.
- ER is capable of accommodating or representing the uncertainty and risk that is inherent in decision analysis.
- The ER approach is capable of offering a rational and reproducible methodology through its hierarchical evaluation process to aggregate the assessed data.
- By using calculating software, called the Intelligent Decision System (*IDS*), the ER approach is capable of reaching the output of the assessment model.

The ER approach has been widely and successfully used in several fields for dealing with MADM problems under uncertainty in a reliable, transparent, and reasonable way. For example, Yeo *et al.* (2014) highlighted the advantage of using a Fuzzy Evidential Reasoning (FER) approach. To illustrate this, according to Yeo *et al*. (2014), FER is a reasonable solution and provides an appropriate foundation to model any type of port selection scenarios under uncertainties. Yang *et al.* (2009a) confirmed the ability of FER to deal with MADM problems in selecting appropriate vessels for shipping activities. Liu *et al.* (2004) used the FER approach to model the safety of an engineering system with various types of uncertainties. John *et al.* (2014a) applied the ER approach to evaluate seaport operations, due to the high level of uncertainty in these operations. Xu (2012) provided a list of multiple-criteria decision computer software, for example, Intelligent

Decision System (IDS), Expert Choice (EC), Logical Decisions (LD), and Banxia Decision Explorer (BDE).

When using an ER approach with a Multi Criteria Decision Making (MCDM) problem, the following steps need to be carried out (Xu and Yang, 2001; Chen *et al.*, 2014; Alyami *et al.*, 2016):

- Identification and analysis of the hierarchal structure of the problem. This step includes identifying the problem and modelling the problem by using the belief matrix, which includes the decision-makers' preferences with regard to weight of criteria and utility or value.
- Use of rule- or utility-based evidence transformation procedures to transfer various belief structures to a unified belief structure.
- Aggregation of the hierarchal criteria by using the evidential algorithm.
- Use of validation analysis and utility scores to validate the ER algorithm outcomes and analysis reports.

To aggregate the hierarchal criteria using the ER algorithm, a software package known as IDS is used. The software package in the case study section is used firstly for data aggregation followed by sensitivity analysis.

5.2.1 Intelligent Decision System Software

Intelligent Decision System (IDS) is a computer software program developed in the late 1990s on the basis of the ER approach (Xu, 2012). This Windows-based software has been developed to assist Multi Attribute Decision Analysis (MADA), or Multi Criteria Decision Making (MCDM). The software simplifies the complexity of the aggregation process of the ER algorithm. The software makes it easier to present the hierarchical structure, to key in that structure’s inputs, and to read the outputs of the structure. In addition, there is no limit to the number of attributes in the IDS hierarchy. The software will be used for the following aggregation process of the ER approach. To apply the IDS software for the aggregation process of the ER approach, the following steps should be taken (Xu and Yang, 2005):

- The hierarchy attributes must be mapped out.
- The attributes’ data must be defined.
- The attributes’ weight must be defined.

For the purpose of this research, the ER technique is adopted. This method evaluates the safety of petroleum transportation as a complete system in uncertain situations. Moreover, for weighting each criterion, an adoption of AHP was employed in this chapter. Therefore, it is important to understand the AHP method for applying the ER technique in the transportation system.

5.3 Analytical Hierarchy Process (AHP) Background and Approach

In the 1970s, Thomas L. Saaty introduced a Multi Criteria Decision Making (MCDM) approach known as AHP. Saaty developed this approach while he was directing research projects in the U.S. Arms Control and Disarmament Agency (Alexander, 2012). According to Saaty (2000), AHP is *“a framework of logic and problem-solving that spans the spectrum from instant awareness to fully integrated consciousness by organising perceptions, feelings, judgments and memories into a hierarchy of forces that influence decision results.”*

The AHP approach is a powerful technique which has been extensively used for its capability in dealing with complex systems, which includes choosing an alternative from several alternatives and also providing a comparison of the considered options. Moreover, the technique has the ability to deal with large numbers of decision-making criteria of both a quantitative and a qualitative nature, and it also simplifies the decision-making problem with its hierarchical structure formation (Cheng *et al.,* 2002). The technique has been widely applied in different fields due to its simplicity in calculation and the advantages it offers as a decision-making tool and mechanism for weighting the risk factors, such as in engineering (Katarne and Negi, 2013; Triantaphyllou and Mann, 1995), healthcare (Pecchia *et al.*, 2011), marketing (Wickramasinghe and Takano, 2009), and accounting (Apostolou and Hassell, 1993).

When using the AHP approach in a MCDM problem, four steps need to be considered:

- Establish the hierarchy structure of the problem through breaking it down into lower criteria.
- Collect input data by performing a pairwise comparison.
- Calculate the criteria relative weights to obtain scores and rank the criteria.
- Perform a consistency test to determine whether the input is consistent or not.

According to Zahedi (1986), creating a hierarchy structure of the problem is the first step in the AHP process. This step is the graphical representation of the problem in terms of main goal, criteria, and decision alternative. For the purpose of this example, the hierarchy structure of the problem is based on Figure 5.1.

As per the decision-makers' pairwise comparisons for a group of criteria, each criterion is evaluated by its weight, as generated from the technique. A criterion with a higher weight is considered more important than a criterion with a lower weight (for example, criterion A is more important than criterion B).

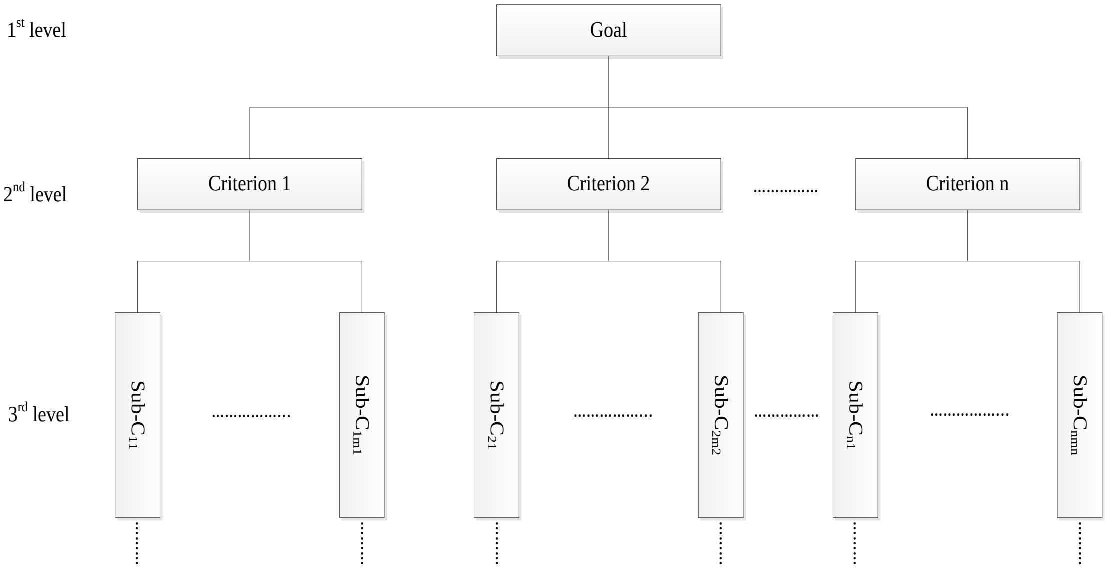

Figure 5.1: The hierarchical structure of AHP (Source: Tzeng and Huang, 2011)

The AHP technique has been widely applied in various studies as a weighting technique due to the following advantages (Zahir, 1999; Ishizaka *et al.*, 2011; Kabli, 2009):

- The AHP technique helps the decision maker to take its advice into account without totally overriding the initial, tentative choice.
- The AHP is suitable for analysing both qualitative and quantitative decision-making criteria.
- The AHP technique supports group decision making through consensus by calculating the geometric mean of the individual pairwise comparisons.
- The AHP technique can consider a large quantity of criteria to reform pairwise comparisons.
- The AHP technique is able to present a graphical representation of the decision-making problem to clarify the construction of a hierarchy.

- The AHP technique uses the consistency index to determine whether the provided judgements are consistent or need reassessment.
- The AHP technique has been widely accepted and successfully applied in many different fields.

5.4 Methodology

Figure 5.2 illustrates a flow chart of the methodology used for this chapter. The procedure contains four parts: 1) the list of techniques used for the local/internal evaluation of the transportation system (steps 1, 2, 3, and 4); 2) the global/external evaluation (step 5); 3) the merging of the internal and external evaluation (steps 6 and 7); and 4) the validation process (step 8). The flow chart begins by identifying the hazards associated with petroleum transportation as a complete system and sets a goal that needs to be accomplished. This step is followed by the evaluation processes of both internal and external systems. The application of ER is then also highlighted for aggregating the internal and external evaluations. Finally, the diagram ends with the validation process of the model.

The steps in analysing petroleum transportation as a system are listed as follows:

- **Hazard hierarchy development:** Identify the operational hazards within the PTSs and present them in a hierarchical structure.
- **Application of AHP:** Apply the AHP method to determine the weight of the hierarchical criteria.
- **Application of FRBBR:** Apply established Fuzzy Rule-Based Bayesian Reasoning (FRBBR) to measure the internal operational risks.

- **Aggregation of risks through ER:** Apply the ER approach to aggregate the assessed risks.
- **Application of network analysis.** Apply a network analysis technique to determine the weight of the ports and transportation modes within the PTNs.
- **Aggregation of internal and external analysis through ER:** Aggregate the internal and external analysis of the transportation system by using the ER approach.
- **Application of utility approach:** Obtain a crisp value for the petroleum transportation network by using a utility approach.
- **Sensitivity analysis:** perform a series of tests to determine how sensitive the developed model is.

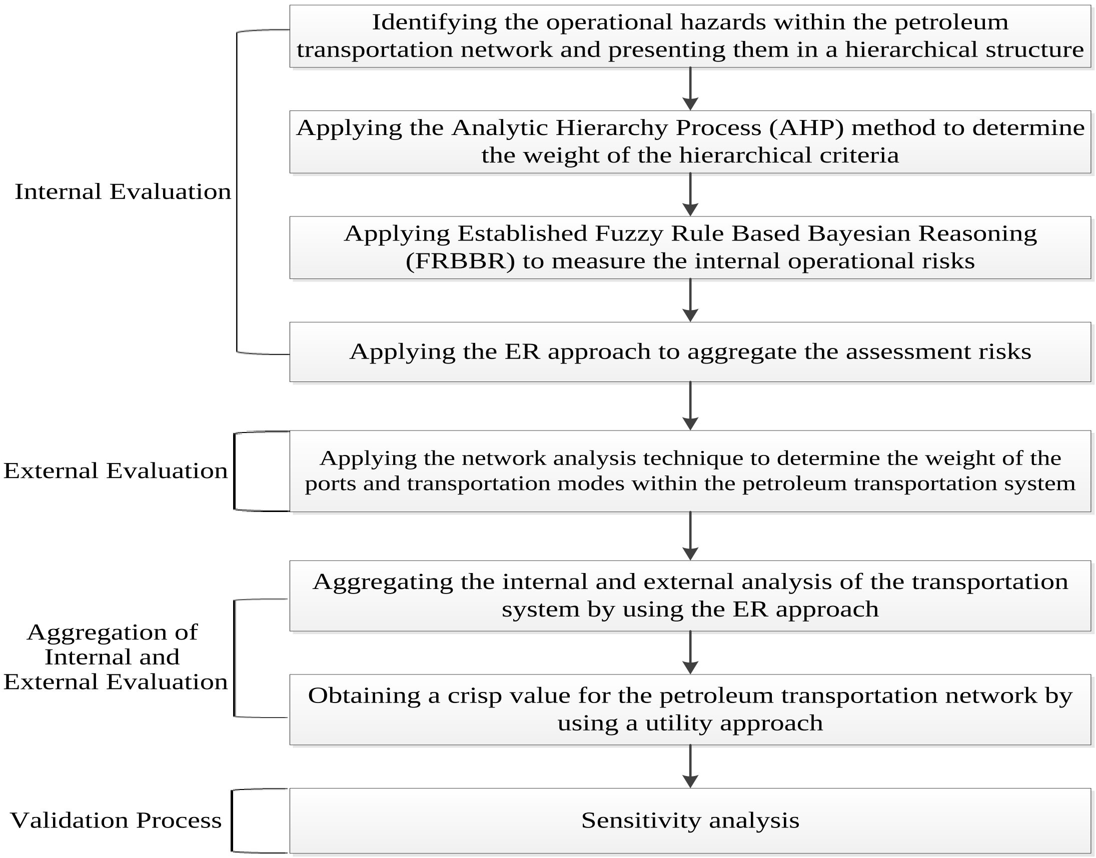

Figure 5.2: The PTSs assessment methodology structure

5.4.1 Step I: Identifying the Hazards within the Petroleum Transportation Network and Presenting them in a Hierarchical Structure

Decision-makers should have a clear understanding of the hazards associated with the working environment to ensure the safety of the system. In the case of PTS safety, it is important to identify the hazards that may lead to crude oil spill whilst the product is being transported. The identified hazards are presented in a hierarchical structure to provide a clear picture to decision-makers to assist them in solving the problem.

The hierarchical structure of Petroleum Transportation Networks (PTNs) hazards is presented in Figures 5.3, 4.4, 4.5, and 4.6. The first level represents the goal. The second level represents crude oil transportation system criteria; these criteria include petroleum port operation, ship transportation operation, and pipeline transportation operation hazards. For a petroleum spill caused during the operational process, accidents are often initiated by errors induced by machinery failures, human failures, or a combination of the two. As a result, level two criteria are broken into lower levels, which allows decision makers to have a more complete understanding of PTSs hazards to make a practical decision

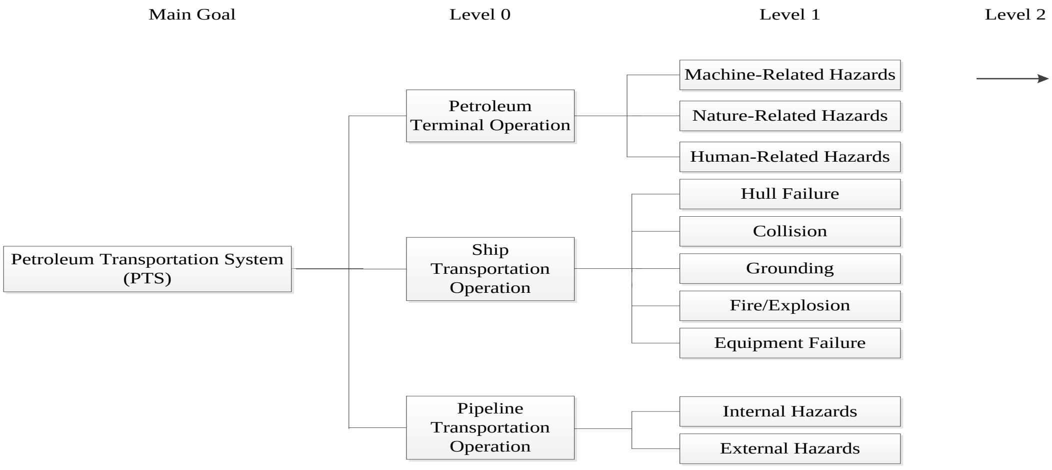

Figure 5.3: Main hieratical structure of the risk in Petroleum Transportation Networks (PTNs)

The operational hazards that lead to oil spill within the PTNs were identified through conducting an extensive literature review for each of the criteria in level zero separately (e.g. Kim *et al.*, 2014; Ceyhun, 2014; Vinnem *et al.*, 2012; Yuhua and Datao, 2005; ITOPF, 2015; Ismail and Karim, 2013). This stage allowed the researcher to identify the hazards in the PTNs. With respect to operational activities that occur in PTNs, oil spill is a widespread hazard associated with various hazards events within the PTSs. The identified hazards were also validated by experts to improve the quality of the identification process. The validation process benefits from the experts' personal perspectives regarding whether the identified hazards are related to petroleum transportation or not, and the experts also added other hazards that exist in real life that had not been addressed by the literature review.

5.4.2 Step II: Applying the Analytical Hierarchy Process Method to Determine the Weight of the Hierarchical Criteria

To identify the relative importance of each criterion within PTSs that was identified in the first step and that criterion's contribution to the upper level, the weight of the criterion had to be taken into consideration. Therefore, the AHP approach was applied to identify the weight of the PTSs hierarchy criteria. The weighting process involved experts' judgement presented in a pairwise comparison method. The technique was used on each group of criteria to form a matrix. A questionnaire was built and sent to PTSs experts to weight the hierarchical criteria. The PTSs experts selected a set of pairwise comparisons by using a preference scale (see Table 5.1). The process of building a pairwise comparison matrix is as follows: First, n criteria need to be present in an n x n matrix. Applying a ratio scale assessment enables all the n criteria to perform the pairwise comparison. Before answering the questionnaire, each expert had to understand the preference scale. For comparison purposes, Saaty (1980) introduced a pairwise comparison scale. The presented scale consists of two parts that represent the importance and the unimportance of the attributes (see Table 5.1). The first part is a 1 to 9 scale which lies between equally important and extremely important; the second part is a 1 to 1/9 scale that lies between equally unimportant and extremely unimportant (Wu, 2007). Therefore, when the importance/unimportance of one of the PTSs factor to another factor in the same level was given, then the importance/unimportance of the second factor to the first factor was recognised. For example, if the importance of A to B was given as 1 (i.e. Equally important) then the importance of B to A was recognised as the same (i.e. Equally important).

Table 5.1: The ratio scale for the pairwise comparison

Attribute's relative importance	Linguistic Explanation
1	Equally important
3	Somewhat important
5	Important
7	Very important
9	Extremely important
2, 4, 6, 8	Intermediate values of importance between the two adjacent judgements

Attribute's relative unimportance	Linguistic Explanation
1	Equally unimportant
1/3	Somewhat unimportant
1/5	Unimportant
1/7	Very unimportant
1/9	Extremely unimportant
1/2, 1/4, 1/6, 1/8	Intermediate values of unimportance between the two adjacent judgements

To determine the priorities, a pairwise comparison matrix had to be constructed (i.e. Equation 5.1). Therefore, an *n* x *n* matrix was constructed to represent the judgement on pairs of PTSs criteria (*Ci* and *Cj).* Equation 5.1 shows an *n* x *n* matrix C as follows:

$$C = (c_{ij}) = \begin{bmatrix} 1 & c_{12} & \cdots & c_{1n} \\ {}^{c}\!/_{c_{12}} & 1 & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ {}^{1}\!/_{c_{1n}} & {}^{1}\!/_{c_{2n}} & \cdots & 1 \end{bmatrix} \qquad 5.1$$

where i, j = 1, 2, 3, …, n and each c_{ij} represents the relative importance of criteria Ci to criteria Cj.

For a matrix of order n, ($n(n-1)/2$), comparisons are required. According to Pam (2010), the weight indicates the importance of each element in the pairwise comparison matrix in terms of its overall contribution to the decision-making process. The weight value of each factor within PTSs was calculated using the following equation (Saaty, 1990):

$$W_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{j=1}^{n} a_{ij}}\right) \qquad (k = 1, 2, 3, \dots, n) \qquad 5.2$$

where a_{ij} stands for the entry of row i and column j in a comparison matrix of order n.

In this research, a group of decision makers presented their judgement. Therefore, an averaging technique was required to combine all the experts' judgements. The arithmetic mean takes the sum of the data, and then divides the sum by the total number of values in the set. The arithmetic mean can be calculated by using the following equation:

$$A(n) = \frac{\sum_{j=1}^{n} a_i}{n} \qquad 5.3$$

To ensure the consistency of the judgement comparison, the obtained weight in the pairwise comparison matrix had to be checked by using a Consistency Ratio (*CR*). The *CR* was calculated by using the following equations (Saaty, 1990):

$$CR = \frac{CI}{RI} \qquad 5.4$$

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \qquad 5.5$$

where n is the number of items being compared, λ_{max} represents the maximum weight value of the $n \times n$ comparison matrix, RI is the average random index (see Table 5.2), and CI represents the consistency index.

Table 5.2: Random Index (RI) values (Saaty, 2013)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

The CR was designed in such a way that a value had to be in an acceptable range. Therefore, if the CR was 0.10 or less ($CR \leq 0.10$), the consistency of the pairwise comparisons was considered reasonable. However, if the CR was greater than 0.10 ($CR > 0.10$), the pairwise comparison was considered unreasonable (inconsistency) (Saaty, 1980).

5.4.3 Step III: Applying Established Fuzzy Rule-Based Bayesian Reasoning to Measure the Internal Operational Risks

After the identification process (i.e. step 1), a hybrid technique known as Fuzzy Rule-Based Bayesian Reasoning (FRBBR) was used to analyse the identified hazards of petroleum ports and petroleum transportation modes. This technique defined and evaluated the Failure Modes and Effects Analysis (FMEA) parameters (i.e. occurrence probability of a risk event during the process of oil transportation (P_l), consequence severity that the risk event causes when it occurs (S_c), and probability that the risk event cannot be detected before it occurs (D_p)) by using a Fuzzy Rule Based (FRB) approach with a belief structure. Furthermore, the relevant rules of a failure were aggregated by using a Bayesian Network (BN) mechanism. The steps of this technique are explained in depth in Section 4.4.

5.4.4 Step IV: Applying the Evidential Reasoning Approach to Aggregate the Assessment Risks

ER was developed in 1976 by Shafer (1976) from the approach introduced by Dempster. The theory, which is also known as the Dempster–Shafer theory of evidence, is used to aggregate criteria starting from the lowest level criteria that are related to the criteria in the upper level.

To simplify the explanation of the aggregation process of ER, suppose the hierarchical structure of a PTS consists of two levels. The operational risk R is the first level in the hierarchy (i.e. general attribute). R is associated with two hazards in the second level (i.e. sub-criteria), which are given by R_1 and R_2.

R is identified by aggregating the hazards (i.e. criteria) in level two. Each R_1 and R_2 is defined by five risk expressions (i.e. Very High, High, Medium, Low, and Very Low), which are associated with the belief degree. As a result R, R_1, and R_2 are expressed as follows (Yang and Xu, 2002):

$$R = \{(\beta^1 \text{"}Very\ High\text{"}), (\beta^2 \text{"}High\text{"}), (\beta^3 \text{"}Medium\text{"}), (\beta^4 \text{"}Low\text{"}), (\beta^5 \text{"}Very\ Low\text{"})\}$$

$$R_1 = \left\{(\beta_1^1 \text{"}Very\ High\text{"}), (\beta_1^2 \text{"}High\text{"}), (\beta_1^3 \text{"}Medium\text{"}), (\beta_1^4 \text{"}Low\text{"}), \left(\beta_1^5 \text{"}Very\ Low\text{"}\right)\right\}$$

$$R_2 = \left\{(\beta_2^1 \text{"}Very\ High\text{"}), (\beta_2^2 \text{"}High\text{"}), (\beta_2^3 \text{"}Medium\text{"}), (\beta_2^4 \text{"}Low\text{"}), \left(\beta_2^5 \text{"}Very\ Low\text{"}\right)\right\}$$

w_1 and w_2 are the associated weights of R_1 and R_2 respectively. The weights of R_1 and R_2 were established by using the AHP technique (i.e. step 2), where the sum of w_1 and w_2 is equal to 1 (w_1 + w_2 =1). Suppose the individual degree for each of the five risk parameters (Very High, High, Medium, Low, Very Low) is identified as D_n^h, where *h* is the risk expression and *n* is the assigned criterion. Therefore, the individual degrees for each of R_1 and R_2 are identified as follows (Yang and Xu, 2002; Riahi *et al.*, 2012):

$$D_1^h = w_1\beta_1^h$$

$$D_2^h = w_2\beta_2^h \qquad 5.6$$

$$(h = 1, \ldots, 5)$$

Suppose H_n represents the remaining belief values that are unassigned for D_n^h. Therefore, the individual remaining belief values for both H_1 and H_2 are identified as follows (Yang, 2001):

$$H_1 = \overline{H}_1 + \widetilde{H}_1$$

$$H_2 = \overline{H}_2 + \widetilde{H}_2 \qquad 5.7$$

where $\overline{H}_n$ (n = 1 or 2) represents the degree to which the other assessor can play a role in the assessment. However, $\widetilde{H}_n$ (n = 1 or 2) is caused by the possible incompleteness in the subsets R_1 and R_2. To identify the value of $\overline{H}_n$ (n = 1 or 2) and $\widetilde{H}_n$ (n = 1 or 2), they are calculated as follows (Yang and Xu, 2002; Riahi *et al.*, 2012):

$$\overline{H}_1 = 1 - w_1 = w_2$$

$$\overline{H}_2 = 1 - w_2 = w_1$$

$$\widetilde{H}_1 = w_1\left(1 - \sum_{h=1}^{5} \beta_1^h\right)$$

$$\widetilde{H}_2 = w_2\left(1 - \sum_{h=1}^{5} \beta_2^h\right) \qquad 5.8$$

Suppose the non-normalised degree to which the risk assessment is confirmed for each of the five risk expressions as a result of the synthesis of the judgements produced by assessors 1 and 2 is presented by $\beta^{\grave{h}}(h = 1, \ldots, 5)$. On the other hand, the non-normalised remaining belief unassigned after the commitment of belief to the five risk expressions because of the synthesis of the judgements produced by assessors 1 and 2 is presented by $\grave{H}_U$. Therefore, the ER is calculated as follows (Yang and Xu, 2002):

$$\beta^{\grave{h}} = K\left(D_1^h D_2^h + D_1^h H_2 + D_2^h H_1\right)$$

$$\bar{H}_{\acute{U}} = K(\bar{H}_1 \bar{H}_2)$$

$$\tilde{H}_{\acute{U}} = K(\tilde{H}_1 \tilde{H}_2 + \tilde{H}_1 \bar{H}_1 + \tilde{H}_2 \bar{H}_1)$$

$$K = \left[1 - \sum_{T=1}^{5} \sum_{\substack{R=1 \\ R \neq T}}^{5} M_1^T M_2^R\right]^{-1} \qquad 5.9$$

Finally, by assigning $\bar{H}_{\acute{U}}$ to the five linguistic risk terms, the combined belief degree could be generated by using the normalisation process, which could be calculated as follows (Yang and Xu, 2002):

$$\beta^h = \frac{\beta^{\grave{h}}}{(1 - \bar{H}_{\acute{U}})} \qquad (h = 1, \dots, 5)$$

$$H_U = \frac{\tilde{H}_{\acute{U}}}{(1 - \bar{H}_{\acute{U}})} \qquad 5.10$$

where H_U is the unassigned degree of belief for any individual assessment after all the *R* subsets have been assessed. It represents the extent of incompleteness in the overall assessment. The above explanation was for the aggregation process of two sub-criteria. However, if there were three sub-criteria, any two of the three criteria were combined, and the result of this combination was synthesised with the last sub-criteria by using the above process (Riahi *et al.*, 2012).

5.4.5 Step V: Applying Network Analysis Technique to Determine the Weight of the Ports and Transportation Modes within the Petroleum Transportation Network

A network is a representation of a system (Benzi and Klymko, 2013). PTNs consist of ports connected by transportation modes (i.e. nodes and links). To identify the safety of the transportation system within the petroleum supply chain, the weight of each port and transportation mode was considered. Therefore, centrality measures were applied to identify the weight of the ports and transportation modes within PTNs. The weighting process contained real data provided from trusted sources. Section 3.5 explained in depth the weighting process for the safety of the petroleum ports within the transportation system.

5.4.6 Step VI: Aggregation of Internal and External Analysis through Evidential Reasoning Approach

The ER approach was applied in this step to aggregate the internal and external evaluation of the transportation system (i.e. port and transportation modes). The internal evaluation step was performed by applying ER to aggregate the internal evaluation of the port and each transportation mode (step 4). The external evaluation step was performed by applying the centrality measure (step 5) to identify the safety of the petroleum ports and transportation modes within PTNs. Therefore, with the application of ER, the evaluated values of steps 4 and 5 were aggregated to evaluate the safety of petroleum transportation as a complete system. The steps of the ER aggregation process were briefly explained in step 4.

5.4.7 Step VII: Obtaining a Crisp Number for the Petroleum Transportation Network by using a Utility Approach

Presenting the results of the aggregation process in one single value is more useful for decision makers. Therefore, in this step the results of step 6 were presented in one value rather than in the formation of five linguistic variables (i.e. Very High, High, Medium, Low, and Very Low). To accomplish this, a utility values approach (U_{Rh}) developed by Yang (2001) was used. Consequently, the output belief degree of PTNs was synthesised in one single value as follows:

$$R_{PTN} = \sum_{h=1}^{5} \text{Ƥ}(\beta_h)\, U_{Rh} \qquad 5.14$$

where P(β_h) is the assigned belief degree for each linguistic term within the PTNs. U_R = (1,2,3,4,5), and U_{Rh} = (0,0.25,0.5,0.75,1). R_{PTN} is the utility of the evaluated network. The higher the R_{PTN} value is, the more significant the level of risk of the PTN.

5.4.8 Step VIII: Sensitivity Analysis

Sensitivity analysis is a powerful validation tool that has been widely used to analyse the sensitivity of a model through performing a series of tests (Riahi *et al.*, 2012; Alyami *et al.*, 2014; John *et al.*, 2014a). This partially validation technique is explained at greater depth in Section 4.4.6. For the purpose of this study, two axioms were used to partially validate the model. These two axioms are listed as follows (Yang, *et al.*, 2009b):

Axiom 1: A slight increase or decrease in the belief degree of any of the linguistic variables associated with the system hazards impacts the system with an increase or decrease in its belief degree.

Axiom 2: If any increase or decrease occurs to any of the system hazards, input data (i.e. belief degree) should impact the system overall output average.

5.5 Case Study and Results Analysis

A case study was conducted in this chapter to evaluate the safety of PTNs. This assessment determined the safety of the local transportation system for one of the world’s major petroleum producers. The system contains four petroleum ports and two transportation modes (i.e. ship transportation and pipeline transportation). For the evaluation process, the petroleum ports’ operational hazards (see Figure 4.4) were selected as an example to present the complexity of evaluating petroleum transportation as a complete system.

5.5.1 Hazard Hierarchy Development

According to Sii *et al.* (2001), all the hazards that may lead to a major accident that are associated with a particular system should be managed and reduced to a low level to ensure the safety of the system. Therefore, in the first step, all the hazards associated with PTSs were identified through conducting an extensive literature review.

The operational port, ship, and pipeline transportation hazards were then discussed with experts, and each criterion was validated by an expert in a relevant field to ensure the efficiency of the model. The expert participants in this study are involved in the operation practices of petroleum transportation in several leading companies. The experts were able to add or recommend dropping any of the hazard events based on their previous experience. After discussions with the selected experts in several meetings in 2015 and 2016, the PTN hazards were identified through a combination of the literature review and experts’ suggestions (see Figures 5.3, 4.4, 4.5, and 4.6). To present the evaluation process in this case study, a petroleum port operation evaluation was carried out as an example.

5.5.2 Application of Analytical Hierarchy Process

In this step, the weight of the hierarchical criteria was identified by applying the AHP technique. The experts played a role in implementing the pairwise comparison technique by analysing the importance of each criterion through considering the pairwise comparison ratio scale (see Table 5.1).

For the criteria to be evaluated and for comparisons to be drawn, three questionnaires were designed and sent to twenty-seven experts (nine from each operational sector). The first questionnaire was for evaluating the port criteria. It was sent to experts in the port operation sector. The second was for evaluating the ship criteria and was sent to ship captains. The final questionnaire was for evaluating the pipeline criteria and was sent to experts in the pipeline operation sector.

Each questionnaire was constructed in four sections. The first section asked about the experts' personal information. The questions involved in this part were asked in order to identify the experts' experience, academic knowledge, and industrial background. The second section presented the ratio scale. Each comparison in the fourth section was answered using this ratio scale; the experts responded based on their knowledge of similar past events. An example of how to fill in the questionnaire was included in every questionnaire (i.e. section three), so each expert had a clear understanding of the measurement used in this study. The fourth section of the questionnaire contained several parts, each part referring to one of the hierarchical levels (see Figures 4.4, 4.5, and 4.6). Each part of this section contained a matrix to be filled out by each expert.

Once completed, the researcher collected the questionnaires in order to calculate and analyse the data received from the experts.

All participants in all three sectors are experts with long experience in port, ship, and pipeline operations in the involved systems in this case study. All participants are still actively working in and holding different managerial positions at these systems. For more detail on the criteria for selecting these experts, see Chapter 4.

After receiving the completed questionnaires from all the participants, the hierarchy criteria were weighted by applying the AHP technique. To demonstrate the calculation process of this step, a 3×3 pairwise comparison matrix was developed to obtain the weight of the Machine Related Hazards (MRH), Human Related Hazards (HRH) and Nature Related Hazard (NRH) criteria as a sample of the calculation process. P$(M_{RH}H_{RH}N_{RH})$ is a pairwise comparison matrix expressing qualified judgement with regard to the relative priority of MRH, HRH and NRH (Table 5.3). Therefore, firstly a 3×3 pairwise comparison matrix had to be formed, as follows:

Table 5.3: Pairwise comparison matrix for the main criteria

P $(M_{RH}H_{RH}N_{RH}) =$

	HRH	MRH	NRH
HRH	1.0000	2.4495	6.0701
MRH	0.4082	1.0000	3.2187
NRH	0.1647	0.3107	1.0000
SUM	1.5730	3.7602	10.2888

Before calculating the weight of each criterion, the performance ratio rate of P$(M_{RH}H_{RH}N_{RH})$ is calculated as shown in Table 5.4.

Table 5.4: The performance ratio of each criterion

HRH	$1 \div 1.5730 = 0.6357$	$2.4495 \div 3.7602 = 0.6514$	$6.0701 \div 10.2888 = 0.59$
MRH	$0.4082 \div 1.5730 = 0.2595$	$1 \div 3.7602 = 0.2659$	$3.2187 \div 10.2888 = 0.3128$
NRH	$0.1647 \div 1.5730 = 0.1047$	$0.3107 \div 3.7602 = 0.0826$	$1 \div 10.2888 = 0.0972$

Secondly, the weighting of each criterion is calculated by Equation 5.2, as follows:

$$W_{HRH} = \frac{0.6357 + 0.6514 + 0.59}{3} = 0.6257$$

Similarly, the weights of each criterion are shown in Table 5.5 as follows:

Table 5.5: The weight value of each criterion

				Weight value
HRH	0.6357	0.6514	0.5900	0.6257
MRH	0.2595	0.2659	0.3128	0.2794
NRH	0.1047	0.0826	0.0972	0.0948

After calculating the weight of each criterion, the experts judgment consistency was identified by using Equation 5.4. To find the Consistency Ratio (CR), the CI and λ_{max} had to be identified by using Equations 5.4 and 5.5. Therefore, the CR is calculated as follows:

To calculate λ_{max}, firstly each value in the 3×3 pairwise comparison matrix (i.e. Table 5.3) was multiplied by the weight (i.e. Table 5.5) as follows:

$$0.6257 \begin{array}{|c|}\hline \text{HRH} \\ \hline 1.0000 \\ \hline 0.4082 \\ \hline 0.1647 \\ \hline \end{array} + 0.2794 \begin{array}{|c|}\hline \text{MRH} \\ \hline 2.4495 \\ \hline 1.0000 \\ \hline 0.3107 \\ \hline \end{array} + 0.0948 \begin{array}{|c|}\hline \text{NRH} \\ \hline 6.0701 \\ \hline 3.2187 \\ \hline 1.0000 \\ \hline \end{array}$$

The results of these calculations are summarised in Table 5.6.

Table 5.6: The calculation results

				Total
HRH	0.6257	0.6845	0.5757	1.8859
MRH	0.2554	0.2794	0.3053	0.8402
NRH	0.1031	0.0868	0.0948	0.2847

By using Equation 5.5, the $\lambda_{max}$is calculated as follows:

$$\lambda_{max} = \frac{\frac{1.8859}{0.6257} + \frac{0.8402}{0.2794} + \frac{0.2847}{0.0948}}{3} = \frac{9.0228}{3} = 3.0076$$

Next CI was calculated by using Equation 5.4 as follows:

$$CI = \frac{3.0076 - 3}{3 - 1} = 0.0038$$

Based on the Random Index (RI) values table (i.e. Table 5.2), RI = 0.52. Therefore, CR is identified by using Equation 5.4 as follows:

$$CR = \frac{0.0038}{0.52} = 0.0073$$

The same technique could be applied to calculate the weight of each criterion. For an easier and faster way to perform this calculation, a computer software tool (i.e. AHP calc. version 12.08.13) was used to analyse the weight of the hierarchy criteria. As a result, the weight values of the model are shown in Table 5.7 and Appendix 3.39 - 3.45 as follows:

Table 5.7: Weight of port operation criteria in each level

Level 1	Weight	Level 2	Weight	Level 3	Weight	Level 4	Weight
MRH	0.2794	MRHD	0.1628	MRHDA	0.6772		
				MRHDB	0.3228		
		MRHC	0.1894	MRHCA	0.2067		

				MRHCB	0.218		
				MRHCC	0.1789		
				MRHCD	0.1632		
				MRHCE	0.1121		
				MRHCF	0.1219	MRHCFA	0.4709
						MRHCFB	0.2518
						MRHCFC	0.2773
		MRHB	0.2759	MRHBA	0.4121		
				MRHBB	0.2784		
				MRHBC	0.1999		
				MRHBD	0.1096		
		MRHA	0.3718	MRHAA	0.3719		
				MRHAB	0.2854		
				MRHAC	0.3427		
NRH	0.0948	NRHA	0.3121	NRHAA	0.4882		
				NRHAB	0.3561		
				NRHAC	0.1557		
		NRHB	0.3848	NRHBA	0.5039		
				NRHBC	0.2219		
				NRHBB	0.2742		
		NRHC	0.3031	NRHCA	0.7691		
				NRHCB	0.2309		
HRH	0.6257	HRHA	0.5635	HRHAA	0.6101	HRHAAA	0.4154
						HRHAAB	0.3134
						HRHAAC	0.2712
				HRHAB	0.3899		
		HRHB	0.4365	HRHBA	0.5794	HRHBAA	0.3798
						HRHBAB	0.2929
						HRHBAC	0.14
						HRHBAD	0.1874
				HRHBB	0.4206	HRHBBA	0.1846
						HRHBBB	0.0853
						HRHBBC	0.0819
						HRHBBD	0.0932

						HRHBBE	0.0896
						HRHBBF	0.1417
						HRHBBG	0.0935
						HRHBBH	0.2015
						HRHBBI	0.0287

5.5.3 Application of Fuzzy Rule-Based Bayesian Reasoning

This step utilises steps 2, 3, and 4, which were established in Section 4.4. Three questionnaires were constructed, one each for port, ship, and pipeline operator. The questionnaires were then given to experts in these fields (i.e. twelve experts for port transportation systems and six experts for ship and pipeline transportation systems), with the aim of collecting the failure information from the experts' evaluation of hazards in PTSs.

For the evaluation process of this case study, twelve selected experts (three from each port) evaluated the operational hazards within the four petroleum ports by using the linguistic variables described in Tables 4.1, 4.2, and 4.3. Based on the experts' knowledge of similar past events, the experts provided an appropriate answer for the attributes (i.e. the occurrence probability of a risk event during the process of oil transport (P_l), consequence severity that the risk event causes when it occurs (S_c), and probability that the risk event cannot be detected before it occurs (D_p)) of each hazard through using the proportion technique in order to evaluate the petroleum ports.

Based on expert evaluation, the degree of belief for occurrence probability of a risk event during the process of oil transport (P_l), consequence severity that the risk event causes when it occurs (S_c), and probability that the risk event cannot be detected before it occurs (D_p) of port B hazards was identified and presented in Table 5.8 (for other ports, ships and pipelines belief degrees, see Appendixes 3.1-3.29).

Table 5.8: Prior probability of P_l, S_c and D_P for petroleum port B hazards

	Hs	Degree of Belief (VH, H, M, L, VL)		
		Likelihood	**Consequences**	**Probability**
H1	MRHAA	10, 12.5, 20.8333, 35, 21.6667	11.6667, 14.1667, 25.8333, 29.1667, 19.1667	3.8333, 17.5, 25.3333, 27.5, 25.8333
H2	MRHAB	10.8333, 20.8333, 28.3333, 27.5, 12.5	12.5, 15.8333, 36.6667, 21.6667, 13.3333,	10, 22.5, 28.3333, 20.8333, 20.8333, 18.3333
H3	MRHAC	9.1667, 19.1667, 23.3333, 34.1667, 14.1667	11.6667, 21.6667, 30.8333, 20.8333, 15	10, 19.1667, 28.3333, 31.6667, 10.8333
H4	MRHBA	10, 30.8333, 23.3333, 27.5, 8.3333	11.6667, 12.5, 27.5, 35.8333, 12.5	10, 19.1667, 22.5, 37.5, 10.8333
H5	MRHBB	11.6667, 17.5, 30.8333, 31.6667, 8.3333	10.8333, 20.8333, 28.3333, 29.1667, 10.8333	10.83333, 12.5, 35, 31.6667, 10
H6	MRHBC	9.1667, 10.8333, 28.3333, 30, 21.6667	10.8333, 11.6667, 28.3333, 35.8333, 13.3333	11.6667, 15, 35.8333, 25.8333, 11.6667
H7	MRHBD	13.3333, 18.3333, 27.5, 29.1667, 11.6667	13.3333, 18.3333, 30, 21.6667, 16.6667	11.6667, 10.8333, 28.3333, 38.3333, 10.8333
H8	MRHCA	11.6667, 20, 25, 35, 8.3333	13.3333, 15, 30, 25.8333, 15.8333	9.1667, 10.8333, 37.5, 30, 12.5
H9	MRHCB	10.83333, 18.3333, 22.5, 36.6667, 11.6667	12.5, 20, 26.6667, 25.8333, 15	12.5, 19.1667, 28.3333, 30.8333, 9.1667
H10	MRHCC	11.6667, 10.8333, 29.1667, 36.6667, 11.6667	12.5, 19.1667, 29.1667, 23.3333, 15.8333	14.1667, 17.5, 29.1667, 28.3333, 10.8333
H11	MRHCD	10.83333, 17.5, 30.8333, 30, 10.8333	5, 15.8333, 30.8333, 28.3333, 20	10.8333, 11.6667, 28.3333, 39.1667, 10
H12	MRHCE	11.6667, 10.8333, 28.3333, 37.5, 11.6667	11.6667, 18.3333, 28.3333, 29.1667, 12.5	11.6667, 18.3333, 30.8333, 29.1667, 10
H13	MRHCFA	25.8333, 30.83333, 23.3333, 19.1667, 0.8333	10.8333, 19.1667, 29.1667, 30.8333, 10	10, 10.8333, 29.1667, 39.1667, 10.8333
H14	MRHCFB	17.5, 28.3333, 22.5, 20.8333, 10.8333	10, 27.5, 23.3333, 29.1667, 10	10.8333, 19.1667, 29.1667, 28.3333, 12.5
H15	MRHCFC	16.6667, 22.5, 28.3333, 21.6667, 10.8333	11.6667, 18.3333, 30.8333, 29.1667, 10	10.8333, 19.1667, 23.3333, 36.6667, 10
H16	MRHDA	10.8333, 14.1667, 20, 21.6667, 33.3333	30, 29.1667, 19.1667, 11.6667, 10	34.1667, 35.8333, 15.8333, 7.5, 6.6667
H17	MRHDB	12.5, 13.3333, 18.3333, 20.83333, 35	28.3333, 30.8333, 21.6667, 10, 9.1667	36.6667, 35.8333, 12.5, 9.1667, 7.5
H18	HRHAAC	13.3333, 20, 21.6667, 24.1667, 20.8333	11.6667, 28.3333, 20, 28.3333, 11.6667	11.6667, 18.333, 30.8333, 27.5, 11.6667
H19	HRHAAB	14.1667, 20.8333, 22.5, 30, 12.5	11.6667, 18.3333, 30.8333, 29.1667, 10	11.6667, 18.3333, 29.1667, 30, 10.8333
H20	HRHAAA	20.8333, 28.3333, 20.83333, 20, 10	11.6667, 28.3333, 23.3333, 28.3333, 8.3333	11.6667, 19.1667, 30, 28.3333, 10.8333
H21	HRHAB	13.3333, 18.3333, 28.3333, 30, 10	11.6667, 18.3333, 29.1667, 30, 10.8333	10.8333, 12.5, 36.6667, 29.1667, 10.8333
H22	HRHBAA	26.6667, 28.3333, 20.8333, 19.1667, 5	11.6667, 18.3333, 21.6667, 36.6667, 11.6667	14.1667, 15, 34.1667, 26.6667, 10
H23	HRHBAB	3.3333, 3.3333, 25.8333, 37.5, 30	20.8333, 21.6667, 28.3333, 19.1667, 10	24.1667, 30, 20.83333, 19.1667, 5.8333
H24	HRHBAC	6.6667, 8.3333, 20.8333, 35.8333, 28.3333	12.5, 13.3333, 28.3333, 26.6667, 19.1667	11.6667, 18.3333, 23.3333, 28.3333, 18.3333
H25	HRHBAD	14.1667, 15, 27.5, 16.6667, 26.6667	1.6667, 3.3333, 29.1667, 37.5, 28.3333	10.8333, 29.1667, 37.5, 12.5, 10
H26	HRHBBA	29.1667, 30, 20.8333, 17.5, 2.5	11.6667, 18.3333, 30, 29.1667, 10.8333	10.8333, 11.6667, 28.3333, 38.3333, 10.8333
H27	HRHBBB	12.5, 19.1667, 30, 28.3333, 10	37.5, 30, 11.6667, 10.8333, 10	10, 12.5, 35.8333, 30, 11.6667
H28	HRHBBC	13.3333, 18.3333, 28.3333, 29.1667, 10.8333	17.5, 18.3333, 27.5, 28.3333, 8.3333	7.5, 11.6667, 20, 52.5, 8.3333
H29	HRHBBD	11.6667, 12.5, 29.1667, 35.8333, 10.8333	2.5, 5.8333, 19.1667, 22.5, 50	6.3333, 12.8333, 28.3333, 38.3333, 14.1667

H30	HRHBBE	10.8333, 19.1667, 26.6667, 34.1667, 9.1667	20, 26.6667, 28.3333, 13.3333, 11.6667	0, 2.5, 22.5, 41.6667, 33.3333
H31	HRHBBF	13.3333, 18.3333, 29.1667, 28.3333, 10.8333,	10.8333, 18.3333, 49.1667, 12.5, 9.1667	34.1667, 28.3333, 13.3333, 12.5, 11.6667
H32	HRHBBG	5.8333, 13.3333, 19.1667, 26.6667, 35	2.5, 24.1667, 48.3333, 23.3333, 1.6667	20, 20.8333, 29.1667, 26.6667, 3.3333
H33	HRHBBH	10, 10.8333, 20, 45, 14.1667	33.3333, 40, 11.6667, 10.8333, 4.1667	10.8333, 10.83333, 29.1667, 30, 19.1667
H34	HRHBBI	11.6667, 16.6667, 29.1667, 27.5, 15	10.8333, 37.5, 35, 12.5, 4.1667	39.1667, 24.1667, 16.6667, 15.8333, 4.1667
H35	NRHAA	10.8333, 11.6667, 19.1667, 21.6667, 36.6667	3.3333, 9.1667, 24.1667, 30, 33.3333	10.8333, 43.3333, 40, 3.3333, 2.5
H36	NRHAB	0, 1.6667, 4.1667, 15, 79.1667	7.5, 20, 25.8333, 25, 21.6667	9.1667, 41.6667, 40, 5, 4.1667
H37	NRHAC	0, 0, 0, 5, 95	3.3333, 10.8333, 25, 30.8333, 30	9.1667, 41.6667, 38.3333, 5.8333, 5
H38	NRHBA	2.5, 4.1667, 19.1667, 37.5, 36.6667	3.3333, 10.8333, 24.1667, 30, 31.6667	10.8333, 17.5, 29.1667, 35.8333, 6.6667
H39	NRHBC	3.3333, 7.5, 21.6667, 52.5, 15	9.1667, 19.1667, 30.8333, 35, 5.8333	3.3333, 10, 35.8333, 46.6667, 4.1667
H40	NRHBB	0, 0, 0, 10, 90	55.8333, 22.5, 12.5, 5, 4.1667	3.3333, 6.6667, 43.3333, 45, 1.6667
H41	NRHCA	0.5, 0.8333, 2.5, 3.6667, 92.5	58.3333, 26.6667, 10.8333, 2.5, 1.6667	2.5, 4.1667, 45.8333, 44.1667, 3.3333
H42	NRHCB	0.5, 0.8333, 2.5, 4.5 91.6667	59.16667, 25, 10.8333, 3.3333, 1.6667	2.5, 4.1667, 45.8333, 44.1667, 3.3333

To analyse these hazards, various BN models have been developed for aggregating the rules. Therefore, by using HUGIN software, the risk analysis values for all the hazards are identified and presented in the form of belief degree in Table 5.9 (for other ports, ships and pipelines belief degrees, see Appendixes 3.30-3.38).

Table 5.9: Analysis of petroleum port B hazards by HUGIN software

	Hs	Degree of Belief (VH, H, M, L, VL)				
		VH	H	M	L	VL
H1	MRHAA	0.0850	0.1472	0.2400	0.3056	0.2222
H2	MRHAB	0.1111	0.1972	0.3111	0.2333	0.1472
H3	MRHAC	0.1028	0.2000	0.2750	0.2889	0.1333
H4	MRHBA	0.1056	0.2083	0.2444	0.3361	0.1056
H5	MRHBB	0.1111	0.1694	0.3139	0.3083	0.0972
H6	MRHBC	0.1056	0.1250	0.3083	0.3056	0.1556
H7	MRHBD	0.1278	0.1583	0.2861	0.2972	0.1306
H8	MRHCA	0.1139	0.1528	0.3083	0.3028	0.1222
H9	MRHCB	0.1194	0.1917	0.2583	0.3111	0.1194
H10	MRHCC	0.1278	0.1583	0.2917	0.2944	0.1278
H11	MRHCD	0.0889	0.1500	0.3000	0.3250	0.1361
H12	MRHCE	0.1167	0.1583	0.2917	0.3194	0.1139
H13	MRHCFA	0.1556	0.2028	0.2722	0.2972	0.0722
H14	MRHCFB	0.1278	0.2500	0.2500	0.2611	0.1111

H15	MRHCFC	0.1306	0.2000	0.2750	0.2917	0.1028
H16	MRHDA	0.2500	0.2639	0.1833	0.1361	0.1667
H17	MRHDB	0.2563	0.2647	0.1743	0.1328	0.1718
H18	HRHAAA	0.1472	0.2528	0.2472	0.2556	0.0972
H19	HRHAAB	0.1250	0.1917	0.2750	0.2972	0.1111
H20	HRHAAC	0.1222	0.2222	0.2417	0.2667	0.1472
H21	HRHAB	0.1194	0.1639	0.3139	0.2972	0.1056
H22	HRHBAA	0.1750	0.2056	0.2556	0.2750	0.0889
H23	HRHBAB	0.1611	0.1833	0.2500	0.2528	0.1528
H24	HRHBAC	0.1028	0.1333	0.2417	0.3028	0.2194
H25	HRHBAD	0.0889	0.1583	0.3139	0.2222	0.2167
H26	HRHBBA	0.1722	0.2000	0.2639	0.2833	0.0806
H27	HRHBBB	0.1944	0.2000	0.2000	0.3083	0.0972
H28	HRHBBC	0.1183	0.1456	0.2833	0.3417	0.1111
H29	HRHBBD	0.0444	0.0917	0.2278	0.3278	0.3083
H30	HRHBBE	0.2250	0.2444	0.2361	0.1806	0.1139
H31	HRHBBF	0.1222	0.1750	0.3250	0.2194	0.1583
H32	HRHBBG	0.1639	0.1944	0.1945	0.3389	0.1083
H33	HRHBBH	0.2056	0.2611	0.2694	0.1861	0.0778
H34	HRHBBI	0.1139	0.1667	0.3222	0.2889	0.1083
H35	NRHAA	0.0833	0.2139	0.2778	0.1833	0.2417
H36	NRHAB	0.0556	0.2111	0.2333	0.1500	0.3500
H37	NRHAC	0.0417	0.1750	0.2111	0.1389	0.4333
H38	NRHBA	0.0556	0.1083	0.2417	0.3444	0.2500
H39	NRHBB	0.1972	0.0972	0.1861	0.2000	0.3194
H40	NRHBC	0.0528	0.1222	0.2944	0.4472	0.0833
H41	NRHCA	0.2044	0.1056	0.1972	0.1678	0.3250
H42	NRHCB	0.2072	0.1000	0.1972	0.1733	0.3222

5.5.4 Aggregation of Risks through Evidential Reasoning Approach

To demonstrate how to aggregate the rules by ER, the Ship/Port Interference (MRHD) failure, which were associated with port B, were examined by aggregating the Procedural Failure hazard (MRHDA) and Collision between Ship and Other Ship/Berth hazard (MRHDB), as follows:

The belief degrees for MRHDA and MRHDB were identified in step 3 as follows:

MRHDA = {(Very High, 0.25), (High, 0.2639), (Medium, 0.1833), (Low, 0.1361), (Very Low, 0.1667)}

MRHDB = {(Very High, 0.2563), (High, 0.2647), (Medium, 0.1743), (Low, 0.1328), (Very Low, 0.1718)}

The weight of these two hazards was identified in step 2 as follows:

w_1= 0.6772, w_2= 0.3228

where $w_1$and $w_2$represent the assigned weight for MRHDA and MRHDB respectively.

By using Equation (5.6), the individual degree values of MRHDA and MRHDB were calculated in Table 5.10 as follows:

Table 5.10: The individual degree values of MRHDA and MRHDB

h1	$D_1^1 = 0.25 \times 0.6772 = 0.1693$	$D_2^1 = 0.2564 \times 0.3228 = 0.0827$
h2	$D_1^2 = 0.2639 \times 0.6772 = 0.1787$	$D_2^2 = 0.2647 \times 0.3228 = 0.0854$
h3	$D_1^3 = 0.1833 \times 0.6772 = 0.1242$	$D_2^3 = 0.1743 \times 0.3228 = 0.0563$
h4	$D_1^4 = 0.1361 \times 0.6772 = 0.0922$	$D_2^4 = 0.1328 \times 0.3228 = 0.0429$
h5	$D_1^5 = 0.1667 \times 0.6772 = 0.1129$	$D_2^5 = 0.17181 \times 0.3228 = 0.0555$

where $D_1^h$and D_2^hrepresent the assigned degree for MRHDA and MRHDB respectively.

H_1 represents the remaining belief values that are unassigned for D_1^h, and H_2 represents the remaining belief values that are unassigned for D_2^h. The individual remaining belief values for both H_1 and H_2 were identified by Equation 5.7 as follows:

$$H_1 = \overline{H}_1 + \widetilde{H}_1$$

$$H_2 = \overline{H}_2 + \widetilde{H}_2$$

By using Equation 5.8, $\overline{H}_1, \overline{H}_2, \widetilde{H}_1$and $\widetilde{H}_2$ were calculated as follows:

$$\overline{H}_1 = 1 - w_1 = 1 - 0.6772 = 0.3228$$

$$\overline{H}_2 = 1 - w_2 = 1 - 0.3228 = 0.6772$$

$$\widetilde{H}_1 = w_1\left(1 - \sum_{h=1}^{5} \beta_1^h\right) = 0.6772 \times \big(1 - (0.25 + 0.2639 + 0.1833 + 0.1361 + 0.1667)\big) = 0$$

$$\widetilde{H}_2 = w_2\left(1 - \sum_{h=1}^{5} \beta_2^h\right) = 0.3228 \times \big(1 - (0.2564 + 0.2647 + 0.1743 + 0.1328 + 0.1718)\big) = 0$$

Therefore, both H_1 and H_2 were identified as follows:

$$H_1 = \overline{H}_1 + \widetilde{H}_1 = 0.3228 + 0 = 0.3228$$

$$H_2 = \overline{H}_2 + \widetilde{H}_2 = 0.6772 + 0 = 0.6772$$

Before using Equation 5.10 to find β^h, Equation 5.9 was used to calculate $\beta^{\grave{h}}, \overline{H}_{\acute{U}}, \widetilde{H}_{\acute{U}}, K$ as follows:

Firstly, K was calculated as follows:

$$K = \left[1 - \sum_{T=1}^{5} \sum_{\substack{R=1 \\ R \neq T}}^{5} M_1^T M_2^R\right]^{-1} =$$

$$K = \left[\begin{array}{cccccc} & - + & D_1^1 D_2^2 + & D_1^1 D_2^3 + & D_1^1 D_2^4 + & D_1^1 D_2^5 + \\ & D_1^2 D_2^1 + & - + & D_1^2 D_2^3 + & D_1^2 D_2^4 + & D_1^2 D_2^5 + \\ 1 - & D_1^3 D_2^1 + & D_1^3 D_2^2 + & - + & D_1^3 D_2^4 + & D_1^3 D_2^5 + \\ & D_1^4 D_2^1 + & D_1^4 D_2^2 + & D_1^4 D_2^3 + & - + & D_1^4 D_2^5 + \\ & D_1^5 D_2^1 + & D_1^5 D_2^2 + & D_1^5 D_2^3 + & D_1^5 D_2^4 + & - \end{array}\right]^{-1}$$

$$K = [1 - (\ 0.0406 + 0.0424 + 0.0331 + 0.0258 + 0.0302)]^{-1} = 1.2079$$

$$K = 1.2079$$

Secondly, $\overline{H}_{\acute{U}}$ was calculated as follows:

$$\bar{H}_{\acute{U}} = K(\bar{H}_1\bar{H}_2) = 1.2079(0.3228 \times 0.6772)$$

$$\bar{H}_{\acute{U}} = 0.2640$$

Thirdly, $\tilde{H}_{\acute{U}}$ is calculated as follows:

$$\tilde{H}_{\acute{U}} = K\left(\tilde{H}_1\tilde{H}_2 + \tilde{H}_1\bar{H}_1 + \tilde{H}_2\bar{H}_1\right)$$

$$= 1.2079[(0 \times 0.6772) + (0 \times 0.3228) + (0 \times 0.3228)$$

$$\tilde{H}_{\acute{U}} = 0$$

Then $\beta^{\grave{h}}$ is calculated as follows:

$$\beta^{\grave{1}} = K(D_1^1 D_2^1 + D_1^1 H_2 + D_2^1 H_1)$$

$$= 1.2079[(0.1693 \times 0.0827) + (0.1693 \times 0.6772) + (0.0827 \times 0.3228)]$$

$$= 0.1877$$

$$\beta^{\grave{2}} = K(D_1^2 D_2^2 + D_1^2 H_2 + D_2^2 H_1)$$

$$= 1.2079[(0.1787 \times 0.0854) + (0.1787 \times 0.6772) + (0.0854 \times 0.3228)]$$

$$= 0.1979$$

$$\beta^{\grave{3}} = K(D_1^3 D_2^3 + D_1^3 H_2 + D_2^3 H_1)$$

$$= 1.2079[(0.1242 \times 0.0563) + (0.1242 \times 0.6772) + (0.0563 \times 0.3228)]$$

$$= 0.1319$$

$$\beta^{\grave{4}} = K(D_1^4 D_2^4 + D_1^4 H_2 + D_2^4 H_1)$$

$$= 1.2079[(0.0922 \times 0.0429) + (0.0922 \times 0.6772) + (0.0429 \times 0.3228)]$$

$$= 0.0969$$

$$\beta^{\grave{5}} = K(D_1^5 D_2^5 + D_1^5 H_2 + D_2^5 H_1)$$

$$= 1.2079[(0.1129 \times 0.0555) + (0.1129 \times 0.6772) + (0.0555 \times 0.3228)]$$

$$= 0.1215$$

By applying Equation 5.10 the results of β^{h} are identified as follows:

$$\beta^{1} = \frac{\beta^{\grave{1}}}{(1-\overline{H}_{\acute{U}})} = \frac{0.1877}{(1-0.2640)} = 0.2550$$

$$\beta^{2} = \frac{\beta^{\grave{2}}}{(1-\overline{H}_{\acute{U}})} = \frac{0.1979}{(1-0.2640)} = 0.2690$$

$$\beta^{3} = \frac{\beta^{\grave{3}}}{(1-\overline{H}_{\acute{U}})} = \frac{0.1319}{(1-0.2640)} = 0.1793$$

$$\beta^{4} = \frac{\beta^{\grave{4}}}{(1-\overline{H}_{\acute{U}})} = \frac{0.0969}{(1-0.2640)} = 0.1317$$

$$\beta^{5} = \frac{\beta^{\grave{5}}}{(1-\overline{H}_{\acute{U}})} = \frac{0.1215}{(1-0.2640)} = 0.1651$$

As a result,

MRHD = {(Very High, 0.2550), (High, 0.2690), (Medium, 0.1793), (Low, 0.1317), (Very Low, 0.1651)}

By using the same technique, other criteria were aggregated until the goal was reached. For an easier and faster ER aggregation process, a computer software tool (i.e. IDS software) was used. The degrees of belief for the ports hierarchy criteria are identified in Table 5.11.

Table 5.11: Internal evaluation of the petroleum ports hazards by IDS software

	Ports	Degree of Belief (VH, H, M, L, VL)				
		VH	H	M	L	VL
P1	A	0.1191	0.1801	0.2834	0.2848	0.1326
P2	B	0.1115	0.1788	0.2793	0.2949	0.1353
P3	C	0.1164	0.1931	0.2737	0.2687	0.1481
P4	D	0.1045	0.1651	0.2723	0.2864	0.1717

5.5.5 Application of Network Analysis

This case study evaluated the local network of one of the major petroleum producing countries (for security purposes, the country name and ports and the collected data are not revealed). The local network contains four petroleum seaports. The ports are connected by two transportation modes (i.e. pipeline and ship transportation). These connections were weighted by the network’s throughput value (i.e. million barrel).

The first petroleum seaport is port A. It is located in the east side of the country, and it has two major petroleum terminals: an onshore terminal and an offshore terminal. Port A is counted as a major petroleum seaport for exporting crude oil not only locally but also internationally. The second petroleum seaport is port D, which is located in the west side of the country. Port D is used for importing crude oil for industries consumptions. Port B is the third petroleum seaport. It is located in the northwest area of the country. It is used for importing and exporting crude oil for business purposes, both locally and internationally. The final port is port C, which is located in the west side of the country. Port C is used for importing crude oil for industrial purposes. The four petroleum seaports (i.e. ports A to D) are connected by shipping transportation and/or pipeline transportation systems.

By feeding the collected information into R computer software, the weights of the ports and transportation modes were identified and presented in normalised values in Table 5.12.

Table 5.12: Normalised values of the external evaluation of the local PTN

	Binary	Weight	Normalised Weight
Port A	4	291.688	0.2642
Port B	5	232.104	0.2102
Port C	3	42.035	0.0381
Port D	2	20.59	0.0186
Pipeline A	2	184.069	0.1667
Pipeline B	2	265.098	0.2401
Pipeline C	2	39.035	0.0354
Shipping Route A	2	6	0.0054
Shipping Route B	2	19.59	0.0177
Shipping Route C	2	1	0.0009
Shipping Route D	2	1	0.0009
Shipping Route E	2	2	0.0018

5.5.6 Aggregation of Internal and External Analysis through Evidential Reasoning Approach

Given the weights of the external evaluation and the degrees of belief of the internal evaluation, the aggregation process for the internal and external evaluation was conducted by using Equations 5.6–5.10. The degrees of belief of the internal evaluation and the external evaluation weights, which were determined in steps 4 and 5 respectively, were input into the IDS software for further aggregation in order to reach the result (i.e. to determine the risk level of the PTN). The result of the PTN aggregation is presented in Table 5.13 (see Figure 5.4).

Table 5.13: The degree of belief of the PTN

	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
PTN	0.0919	0.1345	0.2365	0.2681	0.2691

5.5.7 Application of Utility Approach

The main purpose of obtaining an individual crisp number by using the utility value approach was to enable decision makers to evaluate the goal (i.e. PTNs safety). By using Equation 5.14, the utility values of the investigated PTS were identified.

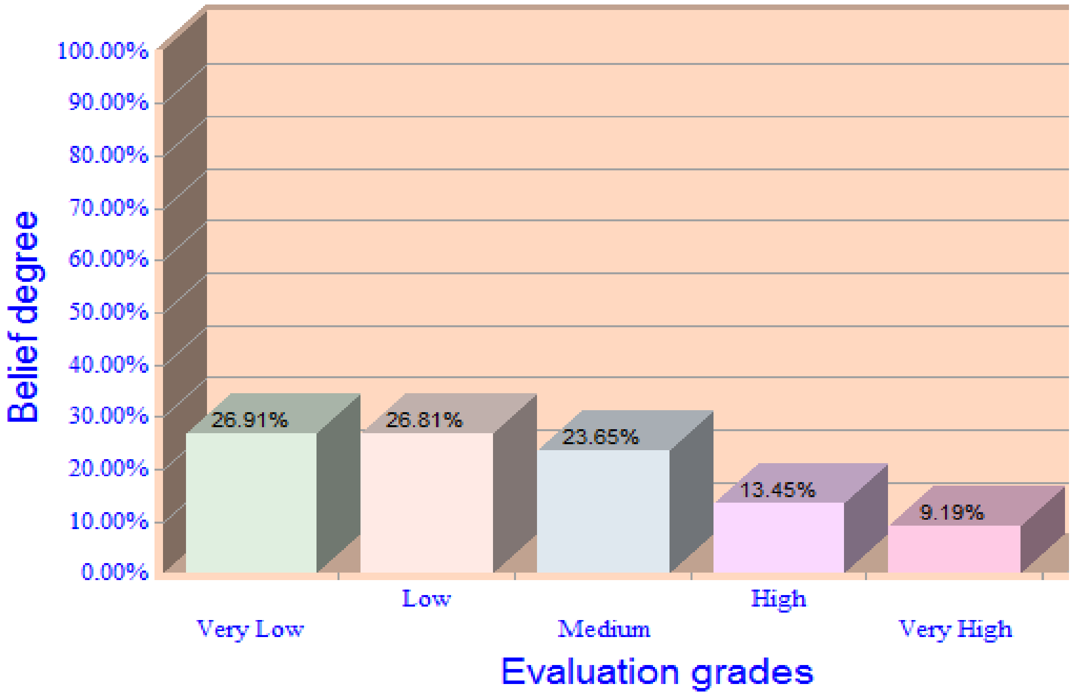

Figure 5.4: The degree of belief of the PTN by IDS software

The risk assessment values of the goal were presented in five linguistic terms (i.e. Very High, High, Medium, Low, and Very Low). To obtain a crisp number for the investigated network, “Very High”, which was the highest-preference linguistic term, was made equal to five. “Very Low”, which was the lowest-preference linguistic term, was made equal to one. As a result, by using IDS software, the utility value of the local PTN is 0.3780 (see Table 5.14).

Table 5.14: The steps for calculating the utility value of PTS

Rh	Very High	High	Medium	Low	Very Low
V_h	5	4	3	2	1
U_{Rh}	$\frac{5-1}{5-1}=1$	$\frac{4-1}{5-1}=0.75$	$\frac{3-1}{5-1}=0.5$	$\frac{2-1}{5-1}=0.25$	$\frac{1-1}{5-1}=0$
$\text{Ƥ}(R_h)$	0.0919	0.1345	0.2365	0.2681	0.2691
$\sum_{h=1}^{5}\text{Ƥ}(R_h)=0.0919+0.1345+0.2365+0.2681+0.2691=1$					
$\text{Ƥ}(R_h)\ U_{Rh}$	0.0919	0.1009	0.1183	0.0670	0
$R_{PTN}=\sum_{h=1}^{5}\text{Ƥ}(\beta_h)\ U_{Rh}=0.3781\approx 0.3780$					

5.5.8 Sensitivity Analysis

To partially validate the developed approach, a sensitivity analysis has been carried out. Two axioms have been used to carry out this partially validation process. As is clear from Table 5.15, the degrees of belief that are associated with the highest-preference linguistic variables of all port B lowest-level criteria (hazards) have decreased by 0.1, 0.2, and 0.3. These decreases led to an increase of all lowest-level criteria by 0.1, 0.2, and 0.3 in their degrees of belief associated with the lowest-preference linguistic variables.

As a result, the increases of the lowest-level criteria, which increased by 0.1, 0.2, and 0.3 respectively, led to a decrease in the upper value (the goal's utility value), as presented in Table 5.15. For instance, the failure probability utility value of the evaluated PTSs has changed due to increasing the hazard Procedural Failure (MRHDA) belief degrees by 0.1, 0.2, and 0.3 respectively. This increasing led to a decreasing in failure probability utility value PTSs from 0.3755 to 0.3713. This highlights that the safety of the PTNs overall system is affected by any of the three systems' hazards events. Figure 5.5 shows the belief degree changes for the lowest-level criteria of the linguistic variables, which decreased by 0.1, 0.2, and 0.3. From Figure 5.5, it is obvious that the model output is sensitive to the changes that occur in it.

Table 5.15: Sensitivity analysis of all lowest-level criteria while decreasing highest preference linguistic variable by 0.1, 0.2, and 0.3

	Hs	The R_{PTN} value of the PTN due to an increase in the degree of belief associated with the lowest-preference linguistic variable of port B's lowest-level criteria		
		0.1	**0.2**	**0.3**
H1	MRHAA	0.3753	0.3729	0.371
H2	MRHAB	0.3761	0.3744	0.3727
H3	MRHAC	0.3757	0.3737	0.3718
H4	MRHBA	0.3758	0.3739	0.3721
H5	MRHBB	0.3768	0.3757	0.3747
H6	MRHBC	0.3772	0.3765	0.3759
H7	MRHBD	0.3776	0.3772	0.3769
H8	MRHCA	0.3774	0.3769	0.3764
H9	MRHCB	0.3774	0.3768	0.3762
H10	MRHCC	0.3775	0.377	0.3766
H11	MRHCD	0.3776	0.3772	0.3768
H12	MRHCE	0.3777	0.3775	0.3772
H13	MRHCFA	0.3779	0.3777	0.3775
H14	MRHCFB	0.378	0.3779	0.3778
H15	MRHCFC	0.378	0.3779	0.3778
H16	MRHDA	0.3755	0.3734	0.3713
H17	MRHDB	0.3774	0.3768	0.3763
H18	CRHAAC	0.3775	0.3771	0.3767
H19	CRHAAB	0.3774	0.3769	0.3764
H20	CRHAAA	0.3771	0.3763	0.3756
H21	CRHAB	0.3771	0.3764	0.3756
H22	CRHBAA	0.3775	0.377	0.3766
H23	CRHBAB	0.3777	0.3774	0.3771
H24	CRHBAC	0.3779	0.3778	0.3777
H25	CRHBAD	0.3778	0.3777	0.3775
H26	CRHBBA	0.3779	0.3778	0.3777
H27	CRHBBB	0.378	0.3779	0.3779
H28	CRHBBC	0.378	0.3779	0.3779
H29	CRHBBD	0.378	0.3779	0.3779
H30	CRHBBE	0.378	0.3779	0.3779
H31	CRHBBF	0.3779	0.3779	0.3778
H32	CRHBBG	0.378	0.3779	0.3779
H33	CRHBBH	0.3779	0.3777	0.3776

H34	CRHBBI	0.378	0.378	0.3779
H35	NRHAA	0.3778	0.3776	0.3774
H36	NRHAB	0.3779	0.3778	0.3777
H37	NRHAC	0.378	0.3779	0.3779
H38	NRHBA	0.3777	0.3775	0.3773
H39	NRHBC	0.3779	0.3778	0.3777
H40	NRHBB	0.3779	0.3779	0.3778
H41	NRHCA	0.3777	0.3773	0.377
H42	NRHCB	0.378	0.3779	0.3779

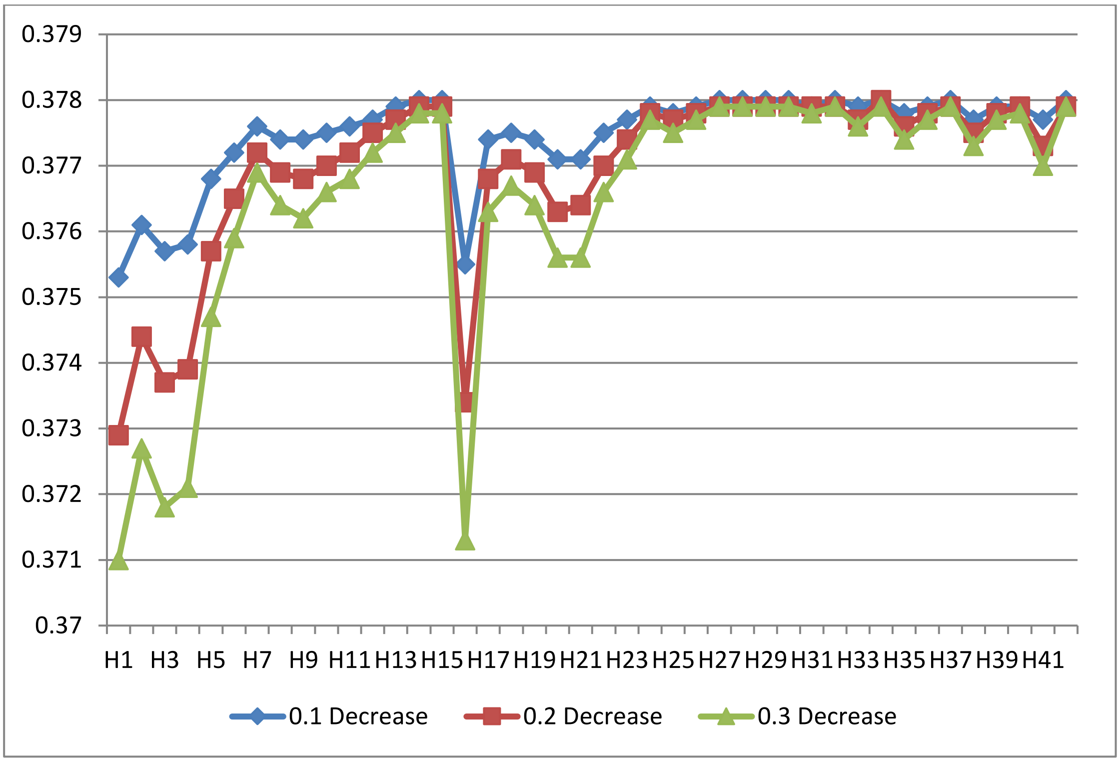

Figure 5.5: Sensitivity analysis output

5.6 Conclusion

To carry out the safety evaluation process for evaluating the risk level of PTNs, this chapter was divided into three sections. The first section introduced the ER and AHP methods. This introduction provided an explanation of these two techniques and how they have been used in previous studies. Furthermore, the introduction explained how to use ER to aggregate relative weights with belief degrees. Chapter 4 explained how to evaluate hazards' degree of belief. A brief review of the computer software (i.e. IDS) was also provided; this review covered how this software was used for the aggregation described in this chapter.

The second section provided a brief explanation of the PTNs evaluation process. This evaluation process included internal evaluation and external evaluation. Firstly, for evaluating the system internally, the evaluation process contained four steps: 1) Identifying the operational hazards within the PTNs. 2) Determining the weight of the hierarchical criteria by using the AHP technique. 3) Applying the established FRBBR to measure the belief degree of the internal operational hazards. 4) Finally, applying the ER approach to aggregate the assessment. Secondly, for evaluating the system externally, the evaluation process contained one step: applying a network analysis technique to determine the weight of the ports and the transportation modes within the PTNs. The ER technique was then used to aggregate both the internal and external evaluation for the PTNs, and the belief degree of this evaluation was presented in a crisp value by using the utility approach. Finally, the model was validated by using sensitivity analysis.

In the final section, a real-life case study was performed on a PTN of one of the major petroleum producing countries. In fact, the model and methodology can be applied in any transportation system, both locally and/or internationally, to evaluate the safety level or the riskiness of the tested PTNs. Within this case study, the petroleum port risk factors are presented as an example in the evaluation process to explain the evaluating steps. Based on the ER aggregation mechanism, the failure probability of the local PTNs was identified as 0.0919, 0.1345, 0.2365, 0.2681, and 0.2691. After performing the utility approach by using IDS software, the utility value of the local PTN was found to be 0.3780. In addition, a brief discussion for Chapter 5 is further presented in Chapter 7.

This chapter has proposed more realistic and flexible results by describing the failure information of the PTNs based on real-life situations. Additionally, the proposed method provides a decision-support system for enhancing the safety practices of the transportation system in general and particularly for the PTS through providing decision-makers with a reliable risk evaluation technique.

Chapter 6: Developing a Risk Based Decision Making Modelling to Enhance Safety in PTSs Operations

In the previous chapters, the hazards associated with petroleum transportation systems (PTSs) were identified. Each of these hazards was individually analysed in order to identify the most significant one in relation to this transportation system. Furthermore, the risk level of PTSs was evaluated after combining the local and global assessment. To enhance the safety of PTSs, the safety level of the most significant hazard needs to be improved. To research this goal, a list of alternatives and criteria was determined. Within this chapter, a VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) technique is introduced in order to rank the risk-control options. With the VIKOR technique, the Analytic Hierarchy Process (AHP) is used to estimate the weight of each criterion.

6.1 Introduction

Since the 19th century, the petroleum industry has become one of the fastest growing businesses. The total volume of petroleum production and movement has increased and is expected to continue increasing in the next years due to the critical role that this natural resource plays in world development (UNCTAD, 2017; OPEC, 2016; IEA, 2017). As a result, the safety operations of Petroleum Transportation Systems (PTSs) are continuously challenged.

As described in the previous chapters, Petroleum Transportation Networks (PTNs) contain two focal points, which are ports and transportation modes. Each hazard within these transportation systems has been evaluated individually in order to identify the most significant hazard that influences the safe operation of PTNs. Furthermore, the transportation system has been evaluated in order to assess the risk level of petroleum transportation as one complete system. To complete the assessment, this chapter aims to investigate the most significant hazard, namely procedural failure during ship/port interference, to determine how to control it in order to enhance the safety level of PTNs.

To investigate the safety control measures of this hazard, a combination of VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method and Analytical Hierarchy Process (AHP) is used (Fouladgar *et al*., 2012). VIKOR is a Multi Criteria Decision Making (MCDM) technique used in this chapter in order to rank the determined options (alternatives) for the decision-maker for mitigating and/or eliminating the hazard. The technique has been applied in different fields due to its simplicity in calculation and the advantages it offers as a decision-making tool due to its mechanism for ranking the system control options, such as in engineering systems (Yazdani-Chamzini *et al*., 2013; Bazzazi *et al.*, 2011), problems (Sanayei *et al.*, 2010; Jahan *et al.*, 2011), management (Rezaie *et al.*, 2014) and finance (Yalcin *et al*., 2012).

This chapter aims to ensure that PTSs operate at an optimal level by offering the best risk-control options. To achieve the objective of this chapter, a brief literature review of VIKOR approach and why the technique is used is firstly introduced in the following section. The third section of the chapter provides step-by-step explanations of the evaluation process. This section identifies the hazard and then outlines the ranking process for the alternatives. A case study is presented in the fourth section to demonstrate the methodology proposed in this chapter. Finally, the conclusion is presented in the final section. The chapter shows overall how this hybrid approach (VIKOR-AHP) can provide a proper method to select a suitable risk-control option.

6.2 VIseKriterijumska Optimizacija I Kompromisno Resenje Background and Review

VIKOR, which is a Serbian term that means multicriteria optimisation and compromise solution, was devised by Opricovic in 1998 and then further developed by Opricovic and Tzeng in 2004 (Tzeng and Huang, 2011; Tzeng *et al.*, 2005; Kaya and Kahraman, 2011). The developed approach is a compromise ranking method that was established to deal with Multi Attribute Decision Making (MADM) problems. Opricovic in 1998 and Opricovic and Tzeng in 2004 developed the VIKOR technique from the basis of the compromise solution created by Yu (1973) and Zeleny (1982), which was in turn developed for distance function from the L_p*-metric* (Opricovic and Tzeng, 2004). VIKOR technique was built around the concept of distance from the Ideal Solution for ranking the alternatives, where the preferred alternative is the one nearest to the ideal solution (Opricovic and Tzeng, 2004; Rezaie *et al.*, 2014; Ebrahimnejad *et al.*, 2012). Unlike other MCDM techniques (e.g. AHP, ELECTRE, TOPSIS), VIKOR formula introduced the ranking index (VIKOR index), which is a collection of all criteria, the relative importance of the criteria, and a balance between total and individual satisfaction, which determines a compromise solution, based on each solution’s distance from the ideal solution (Chu *et al.*, 2007; Tzeng and Huang, 2011). In other words, VIKOR is a decision-making tool that ranks a list of solutions, after taking into account their closeness to the ideal solution. The VIKOR technique has been extensively used because it offers the following advantages (Tzeng and Huang, 2011; Tzeng *et al.*, 2005 Chu *et al.*, 2007; Mir *et al.*, 2016):

- VIKOR presents the criteria and solutions (alternatives) in one clear hierarchal structure.

- VIKOR has a clear, simple, and short calculation process.
- VIKOR takes into consideration the weight of each criterion in the evaluation process.
- The output of VIKOR makes it clear how to rank alternatives to avoid as much risk as possible.
- VIKOR takes into consideration the alternative distances to the ideal solutions in order to rank the alternatives.
- VIKOR has been widely accepted and successfully applied in many different fields.

Due to these advantages, VIKOR has become one of the techniques used in recent years for dealing with multi-attribute decision-making problems.

VIKOR is in the MADM family of techniques. MADM techniques are defined by Yoon and Kim (1989) as “technical decision aids for evaluating alternatives which are characterised by multiple attributes”. Both quantitative and qualitative data are present in MADM problems, especially in the field of engineering (Guo *et al.,* 2009). The VIKOR decision-making technique has been commonly used in engineering and other fields for identifying the best and the worst risk-control options and presenting those options in a ranking order.

VIKOR has nine steps for addressing a multi-attribute decision-making problem:

1. Identifying the hierarchal structure of the MCDM problem. This step includes the identification of the problem and its related criteria and alternatives.
2. Collecting the input data.
3. Developing the VIKOR decision matrix.

4. Normalising the VIKOR decision matrix.
5. Determining the weight of each criterion by using the Analytical Hierarchy Process (AHP) technique.
6. Determining the minimum and maximum criterion function.
7. Determining the utility measure.
8. Determining the regret measure.
9. Determining the maximum and minimum utility and regret measures.
10. Determining the VIKOR index.
11. Ranking all the alternatives in order.

VIKOR technique is a powerful technique which has been extensively used for its capability in dealing with complex systems. It enables selection of the best alternative from several alternatives in a system. VIKOR mechanism provides decision makers with an advanced tool to rank risk-control options. Researchers such as Chu *et al.* (2007) highlighted the advantage of this technique over other multi-attribute decision-making approaches for ranking alternatives (i.e. Simple Additive Weighting (SAW) and Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)). To illustrate VIKOR's superiority, Chu *et al.* (2007) conducted a comparative analysis using these three techniques in order to rank the system alternatives. Liu *et al.* (2012) applied VIKOR approach to prioritise the failures within a medical system after performing a risk evaluation using Failure Modes and Effects Analysis (FMEA). Emovon *et al.* (2015) confirmed the ability of the VIKOR technique to deal with MADM problems in prioritising the risk in marine machinery systems. Liou *et al.* (2011) proposed the VIKOR approach within an airline system to improve the service quality of domestic airlines. The results of this model provided the solution that was closest to the optimum solution as the best alternative for improving the service.

6.3 Risk Mitigation

Risk mitigation is a selecting and implementing process for managing and controlling risks in order to eliminate the frequency of occurrence and minimise the consequences of unwanted hazards (Lassen, 2008). According to MSA (1993), mitigation is one of the major elements that needed to be considered for controlling and improving the safety of systems.

Risk mitigation is defined as a decision-making process that takes place after the assessment phase for taking actions relating to the non-acceptable risks. This process aims to decrease the probability of a failure occurring or to minimise the losses if an accident happens. Usually, Cost-Benefit Analysis (CBA) is combined with this process so decision-makers can reach the best decision.

CBA, which is also known as Benefit-Cost Analysis (BCA), is a widely known method for supporting decisions. According to the Rail Safety and Standards Board Limited (RSSB) (2014), *"Cost-benefit analysis (CBA) weighs the expected costs of one or more options against the expected benefits to support a decision as to which option(s) should be implemented."* In other words, CBA identifies the best benefit-to-cost alternatives for the decision maker. UNCTAD (2006) explained that CBA was first introduced and approved by the International Maritime Organisation (IMO) in Formal Safety Assessment (FSA) in 2001. Later on the technique was approved in agendas such as regulatory assessment of maritime security (UNCTAD, 2006).

Several techniques to manage the risks within a system have been identified and evaluated in earlier chapters. According to Irukwu (1991), all those techniques fall into one or more of the following four categories:

- Avoidance (eliminate, withdraw, or do not become involved).
- Reduction (optimise – mitigate).
- Sharing (transfer – outsource or insure).
- Retention (accept and budget).

In this research, all of the recognised risk factors identified in the literature review and in the discussion meetings with experts were assessed, evaluated, and analysed in Chapters 4 and 5. To complete the cycle of this study, a mitigation process was required to enhance the safety of the system.

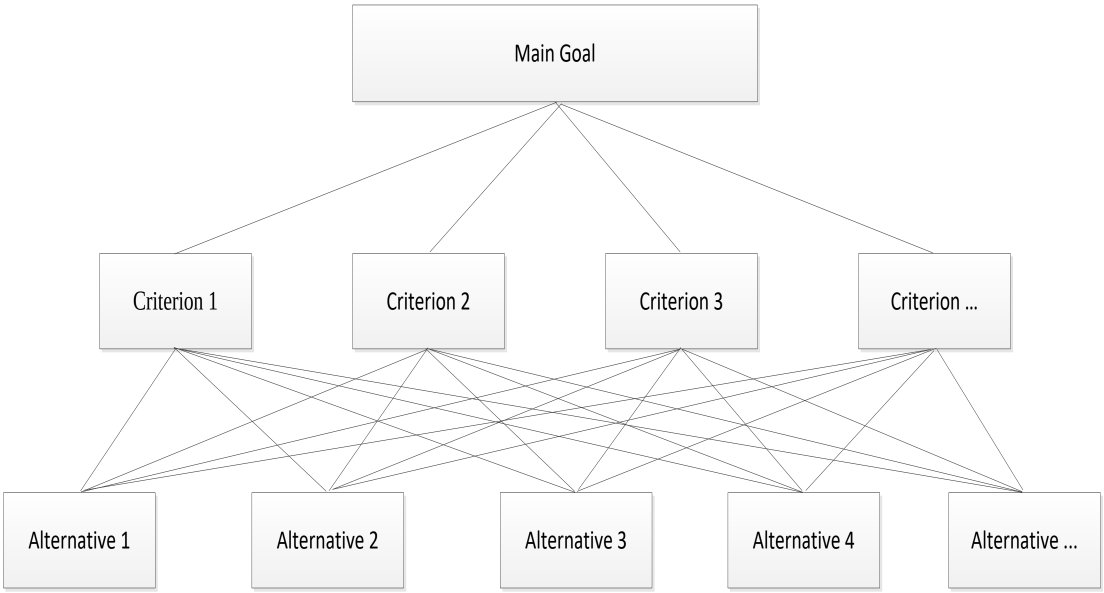

Figure 6.1: The hierarchical structure of the AHP-VIKOR for safety improvement of the hazards

The mitigation process first entailed identifying the most significant hazard that affects the safety of PTSs. Based on this result, different criteria and alternatives were set, and then an appropriate decision-making technique was employed to prioritise these strategic decisions and control the hazard. As explained in Figure 4.3, the PTSs were affected by different sources of risks and uncertainties. These sources were divided into three main categories: port-related hazards, ship-related hazards, and pipeline-related hazards. The lower level hazards (hazards events) in each category were evaluated in an earlier chapter (Chapter 4) to identify the most significant hazard within PTSs. To control this identified hazard for an optimal operation and to improve the safety level within PTNs, it was also necessary to evaluate the risk-control options (alternatives) in light of CBA to identify the best ideal solution for mitigation. Figure 6.1 illustrates a decision hierarchy structured for selection of the best strategies to mitigate the hazards within the PTSs.

6.4 Methodology

For the purposes of this study, the VIKOR technique was used to identify the best solution for controlling the hazards associated with PTSs. The flow chart for the evaluation procedure is presented in Figure 6.2.

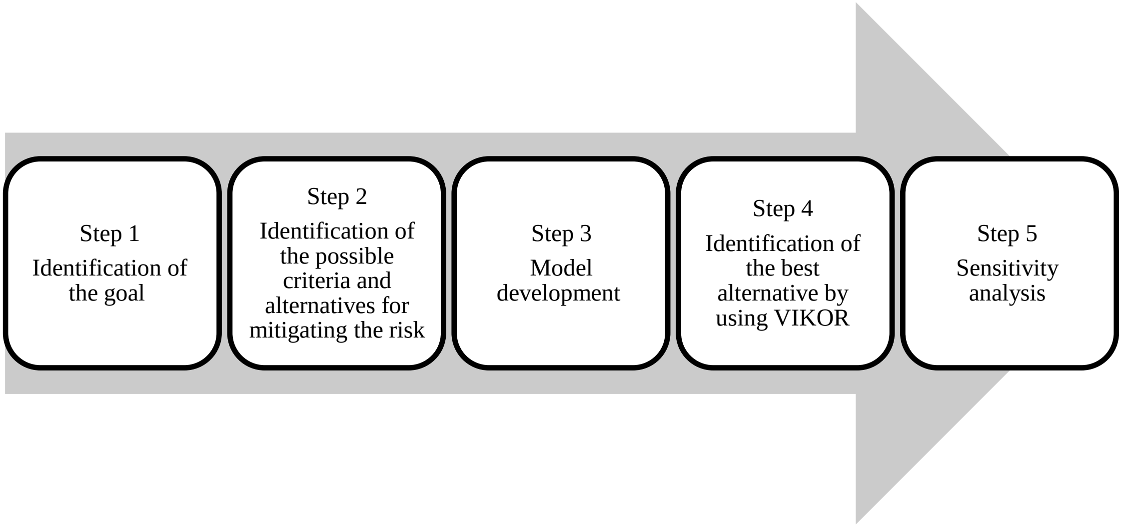

Figure 6.2: The risk-control assessment model flow chart

The evaluation process contained five steps. The procedure began by identifying the most significant hazard affecting the safety of PTSs. It concluded by identifying the best alternative for eliminating and/or mitigating this hazard. Within this process, the AHP technique for determining the weight of the hierarchal criteria was used.

The steps for hazard controlling improvement are listed as follows:

- Identify the system’s most significant hazard.
- Identify the possible criteria and alternatives for mitigating the risk
- Model development
- Identify the best alternative by using VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)
- Sensitivity analysis

6.4.1 Step 1: Identify the Goal

Decision makers need to have a clear understanding of the most significant decision-making problem that affects the safety operation of the PTNs. Through the evaluation process performed in Chapter 3 (i.e. determining the most significant hazards that affect the safe operation of PTSs), the goal of this study was identified. The ultimate goal is to address the problem that has the greatest influence on the safe operation of PTNs. Therefore, to eliminate and/or mitigate that hazard, decision makers first have to identify the criteria and the solution required to ensure the safety of the PTSs.

6.4.2 Step 2: Identification of the Possible Criteria and Alternatives for Mitigating the Risk

To accomplish this step, firstly a set of criteria must be identified and satisfied to fulfil the goal. Secondly, a number of possible alternatives need to be identified for eliminating and/or mitigating the risk. At the end of the evaluation process, these identified alternatives were ranked by considering the collected data. Both the criteria and the alternatives were defined by conducting a brainstorming session and a literature review of previous related studies. The identified criteria and alternatives for the most significant hazard were discussed with operational experts to ensure the efficiency of the presented solutions. As a result, a list of criteria and alternatives for eliminating and/or mitigating the risk was produced (see Table 6.1).

6.4.3 Step 3: Model Development

After setting the goal and defining the criteria and alternatives associated with the goal, a hierarchal structure was built to represent the relationship between these three levels (see Figure 6.1). The purpose of this graphical model was to present a clear picture of how to eliminate and/or mitigate the risk through considering the relationship between each level.

6.4.4 Step 4: Identification of the Best Alternative by using VIKOR

To rank the risk-control options and identify which alternative is the best solution for mitigating the hazards within this system, the VIKOR technique was applied. The final result indicated the best alternative for mitigating the most significant hazard. To achieve the objective of this step, the following sub-steps, namely the steps of VIKOR, were conducted:

6.4.4.1 Step 1: Developing the VIKOR decision matrix

To determine the best alternative for mitigating the risk, firstly a decision matrix had to be constructed (see Equation 6.1). This decision matrix was constructed considering the number of alternatives (A_a), criteria (C_c), and decision-makers (*d*). Equation 6.1 shows the decision matrix:

$$D_d = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_a \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_c \end{array} \\ \begin{bmatrix} n_{11} & n_{21} & \cdots & n_{1c} \\ n_{21} & n_{22} & \cdots & n_{2c} \\ \vdots & \vdots & \vdots & \vdots \\ n_{a1} & n_{a2} & \cdots & n_{ac} \end{bmatrix} \end{array} \qquad ί = 1,2,3,\ldots,a;\ ,j = 1,2,3,\ldots,c \qquad 6.1$$

where *ί*=1,2,3,…,a and *j*=1,2,3,…,c represent the number of alternatives and criteria respectively. Moreover, n_{ac} presents the rate of the alternative A_a with respect to each criterion, which is identified by its average when more than one expert was involved.

6.4.4.2 Step 2: Normalising the VIKOR decision matrix

This step aimed to change the attribute from its original formation (i.e. attribute dimensions) to non-dimensional attributes. This process was achieved by dividing the rating of each attribute n_{ac} by its average. Therefore, the normalised decision matrix N_{ac} was calculated by using the following equation (Opricovic and Tzeng, 2004):

$$N_{ac} = \frac{n_{ac}}{\sqrt{\sum_{i=1}^{a} n_{ac}^{2}}} \qquad ί = 1,2,3,\ldots,a;\ ,j = 1,2,3,\ldots,c \qquad 6.2$$

6.4.4.3 Step 3: Determining the weight of each criterion by using the AHP technique

In this step, all the identified criteria were weighted by using a weighting technique to identify the importance of each criterion compared to another. The AHP approach was applied for weighting the criteria. The process started with a pairwise comparison technique for data collection and then progressed to measuring the consistency, as explained in depth in Section 5.4.2.

6.4.4.4 Step 4: Determining the minimum and maximum criterion function

The maximum function gathers together the maximum rates for all considered criteria (Tzeng and Huang, 2011; Opricovic and Tzeng, 2004). In this study, both the maximum Criterion Function (CF^{+}) and the minimum Criterion Function (CF^{-}) were determined based on the results of step 2 in VIKOR. The following equations (i.e. Equations 6.3 and 6.4) were used to determine the $\mathrm{CF}^{-}$and CF^{+} respectively (Tzeng and Huang, 2011):

$$CF^{+} = [CF_1^{+}, CF_2^{+}, CF_3^{+}, \dots, CF_a^{+}] = \left[\left(max_j CF_{ij} \middle| j \in J\right)\right], \left[\left(min_j CF_{ij} \middle| j \in J'\right)\right] \qquad 6.3$$

$$CF^{-} = [CF_1^{-}, CF_2^{-}, CF_3^{-}, \dots, CF_a^{-}] = \left[\left(min_j CF_{ij} \middle| j \in J\right)\right], \left[\left(max_j CF_{ij} \middle| j \in J'\right)\right] \qquad 6.4$$

where J represents the benefit criteria, and J' represents the cost criteria (Mahmoodzadeh *et al.*, 2007).

6.4.4.5 Step 5: Determining the utility measure

The utility measure was determined after VIKOR steps 2, 3, and 4 were completed (i.e. normalising the decision matrix, identifying the weight of each criterion, and determining the minimum and maximum criterion function). The formula for determining the utility measure (UM_{ac}) for the alternative (a) was calculated as follows (Opricovic and Tzeng, 2004):

$$UM_{ac} = \sum_{j=1}^{c} W_j\left(CF_a^{+} - CF_j\right) / (CF_a^{+} - CF_a^{-})$$

$$i = 1,2,3,\dots,a;\ ,j = 1,2,3,\dots,c \qquad 6.5$$

6.4.4.6 Step 6: Determining the regret measure (RM_{ac})

This step aimed to determine the alternative regret measure. The alternative utility measure identified (i.e. step 5) previously was used to identify the regret measure (RM_{ac}) by applying the following equation (Opricovic and Tzeng, 2004):

$$RM_{ac} = \operatorname*{Max}_{j}\left[W_j\left(CF_a^+ - CF_j\right)/(CF_a^+ - CF_a^-)\right]$$

$$i = 1,2,3,\ldots,a; ,j = 1,2,3,\ldots,c \qquad 6.6$$

6.4.4.7 Step 7: Determining the VIKOR index

The results for the regret measure were used in this step to identify the best risk-control option for the hazard. To determine the VIKOR index, firstly the maximum and minimum utility and regret measure values were identified by using Equations 6.7, 6.8, 6.9, and 6.10 as follows (Opricovic and Tzeng, 2004):

$$UM^+ = \operatorname*{Max}_{j} UM_i = [max(UM_i|i \ = \ 1,2,3,\ldots,a)] \qquad 6.7$$

$$UM^- = \operatorname*{Min}_{j} UM_i = [min(UM_i|i \ = \ 1,2,3,\ldots,a)] \qquad 6.8$$

$$RM^+ = \operatorname*{Max}_{j} RM_i = [max(RM_i|i \ = \ 1,2,3,\ldots,a)] \qquad 6.9$$

$$RM^- = \operatorname*{Min}_{j} RM_i = [min(RM_i|i \ = \ 1,2,3,\ldots,a)] \qquad 6.10$$

The results of Equations 6.7, 6.8, 6.9, and 6.10 were used to calculate the VIKOR index of each solution (VI_{ac}) as follows (Opricovic and Tzeng, 2004):

$$VI_{ac} = v(UM_{ac} - UM^-/UM^+ - UM^-) + (v-1)(RM_{ac} - RM^-/RM^+ - RM^-) \qquad 6.11$$

where v and 1- v represent the weight for the maximum value of group utility and the weight of the individual regret respectively, where the value of v is set to 0.5 (Tzeng and Huang, 2011).

6.4.4.8 Step 8: Ranking the alternatives for mitigating the risk

The results from determining the VIKOR index were finally used to rank the alternatives, where the lower the value of *VI*, the higher the alternative for mitigating the risk (Opricovic and Tzeng, 2004).

6.4.5 Step 5: Sensitivity Analysis

Sensitivity analysis was explained in depth in Section 4.4.6. To partially validate the model, the weighted results obtained from the AHP (step 3 of VIKOR) were slightly increased; this increase was performed on each criterion individually (John *et al.*, 2014b).

6.5 Case Study and Results Analysis

For the purpose of this research, a case study was carried out to demonstrate how the methodology can be employed to mitigate the evaluated hazards associated with PTSs. Based on the analysis procedure presented in Figure 6.2, the case study was conducted as follows.

6.5.1 Identification of the Goal

In Chapter 4, the hazards associated with PTSs were identified. As mentioned in Chapter 4, PTSs contain ports and transportation modes. The hazards within these two systems were evaluated by experts in their fields. All the experts have a great deal of experience in operations and are still actively working in their fields. For more details on the criteria for choosing these experts, see Chapter 4. This evaluation process indicated that procedural failure during ship/port interference has the highest risk within PTSs. Due to the present safety level of this hazard, a list of risk-control measures had to be identified to improve the safety practice for an optimal operation of this identified hazard.

6.5.2 Identification of Possible Criteria and Alternatives for Mitigating the Risk

The goal of this chapter is to improve the safety operations regarding the hazard of procedural failure during ship/port interference. In accomplishing this goal, it was necessary to consider the many criteria that have an effect on the evaluation of the alternatives in order to identify which solution (alternative) would be the best one. Through conducting an extensive literature review (John *et al*., 2014b; Vugrin *et al*., 2011; Hollnagel *et al*., 2007; Omer *et al*., 2012; Wang and Chang, 2007), the criteria and alternatives were identified. The criteria were categorised either as "Benefit" or "Cost" (see Tables 6.1 and 6.2).

Then the identified criteria and alternatives were discussed with petroleum ports operational experts. These consultation meetings took place in 2017, with nine petroleum/refined products' terminal managers, and scholars. With the help of experts, by using a brainstorming technique, the obtained results from the identified criteria and alternatives were validated.

Table 6.1: List of criteria with an explanation of each one

Level number	Criteria	Explanation	Category
Level 1 (Criteria)	Operating Safety (OS)	Safety level offered by applying any of the alternatives	Benefit
	Operating Costs (OC)	Cost of applying any of the alternatives	Cost
	Operating Time (OT)	Cost attributed to period during which infrastructure is working effectively	Cost
	Operating Quality (OQ)	Quality of operation from applying any of the alternatives	Benefit

Table 6.2: List of alternatives with an explanation of each one

Level number	Alternatives	Explanation
Level 2 (Alternatives)	Hiring qualified labour (A1)	Raising the minimum qualifications a new employee is required to have before being hired
	Hiring highly qualified labour (A2)	Hiring only specialists who are competent and have over 7 years' experience and multiple certifications
	Labour training programme (A3)	Implementing training programmes that new and current workers are required to take to improve their

		knowledge, skills and experience
	Enhancing work force capacity (A4)	Increasing the number of workers involved in the operation
	Requiring loading/discharging terminal supervision officer (A5)	Posting an operator (port representative) from the port side to represent the port on the ship during ship-board operations to ensure the safety of the loading and unloading operation
	Intensive regulation for safety and security checks (A6)	Requiring an intensive checklist before, during, and after the operating process to ensure the safety of the loading and unloading operation
	Apply new equipment (A7)	Renewing the equipment (Loading Arm/SBM) involved in the loading/unloading process
	Regulate an intensive maintenance program (A8)	Implementing an intensive maintenance plan to ensure the safety and quality operation of the equipment
	Requiring visual operating signs (A9)	Implementing visual guides to assist the workers during the operation process

The PTSs assessment indicated that the most significant hazard was within the port transportation system, so twelve actively working experts from the port sector were recruited to participate in this study. For more details on the criteria for choosing these experts, see Chapter 4. Through using a brainstorming technique, the experts were invited to discuss whether the identified criteria and control options addressed in the literature review aligned with real-life decision-making regarding the hazard of procedural failure during ship/port interference. The experts were also asked to address whether other criteria or alternatives not revealed in the literature review existed in real-life practice and should be included in the study. The resulting list of criteria is presented in Table 6.1, and a list of alternatives is presented in Table 6.2.

6.5.3 Model Development

In this step, the identified goal, criteria, and alternatives were presented in a hierarchal striation. The identified criteria and alternatives in Tables 6.1 and 6.2 are shown in Figure 6.3. The hierarchal striation comprises three levels: 1) the goal, which is located at the top; 2) the criteria, which are located in the middle where each criterion is connected to the goal; and 3) the alternatives, which are at the bottom of the hierarchy, where each alternative is connected with every criterion. This step aimed to use the models to represent the goal, criteria, and alternatives and their dependencies in order to achieve the goal.

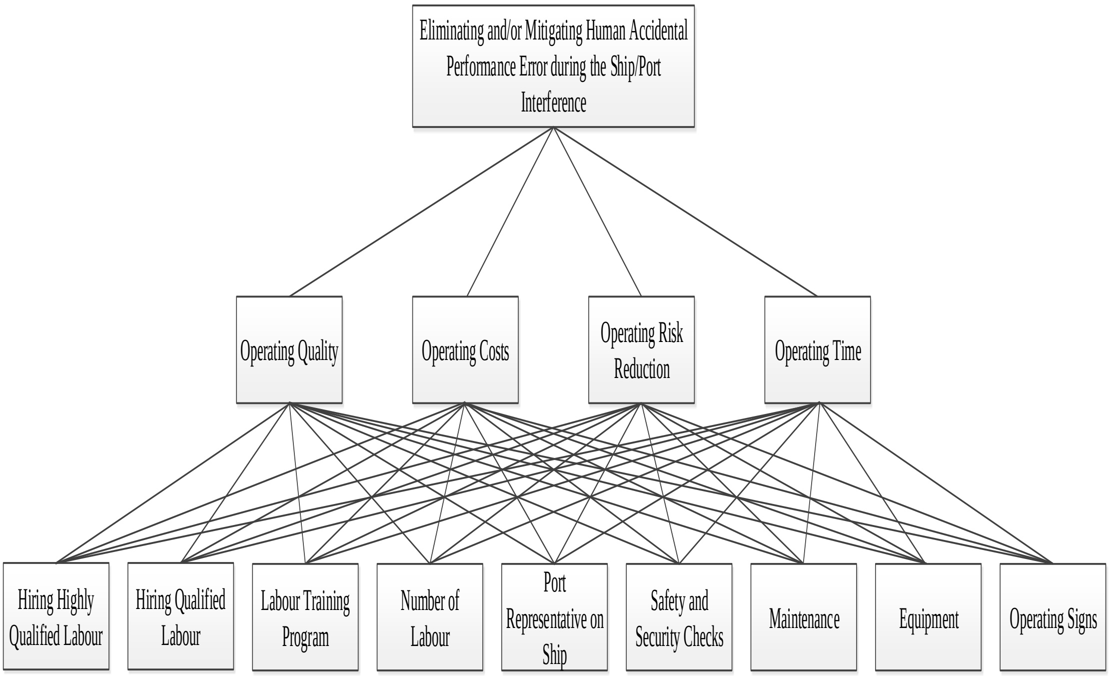

Figure 6.3: The hierarchical structure for mitigating the hazard of procedural failure during ship/port interference

6.5.4 Identification of the Best Alternative by using VIKOR

This step aimed to identify the best alternative in order to improve the safety level of the hazard of procedural failure during ship/port interference by applying the VIKOR technique. Accordingly, the nine steps of VIKOR were applied. However, before starting, a questionnaire was devised for petroleum port operation experts and its results were collected; the criteria for selecting these experts are explained in depth in Chapter 4. Moreover, a pilot test was carried out on this questionnaire to make sure it was clear and easy for the experts to complete.

The questionnaire was constructed in three sections. The first section, as in the previous questionnaires, requested personal information. The second section presented an example of how to fill in the questionnaire. The final section contained four parts, with each part referring to one of the criteria. Each expert was required to fill in each part by using a rating scale ranging from 0 to 10 (see Table 6.3). Once the experts had completed the questionnaires, the researcher collected them and ranked the alternatives to improve the safety operations at petroleum ports.

Table 6.3: Rating scale for benefit criteria

0 Low	1	2	3	4	5 Medium	6	7	8	9	10 High

6.5.4.1 Step 1: Developing the VIKOR decision matrix

After receiving the questionnaires from all the participants, the VIKOR technique was applied to rank the alternatives. The alternatives were rated with respect to the criteria. In order to demonstrate the calculation process of this step, a 9×4 decision matrix was developed by using Equation 6.1 as follows (Table 6.4):

Table 6.4: VIKOR decision matrix

	OS	OC	OT	OQ
HQL (A1)	8.0833	7.8333	6.6667	9.2500
VQL (A2)	7.9167	6.6667	6.7500	8.4167
LTP (A3)	8.0000	6.5833	6.0833	8.5833
NL (A4)	7.5000	7.7500	6.5833	6.5000
PRS (A5)	7.6667	6.7500	5.9167	7.8333
SSC (A6)	9.0833	5.7500	5.0000	8.9167
MS (A7)	8.0000	6.9167	5.5000	8.6667
RE (A8)	7.2500	9.0833	5.6667	9.3333
OS (A9)	6.1667	5.6667	4.9167	7.0833

The rate of OS with respect to SSC was used as an example in designing the decision matrix. After collecting the responses for all experts, an arithmetic averaging technique was used in order to combine the judgements of all twelve experts. Therefore, the rate of SSC in respect to OS was calculated as follows:

$$D_{SSCOS} = \frac{\sum_{E=1}^{12} SSCOS}{E} = \frac{9+9+8+9+10+9+10+10+8+8+9+10}{12}$$

$$= \underline{\underline{9.0833}}$$

Similarly, the values of the other criteria within this decision matrix were calculated by using the same technique, as is clear in Table 6.4.

6.5.4.2 Step 2: Normalising the VIKOR decision matrix

In this step, Equation 6.2 was used to normalise the decision matrix presented in step 2. The rate of the alternative SSC with respect to the criterion OS is presented here as an example of the normalisation process. The normalisation value of the alternative SSC with respect to criterion OS was calculated as follows:

$$N_{ac} = \frac{n_{ac}}{\sqrt{\sum_{i=1}^{a} n_{ac}^2}} = \frac{9.0833}{\sqrt{544.1389}} = 0.3894$$

Through applying the same normalisation procedure, the normalised decision matrix for all the alternatives with respect to all the criteria is presented in Table 6.5.

Table 6.5: Normalisation of the VIKOR decision matrix

	OS	OC	OT	OQ
A1	0.3465	0.3691	0.3745	0.3698
A2	0.3394	0.3142	0.3792	0.3365
A3	0.3430	0.3102	0.3417	0.3432
A4	0.3215	0.3652	0.3698	0.2599
A5	0.3287	0.3181	0.3324	0.3132
A6	0.3894	0.2710	0.2809	0.3565
A7	0.3430	0.3259	0.3090	0.3465
A8	0.3108	0.4281	0.3183	0.3732
A9	0.2644	0.2670	0.2762	0.2832

6.5.4.3 Step 3: Determining the weight of each criterion by using the AHP technique

This step utilised the AHP technique, which was established in Section 5.4.2. Identifying the weight of each of the identified criteria influences the detection of the ideal risk control option for mitigating the risk (Step 8). Therefore, a questionnaire was constructed and sent to experts in order to identify the weight of each criterion. Section 5.5.2 explained the questionnaire structure in depth. After the experts had completed the questionnaires and the resulting responses had been reviewed by the researcher, the steps to calculate the weight of each criterion by using the AHP technique were performed. The steps of this process were explained in depth in Section 5.5.2.

The weight of the P$(O_S O_C O_T O_Q)$ is presented in Table 6.6.:

Table 6.6: AHP Weight of cost criteria

	Weight	Rank
OS	0.3399	1
OC	0.2578	2
OT	0.1895	4
OQ	0.2128	3

This VIKOR step aimed to identify the weight of four criteria. Therefore, for detecting the Consistency Ratio (CR), the Random Index (RI) value was 0.89 (see Table 5.2). Consequently, by using Equation 5.4, CR is 0.1.

6.5.4.4 Step 4: Determining the minimum and maximum criterion function

Based on the outputs of VIKOR steps 1, 2, and 3, the maximum and minimum criterion functions were identified. This step took into consideration whether the criterion is a cost or a benefit criterion for identifying the maximum and minimum criterion functions. By applying Equations 6.3 and 6.4 to the results in Table 6.5, the maximum and minimum criterion function values were identified as shown in Table 6.7.

Table 6.7: Maximum criterion function and minimum criterion function values

	OS	OC	OT	OQ
Max	0.3894	0.4281	0.3792	0.3732
Min	0.2644	0.2670	0.2762	0.2599

6.5.4.5 Step 5: Determining the utility measure

To begin this step, steps 2, 3, and 4 in VIKOR (i.e. normalising the decision matrix, identifying the weight of each criterion, and identifying both the maximum and minimum criterion function) first had to be completed. The alternative SSC (A6) was presented as a sample for how to calculate utility measure. By using Equation 6.5, the utility measure of the alternative A6 was calculated as follows:

$$UM_{ac} = \sum_{j=1}^{c} W_j\left(CF_a^+ - CF_j\right)/(CF_a^+ - CF_a^-) = 0 + 0.0063 + 0.0086 + 0.0313$$

= 0.0462

The measure of the criterion with respect to each alternative is presented in Table 6.8 as follows:

Table 6.8: The criterion function with respect to each alternative

	OS	OC	OT	OQ
HQL	0.1165	0.1635	0.1809	0.0063
VQL	0.1360	0.0755	0.1895	0.0688
LTP	0.1262	0.0692	0.1206	0.0563
NL	0.1845	0.1572	0.1723	0.2128
PRS	0.1651	0.0817	0.1034	0.1127
SSC	0	0.0063	0.0086	0.0313
MS	0.1262	0.0943	0.0603	0.0501
RE	0.2137	0.2578	0.0775	0
OS	0.3399	0	0	0.1690

By using the same technique, the utility measure of other alternatives (i.e. A1, A2, A3, A4, A5, A6, A7, A8, and A9) is presented in Table 6.9.

Table 6.9: The utility measure values

	S
A1	0.4672
A2	0.4698
A3	0.3723
A4	0.7268
A5	0.4629
A6	0.0462
A7	0.3309
A8	0.5490
A9	0.5089

6.5.4.6 Step 6: Determining the regret measure

With the utility measure values identified, the regret measure was determined by using Equation 6.6. By using the values in Table 6.8, the regret measure is identified in Table 6.10 as follows:

Table 6.10: The regret measure values

	R
A1	0.1809
A2	0.1895
A3	0.1262
A4	0.2128
A5	0.1651
A6	0.0313
A7	0.1262
A8	0.2578
A9	0.3399

6.5.4.7 Step 7: Determining the VIKOR index

After identifying the regret measure, the VIKOR index of each solution was identified by using Equation 6.11. To find the VIKOR index (VI), the maximum and minimum utility and regret measure values firstly had to be identified by using Equations 6.7, 6.8, 6.9, and 6.10 (see the highlighted results in Tables 6.9 and 6.10). As a sample, the VI of the alternative SSC was calculated as follows:

$$VI_{ac} = v(UM_{ac} - UM^{-}/UM^{+} - UM^{-}) + (v - 1)(RM_{ac} - RM^{-}/RM^{+} - RM^{-})$$

$$= 0.5(0.0462 - 0.0462/0.7268 - 0.0462) + (0.5 - 1)(0.0313 - 0.0313/0.3399 - 0.0313)$$

$$= 0$$

The resulting VI for each of the alternatives (i.e. A1-A9) is presented in Table 6.11 as follows:

Table 6.11: VIKOR index values

	VK	Rank
A1	0.5516	5
A2	0.5675	6
A3	0.3934	3
A4	0.7941	8
A5	0.5229	4
A6	0.0000	1
A7	0.3630	2
A8	0.7364	7
A9	0.8399	9

6.5.4.8 Step 8: Ranking the alternatives for mitigating the risk

The identified VI of each alternative was used for ranking the alternatives starting from the best solution down to the worst solution: the lower the VI value, the higher the alternative for mitigating the risk. The result from Table 6.11 can be used by decision makers in order to mitigate procedural failure hazard during ship/port interference. As a result of this evaluation, with a value of 0 and rank of 1, the alternative SSC was identified as the best risk control option in order to improve the safety level of the identified hazard. Based on the alternative VIs (see Table 6.11), the solutions going from the top to the bottom were ranked as follows:

A6 > A7 > A3 > A5 > A1 > A2 > A8 > A4 > A9

6.5.5 Sensitivity Analysis

To partially validate the sensitivity of the model, the weight of each criterion (i.e. Operating Safety (OS), Operating Cost (OC), Operating Time (OT), and Operating Quality (OQ)) was increased by 20% in this step. As a result, the increases of the criteria weight, which increased by 0.2, led to a change in the VIKOR index, as presented in Table 6.12. For instance, the VIKOR index of the evaluated A7 has impacted due to increasing the criteria OS weight by 0.2 (from 0.3630 to 0.3756). Furthermore, the analysis revealed that the weight increment by, 20% has not affected the final ranking of the best alternatives for the investigated PTS hazard.

Table 6.12: Sensitivity analysis of all alternatives after increasing the weight of each criterion by 0.2

	Original VK	20% OS	20% OC	20% OT	20% OQ
A1	0.5516	0.50821	0.585445	0.62021	0.527128
A2	0.5675	0.524162	0.564014	0.639984	0.551922
A3	0.3934	0.404473	0.392116	0.428058	0.377624
A4	0.7941	0.752435	0.794074	0.794074	0.860257
A5	0.5229	0.534862	0.520502	0.522123	0.512863
A6	0	0	0	0	0
A7	0.3630	0.375621	0.366533	0.360674	0.347875
A8	0.7364	0.680872	0.83967	0.729064	0.710507
A9	0.8399	0.869819	0.82459	0.823115	0.841917

Based on the result obtained from this analysis, the best control options for the investigated PTS hazard (procedural failure during ship/port interference) are A6 (intensive safety and security checks), A7 (renewing the operational equipment), and A3 (Labour training programme).

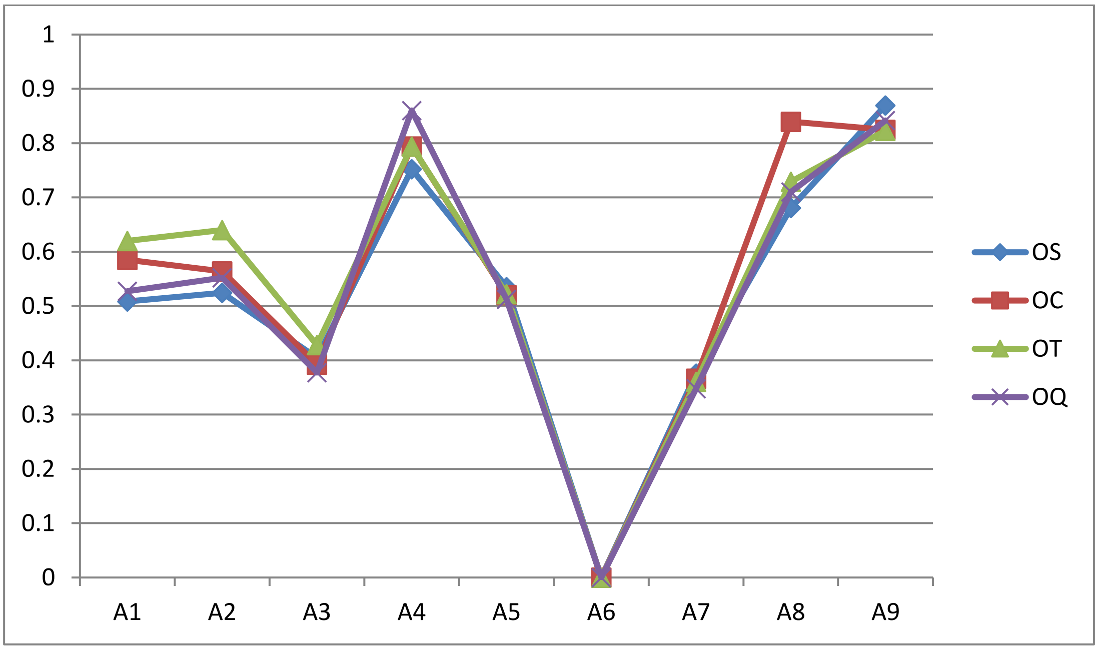

Figure 6.4: Sensitivity analysis output

6.6 Conclusion

The petroleum industry benefits from enhancing its safety level and eliminating the hazards associated with the system's operation and thereby avoiding any unexpected disasters within its supply chain. This goal could be reached by identifying the mitigation solutions and applying multi-attribute decision-making tools. This study is one of the first studies that employed an AHP–VIKOR technique within the petroleum industry in order to identify which control option is the best one for eliminating/mitigating the hazards associated with PTNs. Based on expert judgements, AHP was employed to identify the weight of each criterion, whilst VIKOR was used to rank the solutions.

Finally, the proposed methodology was applied to mitigate the hazards that had been evaluated for the PTSs which were presented in Chapter 4. From Chapter 4, the most significant hazard within the system was identified, followed by the identification of a list of alternatives and a list of criteria in order to mitigate and/or eliminate this hazard. Using the VIKOR index (VI), the solution with the lowest VI value was ranked as the most important one and vice versa. Therefore, A6, which was ranked as 1, is a more effective option than the other risk-control options (i.e. A9 ranks 9) in enhancing PTS operations (a brief discussion is further presented in Chapter 7).

This work has presented a platform that can support decision makers in the petroleum transportation industry in dealing with problems. This model has presented control options for the system's most significant hazards. The proposed methodology is not only suitable for enhancing the safety of PTNs. In fact, the methodology can be applied in any system in order to evaluate the alternatives of the tested system. The proposed method provides a decision-support system for enhancing the safety practices of the transportation system in general and particularly for the PTSs.

Chapter 7: Discussion

This chapter briefly summarises and discusses all the developed models and techniques presented in chapters 3, 4, 5, and 6 for the petroleum terminals and transportation modes operational safety as one complete system. Moreover, it further discusses the research contribution of this study and proposes recommendations for future studies for improving the developed framework.

7.1 Research Implication

This research comprises four technical chapters. These four chapters are discussed in more detail as follows:

7.1.1 Discussion of Applying Network Analysis Techniques for Analysing Nodes' Vulnerability within Petroleum Transportation Systems (PTSs)

Traditional risk assessment techniques generally cannot handle big, complex systems. Chapter 3 aimed to produce assessment techniques that could perform a safety evaluation of Petroleum Transportation Systems (PTSs) externally/globally. Network analysis techniques were employed for analysis of the node situation within Petroleum Transportation Networks (PTNs') operational network. Centrality measures are known for their ability in measuring nodes' importance based on nodes' strategic location within a network. The PTSs network representation structure in Figures 3.3 and 3.4 highlights that every two nodes (ports) within PTNs are connected to each other by a transportation mode. If this connection does not exist, the flow of product between two ports might not occur. Therefore, this chapter aimed to detect node centrality (ports and transportation modes) within PTNs.

Assessing nodes' importance within a system is a challenging task. The challenge is related to identifying the existing connections between the evaluated PTSs and collecting the data of these connections to analyse the evaluated network. Therefore, centrality measures were introduced in order to evaluate PTSs' safety based on the importance of ports and routes regarding direct connections between pairs of nodes and nodes' strategic position in the network. Two maritime PTNs cases were analysed to demonstrate the technique's ability in measuring the complicity of PTSs.

The steps of identifying the importance of each port and shipping route using centrality measures are highlighted in Figure 3.2. As illustrated Case Study 1 in Appendixes 1.5 and 1.6, with respect to ports' importance to other ports within the Maritime Petroleum Transportation Networks (MPTNs), in terms of ports' outgoing service ($\beta = 1$), Ras-Tanura port is the most important port, followed by Basrah Oil Terminal, Malongo port area, and Mina al-Ahmadi. When the network is weighted for the safety of the MPTN, Ras-Tanura port is still considered to be the most critical port, followed by Jebel Dhanna port, Puerta la Cruz port, and Mina al-Ahmadi. Ras-Tanura port's dominant role is due to it attracting significant cargos' capacity from inland systems. In contrast, ports such as Wilhelmshaven port and other ports from different regions have low centrality scores across the changes of MPTN parameters (see Figure 3.7). Based on the ports' effect on inland transportation, Mundra seaport (1) is the most central port, followed by several ports located in the east of Asia such as Zhanjiang port Taesan port and Osaka Sakai port. However, when the network is weighted for the safety of the MPTN, Mundra seaport loses this importance to other ports (i.e. $\alpha \leq 1$). In a vice versa result, the port of Singapore ranks low in importance (0.667 and 0.877). However, when $\alpha \leq 1$, the same port has a high level of criticality in the crude oil maritime transportation network. This highlights that any risk factor striking Singapore port will have a significant impact on the petroleum throughput to its inland market.

On the other hand, measuring the safety criticality of involved ports and choke points in the weighted MPTN (case study 2) assuming different parameters (see Appendix 1.10), and based on the network assessment, with respect to nodes outflow, the Strait of Malacca (1), Cape of Good Hope route (0.7), Malongo port area (0.55), and Puerta la Cruz port (0.55) were considered to be the most important ports and shipping routes within the MPTN. These ports and routes lost their advantages to Strait of Hormuz and Ras-Tanura port upon analysing the safety of the ports and routes within the MPTN. Nevertheless, the Strait of Malacca, Cape of Good Hope route, Malongo port area, and Puerta la Cruz port still obtain safety criticality levels that ranked them in the top critical points. Turning to the nodes' effect on outflow, as represented in Appendix 1.11, the Strait of Hormuz (1) and Cape of Good Hope route (0.667) are the two most critical routes. In the ports sector, Rotterdam (0.667) and Arthur (0.667) ports obtain a high importance level across the network. However, when the network is weighted for the safety of the MPTN, the Strait of Malacca and Singapore port overtakes them and becomes the most safety critical port and shipping route within the MPTN.

In addition, betweenness centrality measured the petroleum ports' and routes' potential as intermediaries within the MPTN. With respect to the changes in the parameters' values, the Strait of Hormuz is the most critical node within the MPTN. This importance is mainly due to its critical position in the petroleum transportation flow, which allows it to attract significant shipping capacity. Therefore, any incident or accident in the Strait of Hormuz shipping route would affect the petroleum flow within the MPTN. Moreover, the Strait of Malacca (0.94) is ranked as the second most critical route in the MPTN (see Appendix 1.12). The Cape of Good Hope and Bab El-Mandab maintain relatively stable positions, ranking third and fourth across the changes of parameter.

Chapter 3 presented a measurement platform to support decision makers within the petroleum transportation industries and other transportation system industries. This platform can be used in various complex industries for analysis of the node situation within a network. The novelty of this chapter was applying the concept of centrality measures to PTNs. The success of this measuring technique within the complex system of PTSs was confirmed in this chapter.

7.1.2 Discussion of an Advanced Risk Assessment Approach for Petroleum Transportation using Fuzzy Rule-Based Bayesian Reasoning

Chapter 4 produced estimations through analysing the local level of each system within PTSs (i.e. port transportation, ship transportation, and pipeline transportation). The chapter also ranked the identified hazards in the systems such as ship collision due to bridge navigation equipment failure, pipeline transportation system failure due to sabotage, release from port loading arm/SBM, tanker tank gauging system failure, and ship or port communication system failure. The work was assessed by the hybrid Fuzzy Rule-Based Bayesian Reasoning (FRBBN) methodology and twenty-seven experts' judgement. The FRBBN technique is a combination of a Fuzzy Rule-Based (FRB) method and Bayesian Network (BN) techniques for the determination of handling the vagueness that is inherent in PTSs' operational hazards/failure modes data. This hybrid method is an advance technique capable of assessing and ranking the hazards associated with PTSs operation. The resulting mathematical model was conducted with the aid of the hazards' three FMEA risk factors: the occurrence probability of a risk event during the process of oil transport (P_l), the consequence severity of the risk event should the event occur (S_c), and the probability that the risk event would not be detected before it occurs (D_p). The participant experts in the study are actively working at inshore and offshore terminals and petroleum ports, tankers, and pipeline systems. Each expert provided his/her experience to this study in the hazard identification process.

The constructed Fuzzy IF-THEN rule with a belief structure for PTSs was built on two parts (i.e. the IF part and the THEN part). While the risk level (R) was represented in the THEN part, P_l, S_c, and D_p are the IF part parameters. Five variable grades (Very High, High, Medium, Low, and Very Low) were used for defining each of the IF-THEN parameters (P_l, S_c D_p, and R). These grades describe the linguistic variables of each attribute associated with the PTSs' hazards. Each of the IF part parameters was described based on knowledge accrued from past events. However, for assigning the belief degrees in the THEN part, the proportion method was used. Table 4.4 presents 125 rules (5 × 5 × 5) and their belief degrees for risk assessment of petroleum port, pipeline, and ship systems.

In the assessment of the 113 PTSs operation identified hazards (42, 61, and 10 hazards within port, ship, and pipeline systems respectively), the arithmetic mean was employed to evaluate the collected failure information. The collected failure information was gathered through the twenty-seven participating experts (nine from each operational sector). All the experts completed three constructed questionnaires (each questionnaire represents one of the three PTSs). The average values were then used in the form of prior probabilities for each of the developed BN models for each hazard in order to aggregate the rules using a BN mechanism. For example, the Company Policies (PPHC) hazard assessed by nine experts from the seaport operation section. The experts' assessment for the hazard parameter $P_{Very\ High}$ was 5%, 10%, 10%, 5%, 20%, 10%, 5% 10% and 5%. By using the arithmetic mean, the average degree of belief was 8.89% (see Table 4.7). HUGIN software, a computer software tool, was used to compute the marginal probability for each of the 113 developed BN models. For example, the marginal probability of PPHC was described in the five linguistics as {(8.25, “very high”), (13.7, “high”), (22.85, “medium”), (30.18, “low”), (25, “very low”)}.

The utility theory method was used to convert the degree of belief for each of the hazards threatening PTSs safety to one crisp value. Presenting degree of belief values in one single value is more helpful for decision makers looking to prioritise the system hazards. The higher the utility value, the riskier the hazard is. Therefore, the utility values for port operational failure due to procedural failure, ship collision due to human fatigue, pipeline transportation system failure due to system sabotage, lack of communication system (port system), and main engine failure (ship collision) are 54.4, 50.1, 38.9, 50.6, and 48.8 respectively as illustrated in Appendixes 2.11 and 2.12 and Table 4.10. Based on these identified crisp values, the hazards procedural failure (port transportation system), human fatigue (ship transportation system), sabotage (pipeline transportation system), lack of communication system (port transportation system), and main engine failure (ship transportation system) are ranked as 1, 3, 5, 2, and 4 respectively. As a result, port operational failure due to procedural failure is considered to be the most significant hazard within PTSs. This finding reveals that hazards such as human fatigue and geological hazards are the most important hazards in ship and pipeline systems respectively, while port operational failure due to procedural failure is the most important one in ports and overall systems. The developed FRBBN method was proven successful in analysing and ranking the system failures in an uncertain environment. This developed technique can be used for evaluating the petroleum industry and other numerous industries with the aim of detecting which hazards are most likely to cause system failures.

Finally, sensitivity analysis was performed on the established model to examine the output sensitivity after changing the inputs. This technique can be employed in the

HAZID and risk evaluation of various maritime, oil, and gas facilities by maritime and oil companies. Therefore, two axioms were accomplished in examining the marginal probability sensitivity for each of the hazards by changing its prior probability. By performing axiom 1 (i.e. increasing the belief degree of $\text{Likelihood}_{Very\ High} = 100\%$") and axiom 2 (i.e. increasing the belief degree for both “$\text{Likelihood}_{Very\ High}$ and “$\text{Probability}_{Very\ High} = 100\%$") for all the hazards, the models’ sensitivity was illustrated (see Figure 4.11).

7.1.3 Discussion of An Advanced Risk Assessment Framework for PTNs using Evidential Reasoning Approach

Traditional techniques can sometimes produce inaccurate outputs when dealing with complex systems. Chapter 5 thus aimed to present a novel approach through margin internal and external evaluation. In the chapter, traditional risk/safety analysis (i.e. ER) was combined with Analytic Hierarchy Process (AHP), FRBBN, and centrality method to analyse PTSs’ operational safety. ER is known for its ability to integrate internal and external evaluation. The hierarchical structure of PTSs in Figure 5.3 revealed that the system failure might follow the occurrence of any number of port, ship, and/or pipeline transportation system hazard events such as Procedural Failure (port transportation system), Human Fatigue (ship transportation system), or Sabotage (pipeline transportation system).

Estimating the failure probability for the safety of PTSs is a complex and challenging task. The challenge is associated with evaluating PTSs locally and globally followed by connecting these two evaluations to measure the failure probability of PTSs as one complete system. To perform the local evaluation incorporation of AHP, FRBBN and ER techniques were used. Via these three techniques, the failure potential of each of the PTSs within the PTN was estimated. Network analysis method was introduced for the global evaluation. After accomplishing the local and the global assessment, ER was finally used to synthesise these evaluations and thereby assess PTSs as one complete system. A case study was conducted in the chapter to demonstrate how to measure the complexity of the PTN. Multiple ports, shipping lines, and pipeline transportation systems were involved within the analysed PTSs.

The assessment for each of the local systems started with identifying the importance of each criterion mentioned in Figures 4.4, 4.5, and 4.6 by using the AHP approach. The mechanism of this method was used to weight each criterion within a PTS hierarchy. For estimating the weights, three constricted surveys (one for each of the three systems) were completed by experts in each field. For example, Machine Related Hazards (MRH), Human Related Hazards (HRH) and Nature Related Hazards (NRH) were three hazards in the same level within the petroleum port system. Based on the assessment of these three hazards via AHP technique, with a CR of 0.0073, the Human Related hazards were ranked the most important hazard (0.6257), followed by Machine Related Hazards (0.2794), and Nature Related Hazards (0.0948) respectively as illustrated in Table 5.5. After accomplishing the weighting process, the hazards of the ports and ship and pipeline systems within PTSs were analysed by using the hybrid FRBBN methodology. It is noteworthy that all hazards failure probabilities were obtained from the synthesis of the experts' judgements.

The failure probability of each local system (ports and ship and pipeline systems) within PTSs was assessed using ER. The technique is well known for its ability to synthesise hierarchy levels, so it was used to analyse the operation of ports and transportation modes within PTSs. ER presented the failure probabilities of each system using the linguistic variables very low, low, average, high, and very high. IDS software was used to aggregate the hierarchal levels of each system in an easier and faster way. As illustrated in Table 5.11, the assessment of the four ports was as follows: (0.119, 0.18, 0.283, 0.285, 0.133), (0.112, 0.179, 0.279, 0.295, 0.135), (0.116, 0.193, 0.274, 0.269, 0.148), and (0.105, 0.165, 0.272, 0.286, 0.171).

After accomplishing the local evaluation, centrality measure mechanisms were applied to assess PTNs globally by identifying the importance of each port and transportation mode within the PTN. The centrality measures were capable of measuring the weights of each port and each ship and pipeline system within the PTN. For analysing the weights of the local evaluated PTN as one of the major petroleum producers, real data were provided from the company to support this study. The name of the country and the ports are not revealed to protect the country's safety and security. Based on the network assessment, port A, ship B, and pipeline B are considered to be the most important ports and transportation modes within each system with normalised weights of 0.26, 0.02, and 0. 24 respectively (see Table 5.12). In the overall system, with four connections, port A was found to be the most important node within the PTN. This result highlights that the number of connections linked to a port does not necessarily indicate the importance of the node within the system. The same was true for port D, which had fewer links connected to it than other nodes. It is worth mentioning that all the values in Table 5.12 were obtained by measuring the nodes within the PTNs using the degree centrality measure.

To evaluate the local PTN as one complete system, ER approach was used to aggregate the local and global assessments. The ER aggregation mechanism used five linguistic terms as shown in Figure 5.4 and Table 5.13. The failure probability of the local PTNs was identified as 0.0919, 0.1345, 0.2365, 0.2681, and 0.2691 respectively. After performing the utility approach by using IDS software, the utility value of the local PTN was found to be 0.3780 (see Table 5.14). These results highlight that consequences of hazard events would be disastrous if the correct protective and mitigating measures for the identified hazards are not taken into consideration.

Finally, two axioms were performed on the established model. Sensitivity analysis was performed on the model to examine the output sensitivity after changing the inputs. Performing axiom 1 and axiom 2 for all the hazards highlights that any change in the lower events (hazards) belief degree affects the failure probability of PTNs' belief degree and the utility number with an increase or a decrease on the system output as illustrated in Figure 5.5 and Table 5.15.

This research identified that hazards such as Procedural Failure (port transportation system), Human Fatigue (ship transportation system), and Sabotage (pipeline transportation system) are the most important ones in each system, while Procedural Failure (port transportation system) is the most significant one overall. The developed ER–FRBN approach is a novel approach for examining PTS operation at a systematic level. This approach can also be used in risk management studies for other industries that need to detect their system's most important hazards and measures the operational system as one complete system. Therefore, risk-control measures must be addressed in order to mitigate and prevent future failures.

7.1.4 Discussion of Developing a Risk Based Decision Making Modelling Tool to Enhance Safety in PTSs Operation

Chapter 6 presented the combination of AHP and VIKOR techniques for selecting the most appropriate and most effective risk-control options for optimal operation regarding the most significant hazard within PTSs. Combining these multi-criteria decision making techniques has provided decision makers with an effective solution to overcome the system hazards identified within this study. The analyses presented in Chapter 3 estimated that procedural failure during ship/port interference within seaport systems is considered as the most significant hazard within PTSs. The main challenge is to detect how to control this hazard to operate PTSs in an optimal manner. Therefore, based on the literature review and the experts' judgement, several risk-control options and their relevant criteria were identified. Furthermore, the identified criteria and solutions were presented in a hierarchical structure by linking each of the identified criteria (i.e. OS, OC, OT, and OQ) to every alternative (i.e. A1 – A9). The AHP–VIKOR technique was then performed to select the most efficient solutions as illustrated in Figure 6.3 and Tables 6.1 and 6.2.

An AHP pair-wise comparison was also carried out to assess the weight of each criterion by comparing each criterion to others in the same level in the hierarchical structure. Twelve experts participated in analysing the best solution in this chapter. The experts' judgements were calculated and used to assess the weights of each criterion. With a CR of 0.1, the weights of the Operating Safety (OS), Operating Costs (OC), Operating Time (OT), and Operating Quality (OQ) were found as 0.3399, 0.2578, 0.1895, and 0.2128 respectively as evidenced in sub-section 6.5.4.3. These weights revealed that the criteria OS was considered to be the most important criteria, followed by OC, OQ, and OT respectively.

The criteria's weights were further combined with the experts' judgment regarding each risk-control option by using VIKOR to identify the best solution most capable of mitigating the procedural failure during ship/port interference hazard. To detect the best hazard mitigation option, Tables 6.3 and 6.4 respectively illustrate a rating scale and VIKOR decision matrix. Each of the identified criteria was classified as cost or benefit in order to facilitate the maximum and minimum criterion functions, detection of the calculated utility measure, determination of the regret measure for each solution, and identification of the VIKOR index values (VI) of each solution. The VI values were used for prioritising the alternatives starting from the best solution to the worst. VI values of A1, A2, A3, A4, A5, A6, A7, and A8 were revealed in Table 6.11 as 0.5516, 0.5675, 0.3934, 0.7941, 0.5229, 0, 0.3630, 0.7364, and 0.8399 respectively. Based on VI, the solution with the highest VI value is ranked as the least important one and vice versa. Therefore, A6, which was ranked as 1, is a better option compared to the other risk-control options (i.e. A9 ranks 9) for enhancing PTS operations.

Finally, a sensitivity analysis was performed to partially validate the sensitivity of the developed model. Performing axiom 1 (increases the criteria weight by 0.2) on all the risk control options highlights that any change in the criteria weight affects the VIKOR index of PTS' risk control option with an increase or a decrease as presented in Table 6.12. In addition, the modal outputs highlighted that the weight increasing by, 20% will not influence the position of the most efficient risk control option for the investigated PTS hazard.

This work presented a platform that can support decision makers within the petroleum transportation industry in dealing with problems. This model presented control options for the system's most significant hazards. In the real world, every hazard is controlled by different measures, so these control options might have different influences on improving the system safety level.

7.2 Research Contribution

This research's main contribution was forming a novel risk assessment framework for estimating, controlling, and monitoring the operation risks in PTSs as one complete system. This advanced framework comprises relevant tools and techniques that are capable of performing an advanced risk assessment for measuring, evaluating, and controlling the operational hazards that affect the desired functions of PTSs. The study integrated assessment of the involved operational systems (ports and transportation modes) for PTNs' overall safety because these three operational systems work together to ensure that the product is flowing in a safe condition. The developed assessment models are powerful models tailored to the PTSs industry. The models can assist PTSs industrial risk management specialists toward managing safety and risk problems. Furthermore, the models present a chain of required steps that will help to direct PTSs safety officers in controlling and enhancing the overall safety of PTSs operation in uncertainty situations.

The novelty and originality of this research comes from 1) identifying the gap that urgently needs to be filled, 2) developing the method that provided the ability to deal with the complexity of the PTSs as one complete system for the system safety, 3) estimating and controlling the failures that threaten the safety of PTSs, 4) providing decision makers with the tools to measure local and/or global levels of PTNs operation. The key achievement behind these accomplishments was the synthesis of several multi-criteria decision-making approaches (i.e. ER, AHP, and FRBN) and integration of all three with a network analysis technique (i.e. centrality measures) to facilitate decision making for improving the safety operations of PTNs. In addition, a widely used validation method (Sensitivity analysis) was performed to measure the sensitivity of the developed model through performing a series of tests. The implemented framework has been developed into a sequence that aims to improve the safety operations to achieve a high level of safety for PTSs (Alghanmi *et al.*, 2017). The shortage of risk assessment literature in particular for PTS operational safety as one complete system within the petroleum industry further highlights the significance of this research. Therefore, this study has enhanced the knowledge within the PTSs operational domain.

7.3 Research Limitations

This study aims to develop a novel risk assessment framework for estimating, controlling, and monitoring operation risks in PTSs as a complete system. The investigated hazards do not cover operational accident scenarios related to storage tanks, bombing stations, ship manoeuvring at port areas, and ship tank gauge system failures. Due to the security and criticality involved in transporting the crude oil, it has not been possible to find risk assessment related results to fully validate the finding of this research. To overcome this limitation, sensitivity analyses are performed in Chapters 4, 5 and 6. The connections among PTSs form a complex system. These systems are complex because they often operate in dynamic environments. Therefore, in Chapter 5 the research presented a case study to evaluate the local network of one of the major petroleum producing countries. Finally, the nature of operating PTSs within the petroleum industry highlights the difficulties with collecting secondary data for the identified PTSs hazards.

7.4 Recommendations for Future Work

The researcher has accomplished the aim of this research, which was to develop a novel risk assessment framework for estimating, controlling, and monitoring the operation risks in PTSs as one complete system. Nevertheless, this established framework is not an ultimate guideline for evaluating PTSs. During the research process, several critical concerns were raised, analysed, described, and amalgamated. Still, not all of the raised subjects were carried out due to the research scope and time. For that reason, these uncovered subjects are suggestions for further works which are listed as follows:

- Investigation is needed of more operational risk scenarios that cause failures in each of the three operation systems. Such scenarios include the hazards associated with storage tanks, bombing stations, ship manoeuvring at port areas, and ship tank gauge system failures. In addition, consideration of PTSs could be extended to include the operation of rail and truck transportation systems; an in-depth investigation could be conducted to identify the hazards associated with each of these systems.

- Increasing the number of expert participants and comparing the results with those of this study would enable an examination of the effectiveness of the present study. It is recommended that the selected participant experts have operational experience in port, ship, and pipeline operation.
- Proposed closeness and betweenness centrality measures could be used to analyse PTNs operations externally, and the results could be merged with results on the local level. Such an analysis would further enable measurement of PTSs as one complete system based on node critical position and distance.
- Other multi-criteria decision-making techniques such as TOPSIS could be employed in order to measure risk-control options. Those options' values could then be ranked and compare with the VIKOR ranking to obtain the ultimate solution to enhance the safety of the PTSs.
- The findings on evaluated PTNs from small networks (local networks) could be extended to bigger networks (i.e. to a combination of local and global petroleum networks) to examine the model efficiency. Such an examination would encourage petroleum industry operators and other researchers to apply this proposed model to assess any network within PTNs.
- Computer software could be developed to address the complexity of the analysis process. This software could then be continuously updated with historical and

up-to-date petroleum transportation data to help combat the lack of real data. This computer software would further improve PTNs safety and encourage other researchers to develop other assessment models to help evaluate other cargo transportation systems.

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List of Appendix

Appendix Chapter 3

1.1: degree centrality calculation sample

Through applying Equation 3.1, the degree centrality of $C_D(S)$ is as follows:

$$k_S = C_D(S) = \sum_{j}^{P} x_{ij} = 1 + 1 + 1 + 1 + 1 + 1 + 1 = 7$$

Based on Equation 3.1, the Suez Canal/SUMED Pipeline links to seven ports (i.e. Ras-Tanura port, Mina al-Ahmadi, Basrah Oil Terminal, Umm Said and Ras-Laffan Terminal, Jebel Dhanna port, Wilhelmshaven port, and Rotterdam port).

In terms of safety network, Equation 3.2 measures the degree centrality of $C_D^W(S)$ (i.e. weighted by throughput in terms of barrels instead of the number of links) as follows:

$$S_S = C_D^W(S) = \sum_{j}^{P} W_{ij}$$

$$= 31.952 + 0.304 + 68.363 + 0.239 + 77.102 + 80.931 + 97.029$$

$$= 355.92$$

Through introducing a tuning parameter (α) to aggregate the values of Equations (3.1) and (3.2), Equation (3.3) analyses the centrality of (S) in the weighted MPTN $C_D^{w\alpha}(S)$ as follows:

$$C_D^{w\alpha}(S) = k_S \times \left(\frac{s_S}{k_S}\right)^{\alpha} = 7 \times \left(\frac{355.92}{7}\right)^{0} = 7$$

$$C_D^{w\alpha}(S) = k_S \times \left(\frac{s_S}{k_S}\right)^{\alpha} = 7 \times \left(\frac{355.92}{7}\right)^{0.5} = 49.914$$

$$C_D^{w\alpha}(S) = k_S \times \left(\frac{s_S}{k_S}\right)^{\alpha} = 7 \times \left(\frac{355.92}{7}\right)^{1.0} = 355.92$$

$$C_D^{w\alpha}(S) = k_S \times \left(\frac{s_S}{k_S}\right)^{\alpha} = 7 \times \left(\frac{355.92}{7}\right)^{1.5} = 2537.93$$

With respect to the direction of the network, Equations (3.4a) and (3.4b) analyse the safety centrality of (S) in the weighted MPTN.

The safety out-degree centrality is as follows:

$$C_{D-out}^{w\alpha}(S) = k_S^{out} \times \left(\frac{s_S^{out}}{k_S^{out}}\right)^{\alpha} = 2 \times \left(\frac{177.96}{2}\right)^{0} = 2$$

$$C_{D-out}^{w\alpha}(S) = k_S^{out} \times \left(\frac{s_S^{out}}{k_S^{out}}\right)^{\alpha} = 2 \times \left(\frac{177.96}{2}\right)^{0.5} = 18.866$$

$$C_{D-out}^{w\alpha}(S) = k_S^{out} \times \left(\frac{s_S^{out}}{k_S^{out}}\right)^{\alpha} = 2 \times \left(\frac{177.96}{2}\right)^{1} = 177.96$$

$$C_{D-out}^{w\alpha}(S) = k_S^{out} \times \left(\frac{s_S^{out}}{k_S^{out}}\right)^{\alpha} = 2 \times \left(\frac{177.96}{2}\right)^{1.5} = 1678.683$$

The safety in-degree centrality is as follows:

$$C_{D-in}^{w\alpha}(S) = k_S^{in} \times \left(\frac{s_S^{in}}{k_S^{in}}\right)^{\alpha} = 5 \times \left(\frac{177.96}{5}\right)^{0} = 5$$

$$C_{D-in}^{w\alpha}(S) = k_S^{in} \times \left(\frac{s_S^{in}}{k_S^{in}}\right)^{\alpha} = 5 \times \left(\frac{177.96}{5}\right)^{0.5} = 29.83$$

$$C_{D-in}^{w\alpha}(S) = k_S^{in} \times \left(\frac{s_S^{in}}{k_S^{in}}\right)^{\alpha} = 5 \times \left(\frac{177.96}{5}\right)^{1} = 177.96$$

$$C_{D-in}^{w\alpha}(S) = k_S^{in} \times \left(\frac{s_S^{in}}{k_S^{in}}\right)^{\alpha} = 5 \times \left(\frac{177.96}{5}\right)^{1.5} = 1061.692$$

Based on the result of Equations (3.4a) and (3.4b), Equation (3.5) introduced a parameter (β) to aggregate the in and out values.

The safety criticality when $\beta = 1$ is as follows:

$$C_D^{w\beta}(S) = [C_{D-out}^{w\alpha}(S)]^{\beta} \times [C_{D-in}^{w\alpha}(S)]^{(1-\beta)} = 2^1 \times 5^{(1-1)} = 2$$

$$C_D^{w\beta}(S) = [C_{D-out}^{w\alpha}(S)]^{\beta} \times [C_{D-in}^{w\alpha}(S)]^{(1-\beta)} = 18.866^1 \times 29.83^{(1-1)} = 18.866$$

$$C_D^{w\beta}(S) = [C_{D-out}^{w\alpha}(S)]^{\beta} \times [C_{D-in}^{w\alpha}(S)]^{(1-\beta)} = 177.96^1 \times 177.96^{(1-1)} = 177.96$$

$$C_D^{w\beta}(S) = [C_{D-out}^{w\alpha}(S)]^{\beta} \times [C_{D-in}^{w\alpha}(S)]^{(1-\beta)} = 1678.683^1 \times 1061.692^{(1-1)}$$

$$= 1678.683$$

The safety criticality when $\beta = 0$ is as follows:

$$C_D^{w\beta}(S) = [C_{D-out}^{w\alpha}(S)]^{\beta} \times [C_{D-in}^{w\alpha}(S)]^{(1-\beta)} = 2^0 \times 5^{(1-0)} = 5$$

$$C_D^{w\beta}(S) = [C_{D-out}^{w\alpha}(S)]^{\beta} \times [C_{D-in}^{w\alpha}(S)]^{(1-\beta)} = 18.866^0 \times 29.83^{(1-0)} = 29.83$$

$$C_D^{w\beta}(S) = [C_{D-out}^{w\alpha}(S)]^{\beta} \times [C_{D-in}^{w\alpha}(S)]^{(1-\beta)} = 177.96^0 \times 177.96^{(1-0)} = 177.96$$

$$C_D^{w\beta}(S) = [C_{D-out}^{w\alpha}(S)]^{\beta} \times [C_{D-in}^{w\alpha}(S)]^{(1-\beta)} = 1678.683^0 \times 1061.692^{(1-0)}$$

$$= 1061.692$$

Appendix 1.2: Degree centrality scores with different values of turning parameter (case 1)

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port area	34	213.9311	1346.074	8469.6204
Umm Said and RasLaffan Terminal area	14	56.2749	226.205	909.2625
Mina al-Ahmadi area	25	103.6583	429.802	1782.1024
Jebel dhanna port area	20	95.9467	460.288	2208.1546
Basrah Oil Terminal area	29	112.5927	437.142	1697.207
Kharg Island area	20	71.3213	254.336	906.978
Puerta la Cruz port	21	99.0519	467.204	2203.6884
Malongo port Area	27	94.6453	331.768	1162.9736
Niger Delta area	13	44.6094	153.077	525.2829
Corpus Chris port	5	17.9102	64.154	229.8003
Freeport port	3	12.1960	49.581	201.5637
Houston port	6	24.907	103.393	429.2014
Lake Charles port	4	17.5702	77.178	339.0083
Morgan City port	6	27.4046	125.169	571.7018
Philadelphia port	5	19.2703	74.269	286.2374
Port Arthur port	6	34.7199	200.912	1162.6077
Texas City port	6	17.515	51.129	149.2538
Mangalore Sea	6	20.9567	73.197	255.6609
Mumbai Sea	6	21.9116	80.02	292.2282
Mundra Sea	9	45.9717	234.822	1199.4632
Paradeep Sea	5	20.506	84.099	344.9064
Vizag Sea	6	18.113	54.68	165.0696
Onsan port	2	18.9338	179.244	1696.8832
Taesan port	7	26.2638	98.541	369.723
Ulsan port	6	34.4517	197.82	1135.8727
Yosu port	5	31.0561	192.896	1198.1187
Chiba port	7	31.145	138.573	616.5509
Kagoshima port	6	22.6433	85.453	322.4893
Kawasaki port	6	21.7623	78.933	286.294
Mizushima port	6	20.8302	72.316	251.0591
Osaka Sakai port	7	21.5682	66.455	204.7588
Yokkaichi port	7	25.6770	94.187	345.4915
Dalian port	6	29.5908	145.936	719.7274
HangZhou port	6	21.9784	80.508	294.9055
Ningbo port	7	39.7372	225.578	1280.5487
Qingdao port	7	42.1242	253.492	1525.4479
Shenzhen port	5	16.3686	53.586	175.4252
Shijiazhuang port	4	14.3506	51.485	184.7103
Tianjin port	7	18.7004	49.958	133.4623
Xiamen port	4	15.7981	62.395	246.4306
Zhanjiang port	8	32.6745	133.453	545.064
Singapore port	6	40.3368	271.176	1823.0612
Suez Canal/SUMED Pipeline	7	49.914	355.92	2537.93
Wilhelmshaven port area	4	24.9234	155.294	967.6137
Rotterdam port area	4	24.1673	146.014	882.1892

Appendix 1.3: Out-Degree centrality scores with different values of turning parameter (case 1)

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port area	34	213.9311	1346.074	8469.6204
Umm Said and RasLaffan Terminal area	14	56.2749	226.205	909.2625
Mina al-Ahmadi area	25	103.6583	429.802	1782.1024
Jebel dhanna port area	20	95.9467	460.288	2208.1546
Basrah Oil Terminal area	29	112.5927	437.142	1697.207
Kharg Island area	20	71.3213	254.336	906.978
Puerta la Cruz port	21	99.0519	467.204	2203.6884
Malongo port Area	27	94.6453	331.768	1162.9736
Niger Delta area	13	44.6094	153.077	525.2829
Corpus Chris port	0	0	0	0
Freeport port	0	0	0	0
Houston port	0	0	0	0
Lake Charles port	0	0	0	0
Morgan City port	0	0	0	0
Philadelphia port	0	0	0	0
Port Arthur port	0	0	0	0
Texas City port	0	0	0	0
Mangalore Sea	0	0	0	0
Mumbai Sea	0	0	0	0
Mundra Sea	0	0	0	0
Paradeep Sea	0	0	0	0
Vizag Sea	0	0	0	0
Onsan port	0	0	0	0
Taesan port	0	0	0	0
Ulsan port	0	0	0	0
Yosu port	0	0	0	0
Chiba port	0	0	0	0
Kagoshima port	0	0	0	0
Kawasaki port	0	0	0	0
Mizushima port	0	0	0	0
Osaka Sakai port	0	0	0	0
Yokkaichi port	0	0	0	0
Dalian port	0	0	0	0
HangZhou port	0	0	0	0
Ningbo port	0	0	0	0
Qingdao port	0	0	0	0
Shenzhen port	0	0	0	0
Shijiazhuang port	0	0	0	0
Tianjin port	0	0	0	0
Xiamen port	0	0	0	0
Zhanjiang port	0	0	0	0
Singapore port	0	0	0	0
Suez Canal/SUMED Pipeline	2	29.8295	177.96	1061.6921
Wilhelmshaven port area	0	0	0	0
Rotterdam port area	0	0	0	0

Appendix 1.4: In-Degree centrality scores with different values of turning parameter (case 1)

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port area	0	0	0	0
Umm Said and RasLaffan Terminal area	0	0	0	0
Mina al-Ahmadi area	0	0	0	0
Jebel dhanna port area	0	0	0	0
Basrah Oil Terminal area	0	0	0	0
Kharg Island area	0	0	0	0
Puerta la Cruz port	0	0	0	0
Malongo port Area	0	0	0	0
Niger Delta area	0	0	0	0
Corpus Chris port	5	17.9102	64.154	229.8003
Freeport port	3	12.1960	49.581	201.5637
Houston port	6	24.907	103.393	429.2014
Lake Charles port	4	17.5702	77.178	339.0083
Morgan City port	6	27.4046	125.169	571.7018
Philadelphia port	5	19.2703	74.269	286.2374
Port Arthur port	6	34.7199	200.912	1162.6077
Texas City port	6	17.515	51.129	149.2538
Mangalore Sea	6	20.9567	73.197	255.6609
Mumbai Sea	6	21.9116	80.02	292.2282
Mundra Sea	9	45.9717	234.822	1199.4632
Paradeep Sea	5	20.506	84.099	344.9064
Vizag Sea	6	18.113	54.68	165.0696
Onsan port	2	18.9338	179.244	1696.8832
Taesan port	7	26.2638	98.541	369.723
Ulsan port	6	34.4517	197.82	1135.8727
Yosu port	5	31.0561	192.896	1198.1187
Chiba port	7	31.145	138.573	616.5509
Kagoshima port	6	22.6433	85.453	322.4893
Kawasaki port	6	21.7623	78.933	286.294
Mizushima port	6	20.8302	72.316	251.0591
Osaka Sakai port	7	21.5682	66.455	204.7588
Yokkaichi port	7	25.6770	94.187	345.4915
Dalian port	6	29.5908	145.936	719.7274
HangZhou port	6	21.9784	80.508	294.9055
Ningbo port	7	39.7372	225.578	1280.5487
Qingdao port	7	42.1242	253.492	1525.4479
Shenzhen port	5	16.3686	53.586	175.4252
Shijiazhuang port	4	14.3506	51.485	184.7103
Tianjin port	7	18.7004	49.958	133.4623
Xiamen port	4	15.7981	62.395	246.4306
Zhanjiang port	8	32.6745	133.453	545.064
Singapore port	6	40.3368	271.176	1823.0612
Suez Canal/SUMED Pipeline	5	29.8295	177.96	1061.6921
Wilhelmshaven port area	4	24.9234	155.294	967.6137
Rotterdam port area	4	24.1673	146.014	882.1892

Appendix 1.5: Normalised degree safety criticality scores when β = 1 with different values of tuning parameter (case 1)

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	1	1	1	1
Umm Said and Ras-Laffan Terminal	0.4118	0.2631	0.168	0.1074
Mina al-Ahmadi	0.7353	0.4845	0.3193	0.2104
Jebel Dhanna port	0.5882	0.4485	0.3419	0.2607
Basrah Oil Terminal	0.8529	0.5263	0.3248	0.2004
Kharg Island	0.5882	0.3334	0.1889	0.1071
Puerta la Cruz port	0.6176	0.463	0.3471	0.2602
Malongo port area	0.7941	0.4424	0.2465	0.1373
Niger Delta area	0.3824	0.2085	0.1137	0.062
Corpus Chris port	0	0	0	0
Freeport port	0	0	0	0
Houston port	0	0	0	0
Lake Charles port	0	0	0	0
Morgan City port	0	0	0	0
Philadelphia port	0	0	0	0
Arthur port	0	0	0	0
Texas City port	0	0	0	0
Mangalore Sea	0	0	0	0
Mumbai Sea	0	0	0	0
Mundra Sea	0	0	0	0
Paradeep Sea	0	0	0	0
Vizag Sea	0	0	0	0
Onsan port	0	0	0	0
Taesan port	0	0	0	0
Ulsan port	0	0	0	0
Yosu port	0	0	0	0
Chiba port	0	0	0	0
Kagoshima port	0	0	0	0
Kawasaki port	0	0	0	0
Mizushima port	0	0	0	0
Osaka Sakai port	0	0	0	0
Yokkaichi port	0	0	0	0
Dalian port	0	0	0	0
HangZhou port	0	0	0	0
Ningbo port	0	0	0	0
Qingdao port	0	0	0	0
Shenzhen port	0	0	0	0
Shijiazhuang port	0	0	0	0
Tianjin port	0	0	0	0
Xiamen port	0	0	0	0
Zhanjiang port	0	0	0	0
Singapore port	0	0	0	0
Suez Canal/SUMED Pipeline	0.0588	0.0882	0.1322	0.1982
Wilhelmshaven port	0	0	0	0
Rotterdam port	0	0	0	0

Appendix 1.6: Normalised degree safety criticality scores when β = 0 with different values of tuning parameter (case 1).

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	0	0	0	0
Umm Said and Ras-Laffan Terminal	0	0	0	0
Mina al-Ahmadi	0	0	0	0
Jebel Dhanna port	0	0	0	0
Basrah Oil Terminal	0	0	0	0
Kharg Island	0	0	0	0
Puerta la Cruz port	0	0	0	0
Malongo port area	0	0	0	0
Niger Delta area	0	0	0	0
Corpus Chris port	0.5556	0.3896	0.2366	0.1261
Freeport port	0.3333	0.2653	0.1828	0.1106
Houston port	0.6667	0.5418	0.3813	0.2354
Lake Charles port	0.4444	0.3822	0.2846	0.1859
Morgan City port	0.6667	0.5962	0.4616	0.3136
Philadelphia port	0.5556	0.4192	0.2739	0.1570
Arthur port	0.6667	0.7552	0.7409	0.6377
Texas City port	0.6667	0.3810	0.1885	0.0819
Mangalore Sea	0.6667	0.4559	0.2699	0.1402
Mumbai Sea	0.6667	0.4767	0.2951	0.1603
Mundra Sea	1	1	0.8659	0.6579
Paradeep Sea	0.5556	0.4461	0.3101	0.1892
Vizag Sea	0.6667	0.3940	0.2016	0.0905
Onsan port	0.2222	0.4119	0.6610	0.9308
Taesan port	0.7778	0.5713	0.3634	0.2028
Ulsan port	0.6667	0.7494	0.7295	0.6231
Yosu port	0.5556	0.6755	0.7113	0.6572
Chiba port	0.7778	0.6775	0.5110	0.3382
Kagoshima port	0.6667	0.4925	0.3151	0.1769
Kawasaki port	0.6667	0.4734	0.2911	0.1570
Mizushima port	0.6667	0.4531	0.2667	0.1377
Osaka Sakai port	0.7778	0.4692	0.2451	0.1123
Yokkaichi port	0.7778	0.5585	0.3473	0.1895
Dalian port	0.6667	0.6437	0.5382	0.3948
HangZhou port	0.6667	0.4781	0.2969	0.1618
Ningbo port	0.7778	0.8644	0.8318	0.7024
Qingdao port	0.7778	0.9163	0.9348	0.8367
Shenzhen port	0.5556	0.3561	0.1976	0.0962
Shijiazhuang port	0.4444	0.3122	0.1899	0.1013
Tianjin port	0.7778	0.4068	0.1842	0.0732
Xiamen port	0.4444	0.3436	0.2301	0.1352
Zhanjiang port	0.8889	0.7107	0.4921	0.2990
Singapore port	0.6667	0.8774	1	1
Suez Canal/SUMED Pipeline	0.5556	0.6489	0.6563	0.5824

Wilhelmshaven port	0.4444	0.5421	0.5727	0.5308
Rotterdam port	0.4444	0.5257	0.5384	0.4839

Appendix 1.7: Normalised betweenness centrality scores with different values of tuning parameter (case 1).

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	0	0	0	0
Umm Said and Ras-Laffan Terminal	0	0	0	0
Mina al-Ahmadi	0	0	0	0
Jebel Dhanna port	0	0	0	0
Basrah Oil Terminal	0	0	0	0
Kharg Island	0	0	0	0
Puerta la Cruz port	0	0	0	0
Malongo port area	0	0	0	0
Niger Delta area	0	0	0	0
Corpus Chris port	0	0	0	0
Freeport port	0	0	0	0
Houston port	0	0	0	0
Lake Charles port	0	0	0	0
Morgan City port	0	0	0	0
Philadelphia port	0	0	0	0
Arthur port	0	0	0	0
Texas City port	0	0	0	0
Mangalore Sea	0	0	0	0
Mumbai Sea	0	0	0	0
Mundra Sea	0	0	0	0
Paradeep Sea	0	0	0	0
Vizag Sea	0	0	0	0
Onsan port	0	0	0	0
Taesan port	0	0	0	0
Ulsan port	0	0	0	0
Yosu port	0	0	0	0
Chiba port	0	0	0	0
Kagoshima port	0	0	0	0
Kawasaki port	0	0	0	0
Mizushima port	0	0	0	0
Osaka Sakai port	0	0	0	0
Yokkaichi port	0	0	0	0
Dalian port	0	0	0	0
HangZhou port	0	0	0	0
Ningbo port	0	0	0	0
Qingdao port	0	0	0	0
Shenzhen port	0	0	0	0
Shijiazhuang port	0	0	0	0
Tianjin port	0	0	0	0
Xiamen port	0	0	0	0
Zhanjiang port	0	0	0	0
Singapore port	0	0	0	0

Suez Canal/SUMED Pipeline	1	1	1	1
Wilhelmshaven port	0	0	0	0
Rotterdam port	0	0	0	0

Appendix 1.8: Out-Degree centrality scores with different values of turning parameter (case 2).

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	1	1	1346.074	49385.949
Umm Said and Ras-Laffan Terminal	1	1	226.205	3402.1488
Mina al-Ahmadi	1	1	429.802	8910.5118
Jebel Dhanna port	1	1	460.288	9875.1677
Basrah Oil Terminal	1	1	437.142	9139.7392
Kharg Island	1	1	254.336	4056.129
Puerta la Cruz port	11	11	467.204	3044.8331
Niger Delta area	8	8	153.077	669.6069
Malongo port area	11	11	331.768	1822.0295
Strait of Hormuz	8	8	3153.849	62620.4741
Cape of Good Hope	14	14	1023.75	8754.4094
Strait of Malacca	20	20	2531.985	28488.9665
Bab El-Mandab	1	1	177.96	2374.0157
Suez Canal/SUMED Pipeline	2	2	177.96	1678.6826
Mangalore Sea	0	0	0	0
Mumbai Sea	0	0	0	0
Mundra Sea	0	0	0	0
Paradeep Sea	0	0	0	0
Vizag Sea	0	0	0	0
Rotterdam port	0	0	0	0
Wilhelmshaven port	0	0	0	0
Texas City port	0	0	0	0
Freeport port	0	0	0	0
Houston port	0	0	0	0
Lake Charles port	0	0	0	0
Morgan City port	0	0	0	0
Philadelphia port	0	0	0	0
Arthur port	0	0	0	0
Corpus Chris port	0	0	0	0
Dalian port	0	0	0	0
HangZhou port	0	0	0	0
Ningbo port	0	0	0	0
Qingdao port	0	0	0	0
Shenzhen port	0	0	0	0
Shijiazhuang port	0	0	0	0
Tianjin port	0	0	0	0
Xiamen port	0	0	0	0
Zhanjiang port	0	0	0	0
Chiba port	0	0	0	0
Kagoshima port	0	0	0	0
Kawasaki port	0	0	0	0
Mizushima port	0	0	0	0

Osaka Sakai port	0	0	0	0
Yokkaichi port	0	0	0	0
Onsan port	0	0	0	0
Taesan port	0	0	0	0
Ulsan port	0	0	0	0
Yosu port	0	0	0	0
Singapore port	0	0	0	0

Appendix 1.9: In-Degree centrality scores with different values of turning parameter (case 2).

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	0	0	0	0
Umm Said and Ras-Laffan Terminal	0	0	0	0
Mina al-Ahmadi	0	0	0	0
Jebel Dhanna port	0	0	0	0
Basrah Oil Terminal	0	0	0	0
Kharg Island	0	0	0	0
Puerta la Cruz port	0	0	0	0
Niger Delta area	0	0	0	0
Malongo port area	0	0	0	0
Strait of Hormuz	6	137.5612	3153.847	72307.8263
Cape of Good Hope	4	63.9922	1023.75	16378.0004
Strait of Malacca	2	71.1616	2531.987	90090.1291
Bab El-Mandab	1	13.3402	177.96	2374.0157
Suez Canal/SUMED Pipeline	1	13.3402	177.96	2374.0157
Mangalore Sea	2	12.0994	73.197	442.8177
Mumbai Sea	2	12.6507	80.02	506.1542
Mundra Sea	2	21.6713	234.822	2544.4456
Paradeep Sea	2	12.9691	84.099	545.3449
Vizag Sea	2	10.4575	54.68	285.909
Rotterdam port	4	24.1673	146.014	882.1892
Wilhelmshaven port	4	24.9234	155.294	967.6137
Texas City port	4	14.3009	51.129	182.7978
Freeport port	3	12.1960	49.581	201.5637
Houston port	4	20.3365	103.393	525.6622
Lake Charles port	3	15.2162	77.178	391.453
Morgan City port	4	22.3758	125.169	700.1888
Philadelphia port	4	17.2359	74.269	320.0231
Arthur port	4	28.3487	200.912	1423.8978
Corpus Chris port	3	13.8730	64.154	296.6709
Dalian port	1	12.0804	145.936	1762.9649
HangZhou port	1	8.9726	80.508	722.3681
Ningbo port	1	15.0192	225.578	3388.0133
Qingdao port	1	15.9214	253.492	4035.9557
Shenzhen port	1	7.32025	53.586	392.2627
Shijiazhuang port	1	7.1753	51.485	369.4206
Tianjin port	1	7.0681	49.958	353.108
Xiamen port	1	7.8991	62.395	492.8613
Zhanjiang port	1	11.5522	133.453	1541.6739
Chiba port	1	11.7717	138.573	1631.2402

Kagoshima port	1	9.2441	85.453	789.9343
Kawasaki port	1	8.8844	78.933	701.2743
Mizushima port	1	8.5039	72.316	614.9667
Osaka Sakai port	1	8.152	66.455	541.7407
Yokkaichi port	1	9.705	94.187	914.0847
Onsan port	1	13.3882	179.244	2399.7552
Taesan port	1	9.9268	98.541	978.195
Ulsan port	1	14.065	197.82	2782.3086
Yosu port	1	13.8887	192.896	2679.0748
Singapore port	1	16.4674	271.176	4465.5697

Appendix 1.10: Normalised degree safety criticality scores when β = 1 with different values of tuning parameter (case2).

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	0.05	0.1631	0.4268	0.7886
Umm Said and Ras-Laffan Terminal	0.05	0.0668	0.0717	0.0543
Mina al-Ahmadi	0.05	0.0921	0.1363	0.1423
Jebel Dhanna port	0.05	0.0953	0.1459	0.1577
Basrah Oil Terminal	0.05	0.0929	0.1386	0.1459
Kharg Island	0.05	0.0709	0.0806	0.0648
Puerta la Cruz port	0.55	0.3186	0.1481	0.0486
Niger Delta area	0.4	0.1555	0.0485	0.0107
Malongo port area	0.55	0.2684	0.1052	0.0291
Strait of Hormuz	0.4	0.7059	1	1
Cape of Good Hope	0.7	0.5320	0.3246	0.1398
Strait of Malacca	1	1	0.8028	0.4549
Bab El-Mandab	0.05	0.0593	0.0564	0.0379
Suez Canal/SUMED Pipeline	0.1	0.0838	0.0564	0.0268
Mangalore Sea	0	0	0	0
Mumbai Sea	0	0	0	0
Mundra Sea	0	0	0	0
Paradeep Sea	0	0	0	0
Vizag Sea	0	0	0	0
Rotterdam port	0	0	0	0
Wilhelmshaven port	0	0	0	0
Texas City port	0	0	0	0
Freeport port	0	0	0	0
Houston port	0	0	0	0
Lake Charles port	0	0	0	0
Morgan City port	0	0	0	0
Philadelphia port	0	0	0	0
Arthur port	0	0	0	0
Corpus Chris port	0	0	0	0
Dalian port	0	0	0	0
HangZhou port	0	0	0	0
Ningbo port	0	0	0	0
Qingdao port	0	0	0	0
Shenzhen port	0	0	0	0
Shijiazhuang port	0	0	0	0
Tianjin port	0	0	0	0

Xiamen port	0	0	0	0
Zhanjiang port	0	0	0	0
Chiba port	0	0	0	0
Kagoshima port	0	0	0	0
Kawasaki port	0	0	0	0
Mizushima port	0	0	0	0
Osaka Sakai port	0	0	0	0
Yokkaichi port	0	0	0	0
Onsan port	0	0	0	0
Taesan port	0	0	0	0
Ulsan port	0	0	0	0
Yosu port	0	0	0	0
Singapore port	0	0	0	0

Appendix 1.11: Normalised degree safety criticality scores when β = 0 with different values of tuning parameter (case 2).

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	0	0	0	0
Umm Said and Ras-Laffan Terminal	0	0	0	0
Mina al-Ahmadi	0	0	0	0
Jebel Dhanna port	0	0	0	0
Basrah Oil Terminal	0	0	0	0
Kharg Island	0	0	0	0
Puerta la Cruz port	0	0	0	0
Niger Delta area	0	0	0	0
Malongo port area	0	0	0	0
Strait of Hormuz	1	1	1	0.8026
Cape of Good Hope	0.6667	0.4652	0.3246	0.1818
Strait of Malacca	0.3333	0.5174	0.8028	1
Bab El-Mandab	0.1667	0.0970	0.0564	0.0263
Suez Canal/SUMED Pipeline	0.1667	0.0970	0.0564	0.0263
Mangalore Sea	0.3333	0.0880	0.0232	0.0049
Mumbai Sea	0.3333	0.0920	0.0254	0.0056
Mundra Sea	0.3333	0.1575	0.0745	0.0282
Paradeep Sea	0.3333	0.0943	0.0267	0.0061
Vizag Sea	0.3333	0.0760	0.0173	0.0032
Rotterdam port	0.6667	0.1757	0.0463	0.0098
Wilhelmshaven port	0.6667	0.1812	0.0492	0.0107
Texas City port	0.6667	0.1040	0.0162	0.0020
Freeport port	0.5	0.0887	0.0157	0.0022
Houston port	0.6667	0.1478	0.0328	0.0058
Lake Charles port	0.5	0.1106	0.0245	0.0043
Morgan City port	0.6667	0.1627	0.0397	0.0078
Philadelphia port	0.6667	0.1253	0.0235	0.0035
Arthur port	0.6667	0.2061	0.0637	0.0158
Corpus Chris port	0.5	0.1008	0.0203	0.0033
Dalian port	0.1667	0.0878	0.0463	0.0196
HangZhou port	0.1667	0.0652	0.0255	0.0080
Ningbo port	0.1667	0.1092	0.0715	0.0376
Qingdao port	0.1667	0.1157	0.0804	0.0448

Shenzhen port	0.1667	0.0532	0.0170	0.0043
Shijiazhuang port	0.1667	0.0522	0.0163	0.0041
Tianjin port	0.1667	0.0514	0.0158	0.0040
Xiamen port	0.1667	0.0574	0.0198	0.0055
Zhanjiang port	0.1667	0.0840	0.0423	0.0171
Chiba port	0.1667	0.0856	0.0439	0.0181
Kagoshima port	0.1667	0.0672	0.0271	0.0088
Kawasaki port	0.1667	0.0646	0.0250	0.0078
Mizushima port	0.1667	0.0618	0.0229	0.0068
Osaka Sakai port	0.1667	0.0593	0.0211	0.0060
Yokkaichi port	0.1667	0.0705	0.0299	0.0101
Onsan port	0.1667	0.0973	0.0568	0.0266
Taesan port	0.1667	0.0722	0.0312	0.0109
Ulsan port	0.1667	0.1022	0.0627	0.0309
Yosu port	0.1667	0.1010	0.0612	0.0297
Singapore port	0.1667	0.1198	0.0860	0.0496

Appendix 1.12: Normalised Betweenness centrality scores with different values of tuning parameter (case 2).

	Alpha 0.0	Alpha 0.5	Alpha 1.0	Alpha 1.5
Ras-Tanura port	0	0	0	0
Umm Said and Ras-Laffan terminal	0	0	0	0
Mina al-Ahmadi	0	0	0	0
Jebel Dhanna port	0	0	0	0
Basrah Oil Terminal	0	0	0	0
Kharg Island	0	0	0	0
Puerta la Cruz port	0	0	0	0
Niger Delta area	0	0	0	0
Malongo port area	0	0	0	0
Strait of Hormuz	1	1	1	1
Cape of Good Hope	0.5855	0.6538	0.6923	0.6923
Strait of Malacca	0.9402	0.9402	0.9402	0.9402
Bab El-Mandab	0.0897	0.0897	0.0897	0.0897
Suez Canal/SUMED Pipeline	0.0684	0.0684	0.0684	0.0684
Mangalore Sea	0	0	0	0
Mumbai Sea	0	0	0	0
Mundra Sea	0	0	0	0
Paradeep Sea	0	0	0	0
Vizag sea	0	0	0	0
Rotterdam port	0	0	0	0
Wilhelmshaven port	0	0	0	0
Texas City port	0	0	0	0
Freeport port	0	0	0	0
Houston port	0	0	0	0
Lake Charles port	0	0	0	0
Morgan City port	0	0	0	0
Philadelphia port	0	0	0	0
Arthur port	0	0	0	0
Corpus Chris port	0	0	0	0
Dalian port	0	0	0	0

HangZhou port	0	0	0	0
Ningbo port	0	0	0	0
Qingdao port	0	0	0	0
Shenzhen port	0	0	0	0
Shijiazhuang port	0	0	0	0
Tianjin port	0	0	0	0
Xiamen port	0	0	0	0
Zhanjiang port	0	0	0	0
Chiba port	0	0	0	0
Kagoshima port	0	0	0	0
Kawasaki port	0	0	0	0
Mizushima port	0	0	0	0
Osaka Sakai port	0	0	0	0
Yokkaichi port	0	0	0	0
Onsan port	0	0	0	0
Taesan port	0	0	0	0
Ulsan port	0	0	0	0
Yosu port	0	0	0	0
Singapore port	0	0	0	0

Questionnaire used for the purpose of Chapter 4

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Date :

Dear Sir,

My name is Ayman Fahad Alghanmi and I am a PhD student from Liverpool John Moores University. For my research project I am investigating the hazard that influence the operation at ship transportation system that might lead to crude oil spill. The results of this study will be used to determine the hazards that affect the operation at ship transportation system. Because you are an expert in the petroleum transportation industry, I am inviting you to participate in this research study by completing the attached survey.

The following questionnaire will takes a maximum of 30 minutes of your time. There is no compensation for responding nor is there any known risk. In order to ensure that all information will remain confidential, please do not include your name. If you choose to participate in this project, please answer all questions as honestly as possible and e-mail me the completed questionnaires. Your participation in this project is entirely voluntary and you can withdraw from the study at any time.

Thank you for taking the time to assist me in my educational endeavours. If you require additional information or have questions, please contact me at the number/e-mail listed below.

Sincerely,

Ayman Fahad Alghanmi
Liverpool Logistics Offshore and Marine Research Institute (LOOM)
Liverpool John Moores University
Tel: 074 7720 0174
E-mail: A.F.Alghanmi@2013.ljmu.ac.uk

SECTION 1: PERSONAL DETAILS

- Please mark the appropriate answer for each question:

1. Please mark your age range:
    A. Less than 30 years old
    B. Between 30 and 40 years old
    C. 40 years old or more
2. Please mark your appropriate qualification:
    A. Diploma
    B. BSc

C. MSc

D. PhD

3. Please mark your work experiences:

A. Work experience 1-5 Years

B. Work experience 6-10 Years

C. Work experience 11-15 Years

D. Work experience 16-20 Years

E. Work experience over 20 Years

SECTION 2: PARAMETERS DESCRIPTION

P_l: The occurrence probability of a risk event during the process of oil transport

Description of the parameter **P_l** for each hazard where that:

Occurrence Probability of a Hazard	Description
Very Low	The probability of occurrence is unlikely to occur but possible
Low	The probability of occurrence is likely once per year
Medium	The probability of occurrence is likely once per quarter
High	The probability of occurrence is likely once per month
Very High	The probability of occurrence is expected once per month

S_c: The consequence severity that the risk event would cause if it occurs

Description of the parameter **S_c** for each hazard where that:

Consequence Severity of a Hazard	Description
Very Low	At most minor injury involved and negligible damage to the system; no damage to the environment
Low	Minor medical treatment required; slight equipment or system damage but still fully functional and serviceable; minor environmental damage
Medium	Minor injury; moderate incapacity of systems, equipment, or facilities that disrupts operations; moderate damage to the environment
High	Permanent total disability; damage to major facilities; severe environmental damage
Very High	Death; loss of major facilities; major environmental damage

D_p: The probability that the risk event cannot be detected before it occurs

Description of the parameter **S_c** for each hazard where that:

Probability of a Hazard being Undetected	Description
Very Low	Possible to detect without checks or maintenance
Low	Possible to detect through regular checks or maintenance
Medium	Possible to detect through intensive checks or maintenance
High	Difficult to detect through intensive or regular checks or maintenance
Very High	Impossible to detect even through intensive or regular checks or maintenance

SECTION 3: QUESTIONNAIRE EXAMPLE

An expert is required to give a possible judgment to all questions based on his/her expertise and experience in the marine transportation industry. The judgement process has to be focussed on how to achieve the 21 respective goals (Part 1 until Part 61). The total assessment for each attribute must not be over 100%. For instance:

***Goal**: To evaluate the risk of illness in winter*

Risk Parameters / **Event**	**Probability**					**Consequences**				
	VH	*H*	*M*	*L*	*VL*	*VH*	*H*	*M*	*L*	*VL*
How likely to swim during cold weather?	*0%*	*0%*	*0%*	*0%*	*100%*	*90%*	*10%*	*0%*	*0%*	*0%*
How likely to eat ice cream during in winter?	*0%*	*0%*	*5%*	*10%*	*85%*	*0%*	*10%*	*40%*	*30%*	*20%*

The explanation of the above example,

1. The probability of swim during cold weather is 100% Very Low because of the water temperature, and the consequences of swimming is 90% Very High, and10% High because the weather condition. That means the risk assessment of swimming during cold wither reasonably High risk, and recommended not to swim.

2. The probability of eating ice cream during winter is 5% Medium, 10% Low, and 85% Very Low because of the water temperature, and the consequences of eating ice cream is 10% High, 40% Medium, 30% Low, and 20% Very Low because the weather condition. That means the risk assessment of eating ice cream during cold wither reasonably Medium risk, and recommended not to eat to avoid possible illness.

SECTION 4: QUESTIONNAIRE

Part 1: Ship Collison hazards:

Please indicate occurrence of hazard event: Machinery Failure cased because Main Engine Failure		**Likelihood**	**Consequences**	**Probability**
	Very High			
	High			
	Medium			
	Low			
	Very Low			
Please indicate occurrence of hazard event: Machinery Failure cased because Bridge Navigation Equipment Failure		**Likelihood**	**Consequences**	**Probability**
	Very High			
	High			
	Medium			
	Low			
	Very Low			
Please indicate occurrence of hazard event: Machinery Failure cased because Communication System Failure		**Likelihood**	**Consequences**	**Probability**
	Very High			
	High			
	Medium			
	Low			
	Very Low			

Appendix Chapter 4

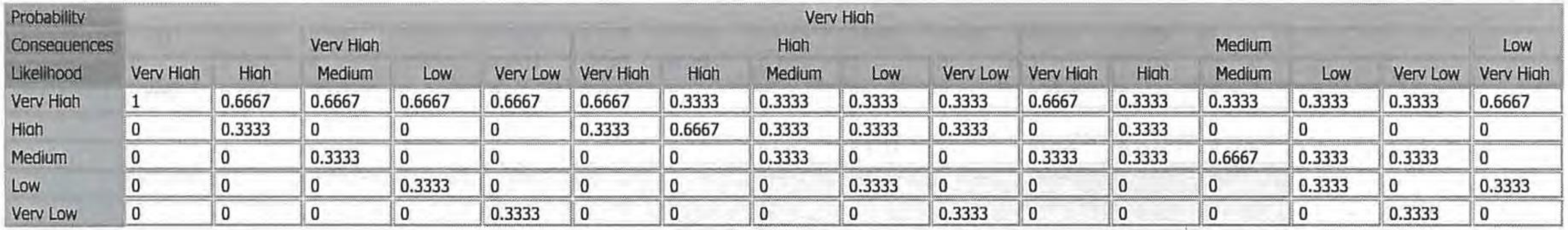
Appendix 2.1: The established FRB with belief structure for petroleum port risk evaluation

Rule No	Risk parameters in the IF part			Belief degree in the THEN part				
	L	C	P	Very High	High	Medium	Low	Very Low
1	Very High (L1)	Very High (C1)	Very High (P1)	1	0	0	0	0
2	Very High (L1)	Very High (C1)	High (P2)	0.67	0.33	0	0	0
3	Very High (L1)	Very High (C1)	Medium(P3)	0.67	0	0.33	0	0
4	Very High (L1)	Very High (C1)	Low (P4)	0.67	0	0	0.33	0
5	Very High (L1)	Very High (C1)	Very Low (P5)	0.67	0	0	0	0.33
6	Very High (L1)	High (C2)	Very High (P1)	0.67	0.33	0	0	0
7	Very High (L1)	High (C2)	High (P2)	0.33	0.67	0	0	0
8	Very High (L1)	High (C2)	Medium(P3)	0.33	0.33	0.33	0	0
9	Very High (L1)	High (C2)	Low (P4)	0.33	0.33	0	0.33	0
10	Very High (L1)	High (C2)	Very Low (P5)	0.33	0.33	0	0	0.33
11	Very High (L1)	Medium (C3)	Very High (P1)	0.67	0	0.33	0	0
12	Very High (L1)	Medium (C3)	High (P2)	0.33	0.33	0.33	0	0
13	Very High (L1)	Medium (C3)	Medium(P3)	0.33	0	0.67	0	0
14	Very High (L1)	Medium (C3)	Low (P4)	0.33	0	0.33	0.33	0
15	Very High (L1)	Medium (C3)	Very Low (P5)	0.33	0	0.33	0	0.33
16	Very High (L1)	Low (C4)	Very High (P1)	0.67	0	0	0.33	0
17	Very High (L1)	Low (C4)	High (P2)	0.33	0.33	0	0.33	0
18	Very High (L1)	Low (C4)	Medium(P3)	0.33	0	0.33	0.33	0
19	Very High (L1)	Low (C4)	Low (P4)	0.33	0	0	0.67	0
20	Very High (L1)	Low (C4)	Very Low (P5)	0.33	0	0	0.33	0.33
21	Very High (L1)	Very Low (C5)	Very High (P1)	0.67	0	0	0	0.33
22	Very High (L1)	Very Low (C5)	High (P2)	0.33	0.33	0	0	0.33
23	Very High (L1)	Very Low (C5)	Medium(P3)	0.33	0	0.33	0	0.33
24	Very High (L1)	Very Low (C5)	Low (P4)	0.33	0	0	0.33	0.33
25	Very High (L1)	Very Low (C5)	Very Low (P5)	0.33	0	0	0	0.67
26	High (L2)	Very High (C1)	Very High (P1)	0.67	0.33	0	0	0
27	High (L2)	Very High (C1)	High (P2)	0.33	0.67	0	0	0
28	High (L2)	Very High (C1)	Medium(P3)	0.33	0.33	0.33	0	0
29	High (L2)	Very High (C1)	Low (P4)	0.33	0.33	0	0.33	0
30	High (L2)	Very High (C1)	Very Low (P5)	0.33	0.33	0	0	0.33
31	High (L2)	High (C2)	Very High (P1)	0.33	0.67	0	0	0
32	High (L2)	High (C2)	High (P2)	0	1	0	0	0
33	High (L2)	High (C2)	Medium(P3)	0	0.67	0.33	0	0
34	High (L2)	High (C2)	Low (P4)	0	0.67	0	0.33	0
35	High (L2)	High (C2)	Very Low (P5)	0	0.67	0	0	0.33
36	High (L2)	Medium (C3)	Very High (P1)	0.33	0.33	0.33	0	0
37	High (L2)	Medium (C3)	High (P2)	0	0.67	0.33	0	0
38	High (L2)	Medium (C3)	Medium(P3)	0	0.33	0.67	0	0
39	High (L2)	Medium (C3)	Low (P4)	0	0.33	0.33	0.33	0
40	High (L2)	Medium (C3)	Very Low (P5)	0	0.33	0.33	0	0.33
41	High (L2)	Low (C4)	Very High (P1)	0.33	0.33	0	0.33	0
42	High (L2)	Low (C4)	High (P2)	0	0.67	0	0.33	0
43	High (L2)	Low (C4)	Medium(P3)	0	0.33	0.33	0.33	0

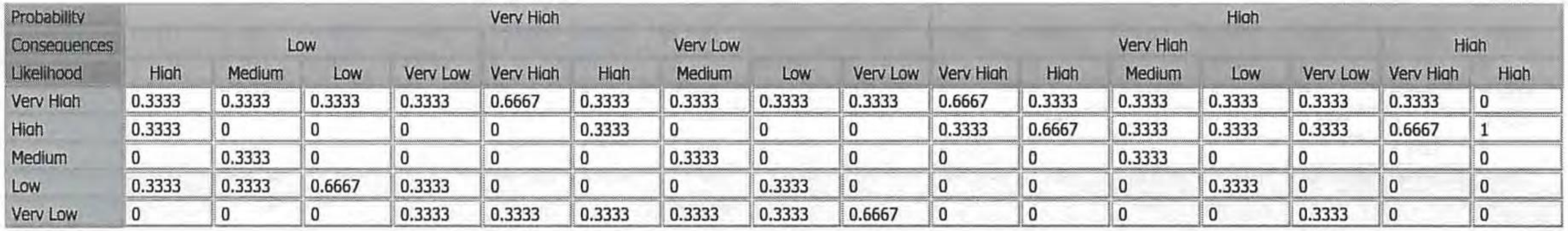
44	High (L2)	Low (C4)	Low (P4)	0	0.33	0	0.67	0
45	High (L2)	Low (C4)	Very Low (P5)	0	0.33	0	0.33	0.33
46	High (L2)	Very Low (C5)	Very High (P1)	0.33	0.33	0	0	0.33
47	High (L2)	Very Low (C5)	High (P2)	0	0.67	0	0	0.33
48	High (L2)	Very Low (C5)	Medium(P3)	0	0.33	0.33	0	0.33
49	High (L2)	Very Low (C5)	Low (P4)	0	0.33	0	0.33	0.33
50	High (L2)	Very Low (C5)	Very Low (P5)	0	0.33	0	0	0.67
51	Medium (L3)	Very High (C1)	Very High (P1)	0.67	0	0.33	0	0
52	Medium (L3)	Very High (C1)	High (P2)	0.33	0.33	0.33	0	0
53	Medium (L3)	Very High (C1)	Medium(P3)	0.33	0	0.67	0	0
54	Medium (L3)	Very High (C1)	Low (P4)	0.33	0	0.33	0.33	0
55	Medium (L3)	Very High (C1)	Very Low (P5)	0.33	0	0.33	0	0.33
56	Medium (L3)	High (C2)	Very High (P1)	0.33	0.33	0.33	0	0
57	Medium (L3)	High (C2)	High (P2)	0	0.67	0.33	0	0
58	Medium (L3)	High (C2)	Medium(P3)	0	0.33	0.67	0	0
59	Medium (L3)	High (C2)	Low (P4)	0	0.33	0.33	0.33	0
60	Medium (L3)	High (C2)	Very Low (P5)	0	0.33	0.33	0	0.33
61	Medium (L3)	Medium (C3)	Very High (P1)	0.33	0	0.67	0	0
62	Medium (L3)	Medium (C3)	High (P2)	0	0.33	0.67	0	0
63	Medium (L3)	Medium (C3)	Medium(P3)	0	0	1	0	0
64	Medium (L3)	Medium (C3)	Low (P4)	0	0	0.67	0.33	0
65	Medium (L3)	Medium (C3)	Very Low (P5)	0	0	0.67	0	0.33
66	Medium (L3)	Low (C4)	Very High (P1)	0.33	0	0.33	0.33	0
67	Medium (L3)	Low (C4)	High (P2)	0	0.33	0.33	0.33	0
68	Medium (L3)	Low (C4)	Medium(P3)	0	0	0.67	0.33	0
69	Medium (L3)	Low (C4)	Low (P4)	0	0	0.33	0.67	0
70	Medium (L3)	Low (C4)	Very Low (P5)	0	0	0.33	0.33	0.33
71	Medium (L3)	Very Low (C5)	Very High (P1)	0.33	0	0.33	0	0.33
72	Medium (L3)	Very Low (C5)	High (P2)	0	0.33	0.33	0	0.33
73	Medium (L3)	Very Low (C5)	Medium(P3)	0	0	0.67	0	0.33
74	Medium (L3)	Very Low (C5)	Low (P4)	0	0	0.33	0.33	0.33
75	Medium (L3)	Very Low (C5)	Very Low (P5)	0	0	0.33	0	0.67
76	Low (L4)	Very High (C1)	Very High (P1)	0.67	0	0	0.33	0
77	Low (L4)	Very High (C1)	High (P2)	0.33	0.33	0	0.33	0
78	Low (L4)	Very High (C1)	Medium(P3)	0.33	0	0.33	0.33	0
79	Low (L4)	Very High (C1)	Low (P4)	0.33	0	0	0.67	0
80	Low (L4)	Very High (C1)	Very Low (P5)	0.33	0	0	0.33	0.33
81	Low (L4)	High (C2)	Very High (P1)	0.33	0.33	0	0.33	0
82	Low (L4)	High (C2)	High (P2)	0	0.67	0	0.33	0
83	Low (L4)	High (C2)	Medium(P3)	0	0.33	0.33	0.33	0
84	Low (L4)	High (C2)	Low (P4)	0	0.33	0	0.67	0
85	Low (L4)	High (C2)	Very Low (P5)	0	0.33	0	0.33	0.33
86	Low (L4)	Medium (C3)	Very High (P1)	0.33	0	0.33	0.33	0
87	Low (L4)	Medium (C3)	High (P2)	0	0.33	0.33	0.33	0
88	Low (L4)	Medium (C3)	Medium(P3)	0	0	0.67	0.33	0
89	Low (L4)	Medium (C3)	Low (P4)	0	0	0.33	0.67	0
90	Low (L4)	Medium (C3)	Very Low (P5)	0	0	0.33	0.33	0.33
91	Low (L4)	Low (C4)	Very High (P1)	0.33	0	0	0.67	0
92	Low (L4)	Low (C4)	High (P2)	0	0.33	0	0.67	0
93	Low (L4)	Low (C4)	Medium(P3)	0	0	0.33	0.67	0
94	Low (L4)	Low (C4)	Low (P4)	0	0	0	1	0
95	Low (L4)	Low (C4)	Very Low (P5)	0	0	0	0.67	0.33
96	Low (L4)	Very Low (C5)	Very High (P1)	0.33	0	0	0.33	0.33
97	Low (L4)	Very Low (C5)	High (P2)	0	0.33	0	0.33	0.33

98	Low (L4)	Very Low (C5)	Medium(P3)	0	0	0.33	0.33	0.33
99	Low (L4)	Very Low (C5)	Low (P4)	0	0	0	0.67	0.33
100	Low (L4)	Very Low (C5)	Very Low (P5)	0	0	0	0.33	0.67
101	Very Low (L5)	Very High (C1)	Very High (P1)	0.67	0	0	0	0.33
102	Very Low (L5)	Very High (C1)	High (P2)	0.33	0.33	0	0	0.33
103	Very Low (L5)	Very High (C1)	Medium(P3)	0.33	0	0.33	0	0.33
104	Very Low (L5)	Very High (C1)	Low (P4)	0.33	0	0	0.33	0.33
105	Very Low (L5)	Very High (C1)	Very Low (P5)	0.33	0	0	0	0.67
106	Very Low (L5)	High (C2)	Very High (P1)	0.33	0.33	0	0	0.33
107	Very Low (L5)	High (C2)	High (P2)	0	0.67	0	0	0.33
108	Very Low (L5)	High (C2)	Medium(P3)	0	0.33	0.33	0	0.33
109	Very Low (L5)	High (C2)	Low (P4)	0	0.33	0	0.33	0.33
110	Very Low (L5)	High (C2)	Very Low (P5)	0	0.33	0	0	0.67
111	Very Low (L5)	Medium (C3)	Very High (P1)	0.33	0	0.33	0	0.33
112	Very Low (L5)	Medium (C3)	High (P2)	0	0.33	0.33	0	0.33
113	Very Low (L5)	Medium (C3)	Medium(P3)	0	0	0.67	0	0.33
114	Very Low (L5)	Medium (C3)	Low (P4)	0	0	0.33	0.33	0.33
115	Very Low (L5)	Medium (C3)	Very Low (P5)	0	0	0.33	0	0.67
116	Very Low (L5)	Low (C4)	Very High (P1)	0.33	0	0	0.33	0.33
117	Very Low (L5)	Low (C4)	High (P2)	0	0.33	0	0.33	0.33
118	Very Low (L5)	Low (C4)	Medium(P3)	0	0	0.33	0.33	0.33
119	Very Low (L5)	Low (C4)	Low (P4)	0	0	0	0.67	0.33
120	Very Low (L5)	Low (C4)	Very Low (P5)	0	0	0	0.33	0.67
121	Very Low (L5)	Very Low (C5)	Very High (P1)	0.33	0	0	0	0.67
122	Very Low (L5)	Very Low (C5)	High (P2)	0	0.33	0	0	0.67
123	Very Low (L5)	Very Low (C5)	Medium(P3)	0	0	0.33	0	0.67
124	Very Low (L5)	Very Low (C5)	Low (P4)	0	0	0	0.33	0.67
125	Very Low (L5)	Very Low (C5)	Very Low (P5)	0	0	0	0	1

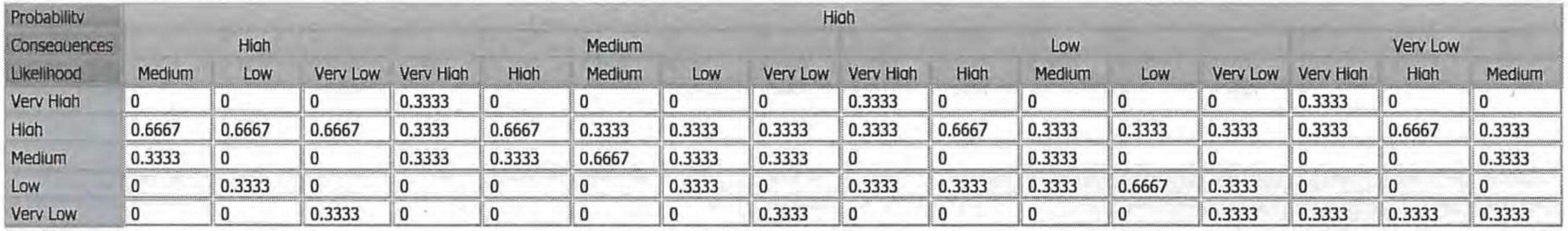
Appendix 2.2: The degree of belief table for MRHAA



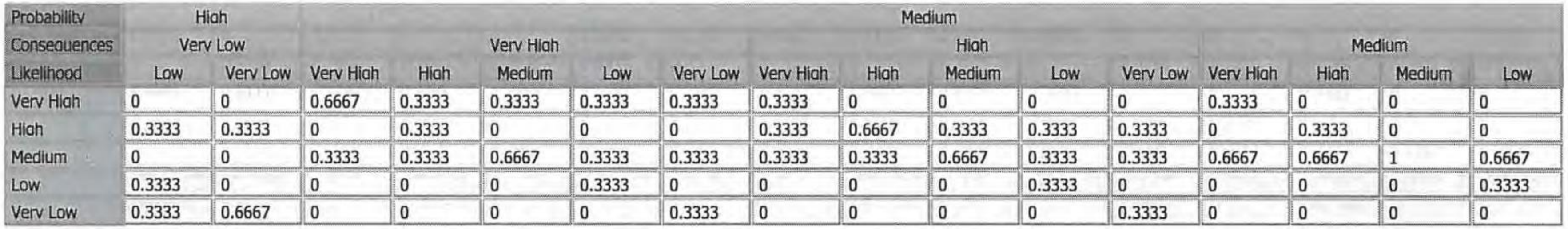
Probability	Very High															
Consequences	Very High					High					Medium					Low
Likelihood	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High
Very High	1	0.6667	0.6667	0.6667	0.6667	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667
High	0	0.3333	0	0	0	0.3333	0.6667	0.3333	0.3333	0.3333	0	0.3333	0	0	0	0
Medium	0	0	0.3333	0	0	0	0	0.3333	0	0	0.3333	0.3333	0.6667	0.3333	0.3333	0
Low	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0.3333
Very Low	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0



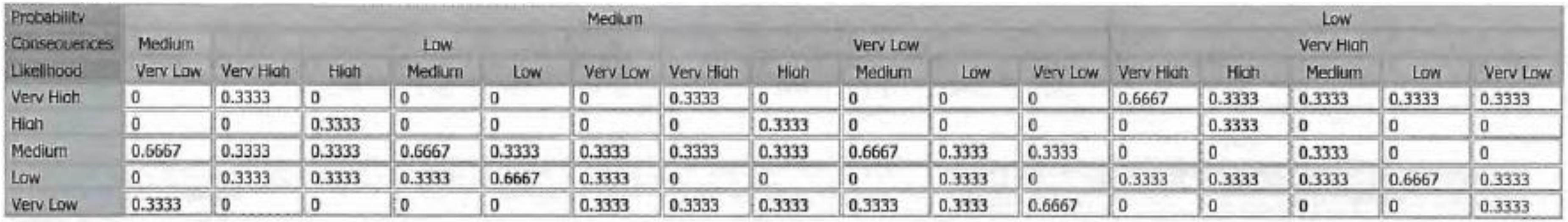
Probability	Very High									High						
Consequences	Low				Very Low					Very High					High	
Likelihood	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High
Very High	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.3333	0
High	0.3333	0	0	0	0	0.3333	0	0	0	0.3333	0.6667	0.3333	0.3333	0.3333	0.6667	1
Medium	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0
Low	0.3333	0.3333	0.6667	0.3333	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0
Very Low	0	0	0	0.3333	0.3333	0.3333	0.3333	0.3333	0.6667	0	0	0	0	0.3333	0	0



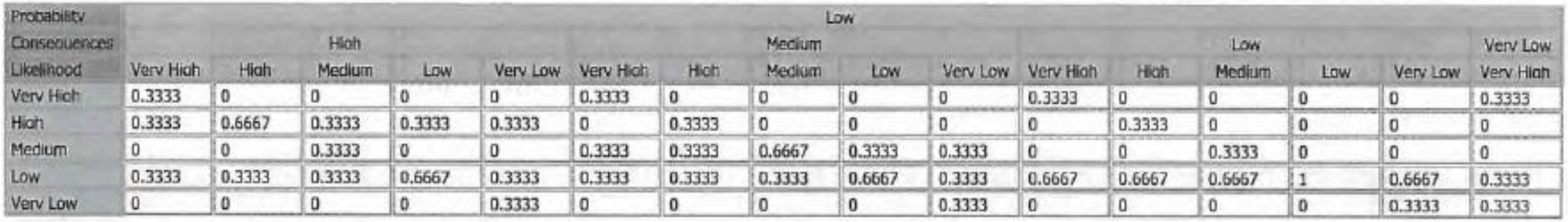
Probability	High															
Consequences	High			Medium					Low					Very Low		
Likelihood	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium
Very High	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0
High	0.6667	0.6667	0.6667	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333
Medium	0.3333	0	0	0.3333	0.3333	0.6667	0.3333	0.3333	0	0	0.3333	0	0	0	0	0.3333
Low	0	0.3333	0	0	0	0	0.3333	0	0.3333	0.3333	0.3333	0.6667	0.3333	0	0	0
Very Low	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0.3333	0.3333	0.3333



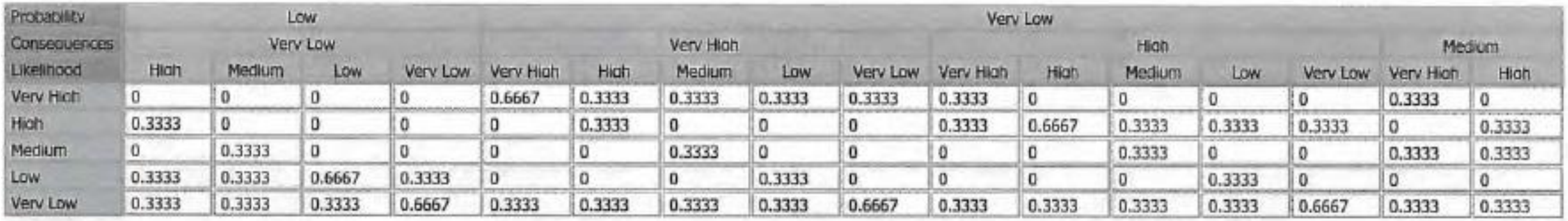
Probability	High		Medium													
Consequences	Very Low		Very High					High					Medium			
Likelihood	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low
Very High	0	0	0.6667	0.3333	0.3333	0.3333	0.3333	0.3333	0	0	0	0	0.3333	0	0	0
High	0.3333	0.3333	0	0.3333	0	0	0	0.3333	0.6667	0.3333	0.3333	0.3333	0	0.3333	0	0
Medium	0	0	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0.6667	0.6667	1	0.6667
Low	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333
Very Low	0.3333	0.6667	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0



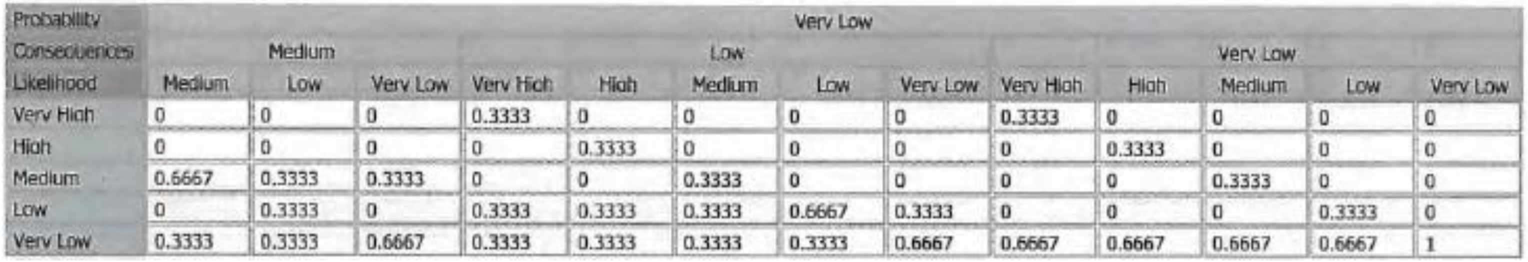
Probability	Medium											Low				
Consequences	Medium	Low					Very Low					Very High				
Likelihood	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low
Very High	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.6667	0.3333	0.3333	0.3333	0.3333
High	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0
Medium	0.6667	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0	0	0.3333	0	0
Low	0	0.3333	0.3333	0.3333	0.6667	0.3333	0	0	0	0.3333	0	0.3333	0.3333	0.3333	0.6667	0.3333
Very Low	0.3333	0	0	0	0	0.3333	0.3333	0.3333	0.3333	0.3333	0.6667	0	0	0	0	0.3333



Probability	Low															
Consequences	High					Medium					Low					Very Low
Likelihood	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High
Very High	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333
High	0.3333	0.6667	0.3333	0.3333	0.3333	0	0.3333	0	0	0	0	0.3333	0	0	0	0
Medium	0	0	0.3333	0	0	0.3333	0.3333	0.6667	0.3333	0.3333	0	0	0.3333	0	0	0
Low	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.6667	0.6667	0.6667	1	0.6667	0.3333
Very Low	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0.3333



Probability	Low				Very Low											
Consequences	Very Low				Very High					High					Medium	
Likelihood	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High
Very High	0	0	0	0	0.6667	0.3333	0.3333	0.3333	0.3333	0.3333	0	0	0	0	0.3333	0
High	0.3333	0	0	0	0	0.3333	0	0	0	0.3333	0.6667	0.3333	0.3333	0.3333	0	0.3333
Medium	0	0.3333	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0.3333	0.3333
Low	0.3333	0.3333	0.6667	0.3333	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0
Very Low	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.3333	0.3333



Probability	Very Low												
Consequences	Medium			Low					Very Low				
Likelihood	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low	Very High	High	Medium	Low	Very Low
Very High	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0	0
High	0	0	0	0	0.3333	0	0	0	0	0.3333	0	0	0
Medium	0.6667	0.3333	0.3333	0	0	0.3333	0	0	0	0	0.3333	0	0
Low	0	0.3333	0	0.3333	0.3333	0.3333	0.6667	0.3333	0	0	0	0.3333	0
Very Low	0.3333	0.3333	0.6667	0.3333	0.3333	0.3333	0.3333	0.6667	0.6667	0.6667	0.6667	0.6667	1

Appendix 2.3: Prior Probability of L, C and P for Ship transportation hazards (Collision)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H1	2.2222, 18.8889, 22.2222, 27.7778, 28.8889	28.8889, 21.6667, 19.4444, 12.2222, 17.7778	22.2222, 24.4444, 16.6667, 20, 16.6667
H2	4.4444, 10, 15.5556, 22.2222, 47.7778	36.6667, 22.7778, 20, 11.4444, 9.1111	11.1111, 15.5556, 27.7778, 25, 20.5556
H3	3.3333, 6.6667, 12.2222, 46.6667, 31.1111	14.4444, 28.3333, 21.1111, 22.5556, 13.5556	21.1111, 23.3333, 19.4444, 18.8889, 17.2222
H4	6.6667, 12.7778, 17.2222, 24.4444, 38.8889	27.7778, 33.3333, 15.5556, 16.6667, 6.6667	16.6667, 17.7778, 22.2222, 16.6667, 26.6667
H5	3.3333, 3.3333, 17.7778, 35.5556, 40	23.8889, 20.5556, 26.6667, 16.6667, 12.2222	12.2222, 17.7778, 23.3333, 26.6667, 20
H6	3.3333, 6.1111, 24.4444, 40, 26.1111	16.6667, 19.4444, 25.5556, 19.4444, 18.8889	15.5556, 14.4444, 22.2222, 28.3333, 19.4444
H7	8.3333, 8.8889, 25, 35.5556, 22.2222	41.1111, 27.7778, 15.5556, 11.1111, 4.4444	10, 16.1111, 15, 37.2222, 21.6667
H8	4.4444, 5.5556, 22.2222, 25.5556, 42.2222	38.8889, 21.6667, 15.5556, 15, 8.8889	7.7778, 11.1111, 21.1111, 21.6667, 38.3333
H9	3.8889, 6.6667, 24.4444, 41.6667, 23.3333	36.6667, 21.1111, 17.7778, 17.2222, 7.2222	7.7778, 16.1111, 15, 35, 26.1111
H10	5.5556, 20, 34.4444, 22.7778, 17.2222	33.8889, 24.4444, 15.5556, 18.8889, 7.2222	7.7777, 15.5556, 35.5556, 18.8889, 22.2222
H11	5, 6.6667, 40, 33.8889, 14.4444	7.2222, 28.8889, 34.4444, 21.1111, 8.3333	12.2222, 10.5556, 29.4444, 28.8889, 18.8889
H12	5.5556, 10.5556, 25.5556, 30, 28.3333	33.3333, 19.4444, 17.2222, 17.7778, 12.2222	15.5556, 17.2222, 28.8889, 20, 18.3333
H13	3.3333, 5.5556, 21.1111, 36.6667, 33.3333	22.7778, 19.4444, 17.2222. 20. 20.5556	6.6667, 14.4444, 37.7778, 19.4444, 21.6667

Appendix 2.4: Prior Probability of L, C and P for Ship transportation hazards (Grounding)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H14	5.5556, 11.1111, 24.4444, 31.1111, 27.7778	25.5556, 21.1111, 22.2222, 16.1111, 15	7.7778, 15.5556 ,34.4444, 23.3333, 18.8889
H15	3.3333, 7.7778, 26.6667, 20, 42.2222	22.2222, 32.2222, 17.2222, 16.1111, 12.2222	8.8889, 20, 26.1111, 22.7778, 22.2222
H16	3.3333, 6.6667, 27.7778, 30, 32.2222	23.3333, 27.7778, 21.1111, 14.4444, 13.3333	8.8889, 13.8889, 25, 28.8889, 23.3333
H17	3.3333, 5.5556, 12.2222, 42.2222, 36.6667	26.6667, 23.3333, 18.8889, 15.5556, 15.5556	11.1111, 14.4444, 17.2222, 41.6667, 15.5556
H18	3.3333, 5.5556, 21.1111, 22.7778, 47.2222	30.5556, 20, 20.5556, 14.4444, 14.4444	7.7778, 11.1111, 33.3333, 21.1111, 26.6667
H19	3.3333, 4.4444, 14.4444, 57.7778, 20	30, 15.5556, 24.4444, 16.1111, 13.8889	10, 10.5556, 20, 17.7778, 41.6667
H20	2.2222, 13.8889, 15.5556, 32.7778, 35.5556	40, 22.2222, 14.4444, 9.4444, 13.8889	12.2222, 15.5556, 26.1111, 30.5556, 15.5556
H21	3.3333, 3.3333, 11.1111, 38.8889, 43.3333	37.7778, 20, 21.1111, 12.2222, 8.8889	6.1111, 12.7778, 23.8889, 26.1111, 31.1111
H22	3.3333, 5.5556, 21.6667, 25, 44.4444	25.5556, 26.6667, 22.2222, 12.2222, 13.3333	5.5556, 13.3333, 24.4444, 25, 31.6667
H23	5.5556, 5.5556, 28.3333, 19.4444, 41.1111	29.4444, 22.7778, 22.2222, 16.6667, 8.8889	5.5556, 15, 25, 24.4444, 30
H24	5.5556, 6.6667, 34.4444, 33.3333, 20	31.1111, 22.2222, 24.4444, 13.3333, 8.8889	5.5556, 16.6667, 31.1111, 23.3333, 23.3333
H25	3.3333, 4.4444, 26.6667, 33.3333, 32.2222	26.6667, 22.7778, 20, 19.4444, 11.1111	8.3333, 13.8889, 20, 31.6667, 26.1111
H26	7.7778, 8.3333, 24.44444, 39.4444, 20	13.3333, 24.4444, 21.1111, 30, 11.1111	14.4444, 15.5556, 32.7778, 17.2222, 20

H27	3.3333, 3.8889, 13.8889, 40, 38.8889	32.2222, 19.4444, 18.8889, 18.3333, 11.1111	11.1111, 17.7778, 22.2222, 25.5556, 23.3333
H28	5, 6.6667, 29.4444, 30.5556, 28.3333	25.5556, 32.2222, 16.6667, 15.5556, 10	6.1111, 13.3333, 20, 32.2222, 28.3333

Appendix 2.5: Prior Probability of L, C and P for Ship transportation hazards (Hull Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H29	3.3333, 3.3333, 7.7778, 26.6667, 58.8889	21.1111, 32.2222, 23.3333, 15.5556, 7.7778	12.7778, 13.3333, 22.7778, 23.8889, 27.2222
H30	8.8889, 11.1111, 14.4444, 37.7778, 27.7778	10, 24.4444, 31.1111, 22.2222, 12.2222	10, 10.5556, 23.8889, 34.4444, 21.1111
H31	5.5556, 17.7778, 18.8889, 21.1111, 36.6667	13.3333, 21.1111, 31.1111, 24.4444, 10	10, 27.7778, 32.2222, 22.2222, 7.7778
H32	5.5556, 9.4444, 16.1111, 30, 38.8889	15.5556, 41.1111, 18.8889, 17.7778, 6.6667	7.7778, 12.2222, 31.1111, 26.6667, 22.2222
H33	3.3333, 5.5556, 8.8889, 33.3333, 48.8889	20, 28.8889, 27.7778, 14.4444, 8.8889	8.8889, 12.2222, 27.7778, 26.6667, 24.4444
H34	4.4444, 18.8889, 16.6667, 23.3333, 36.6667	20, 34.4444, 22.2222, 15.5556, 7.7778	7.7778, 11.1111, 36.6667, 21.6667, 22.7778

Appendix 2.6: Prior Probability of L, C and P for Ship transportation hazards transportation hazards (Fire/Explosion)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H35	3.3333, 6.6667, 18.8889, 38.8889, 32.2222	23.3333, 31.1111, 20, 10.5556, 15	7.7777, 16.6667, 28.8889, 20, 26.6667
H36	4.4444, 6.6667, 12.7778, 39.4444, 36.6667	23.3333, 30, 22.2222, 11.6667, 12.7778	13.3333, 18.8889, 25.5556, 18.8889, 23.3333
H37	4.4444, 6.6667, 12.2222, 36.6667, 40	23.3333, 31.1111, 21.1111, 14.4444, 10	7.7778, 15.8889, 23, 31.1111, 22.2222
H38	5.5556, 8.8889, 17.2222, 20.5556, 47.7778	25.5556, 26.6667, 24.4444, 12.2222, 11.1111	8.8889, 28.8889, 31.1111, 16.6667, 14.4444
H39	6.6667, 6.6667, 15, 36.1111, 35.5556	27.7778, 28.8889, 20, 12.2222, 11.1111	7.7778, 10.5556, 27.2222, 30.5556, 23.8889
H40	1.1111, 3.8889, 11.1111, 37.2222, 46.6667	23.3333, 26.6667, 17.7778, 17.7778, 14.4444	7.7778, 16.1111, 22.7778, 26.1111, 27.2222
H41	3.3333, 5, 10, 30, 51.6667	8.8889, 27.7778, 18.8889, 17.7778, 26.6667	10, 19.4444, 19.4444, 21.6667, 29.4444
H42	2.7778, 5, 10, 30, 52.2222	13.3333, 11.1111, 23.3333, 21.1111, 31.1111	5.5556, 11.1111, 25.2222, 25.7778, 32.3333
H43	3.3333, 5.5556, 13.3333, 22.7778, 55	21.1111, 27.7778, 21.1111, 17.7778, 12.2222	12.2222, 16.6667, 15.5556, 25.5556, 30
H44	2.7778, 3.3333, 8.8889, 22.2222, 62.7778	38.8889, 16.6667, 13.3333, 10, 21.1111	11.6667, 13.3333, 21.1111, 23.8889, 30
H45	3.3333, 4.4444, 10, 30.5556, 51.6667	13.3333, 32.2222, 21.1111, 18.3333, 15	10, 12.7778, 21.1111, 30, 26.1111

Appendix 2.7: Prior Probability of L, C and P for Ship transportation hazards (Equipment Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H46	3.3333, 5.5556, 15.5556, 30, 45.5556	14.4444, 21.1111, 23.8889, 20.5556, 20	7.7778, 15.5556, 32.2222, 24.4444, 20
H47	3.3333, 6.6667, 19.4444, 29.4444, 41.1111	8.8889, 18.8889, 28.8889, 22.2222, 21.1111	7.7778, 15.5556, 28.3333, 23.8889, 24.4444
H48	3.3333, 6.6667, 23.3333, 27.2222, 39.4444	11.1111, 16.6667, 27.7778, 20, 24.4444	11.1111, 16.6667, 37.7778, 22.2222, 12.2222

H49	3.3333, 5.5556, 14.4444, 30.5556, 46.1111	8.8889, 20, 15, 13.8889, 42.2222	7.7778, 13.3333, 31.6667, 26.1111, 21.1111
H50	4.4444, 16.6667, 17.7778, 26.6667, 34.4444	8.8889, 41.1111, 13.3333, 14.4444, 22.2222	7.7778, 20, 31.1111, 25.5556, 15.5556
H51	4.4444, 8.8889, 13.3333, 39.4444, 33.8889	7.7778, 30, 25.5556, 16.6667, 20	8.8889, 17.7778, 21.1111, 28.8889, 23.3333
H52	3.3333, 7.7778, 14.4444, 30, 44.4444	12.2222, 25.5556, 18.8889, 23.3333, 20	7.7778, 13.3333, 21.1111, 27.2222, 30.5556
H53	3.3333, 6.6667, 7.7778, 20, 62.2222	8.8889, 16.6667, 27.7778, 23.3333, 23.3333	7.7778, 14.4444, 17.2222, 27.7778, 32.7778
H54	3.3333, 7.7778, 14.4444, 25, 49.4444	12.2222, 27.7778, 30, 14.4444, 15.5556	10, 19.4444, 25.5556, 22.2222, 22.7778
H55	3.3333, 7.7778, 13.3333, 31.6667, 43.8889	8.8889, 22.7778, 30.5556, 23.3333, 14.4444	14.4444, 18.3333, 25.5556, 18.3333, 23.3333
H56	3.3333, 8.8889, 17.2222, 28.3333, 42.2222	11.1111, 26.6667, 22.2222, 17.7778, 22.2222	10, 17.2222, 26.6667, 23.3333, 22.7778
H57	4.4444, 7.7778, 21.1111, 31.1111, 35.5556	12.2222, 11.1111, 21.1111, 30, 25.5556	7.7778, 15.5556, 16.6667, 28.8889, 31.1111
H58	4.4444, 8.8889, 13.3333, 46.6667, 26.6667	8.8889, 25, 21.6667, 26.1111, 18.3333	4.4444, 17.2222, 17.7778, 34.4444, 26.1111
H59	3.3333, 6.6667, 21.1111, 35.5556, 33.3333	14.4444, 33.8889, 27.7778, 12.7778, 11.1111	9.4444, 17.7778, 22.2222, 31.1111, 19.4444
H60	8.8889, 22.2222, 25.5556, 23.3333, 20	11.1111, 18.8889, 33.3333, 21.1111, 15.5556	8.8889, 26.6667, 31.1111, 20, 13.3333
H61	4.4444, 7.7778, 15.5556, 33.8889, 38.3333	8.8889, 25, 18.3333, 22.2222, 25.5556	5.5556, 14.4444, 27.7778, 25.8889, 26.3333

Appendix 2.8: Prior Probability of L, C and P for Pipeline Transportation hazards

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H1	3.3333, 5, 8.3333, 10.8333, 72.5	16.6667, 28.3333, 25.8333, 15.8333, 13.3333	16.6667, 18.3333, 21.6667, 26.6667, 16.6667
H2	4.1667, 10.8333, 15, 20.8333, 49.1667	6.6667, 11.6667, 19.1667, 21.6667, 40.8333	13.3333, 18.3333, 16.6667, 28.3333, 23.3333
H3	4.1667, 7.5, 10.8333, 20.8333, 56.6667	7.5, 10.8333, 15.8333, 21.6667, 44.1667	16.6667, 18.3333, 23.3333, 21.6667, 20
H4	1.8333, 2.8333, 3.8333, 10.6667, 80.8333	15, 22.5, 25, 22.5, 15	38.3333, 12.6667, 12, 18, 19
H5	3.3333, 6.6667, 13.3333, 23.3333, 53.3333	9.1667, 12.5, 14.1667, 21.6667, 42.5	18.3333, 21.6667, 33.3333, 20, 6.6667
H6	4.1667, 7.5, 10, 13.3333, 65	7.5, 12.5, 17.5, 22.5, 40	16.6667, 23.3333, 31.6667, 20, 8.3333
H7	6.6667, 10, 22.5, 28.3333, 32.5	5, 9.1667, 13.3333, 22.5, 49.1667	11.6667, 16.6667, 31.6667, 28.3333, 11.6667
H8	3.3333, 5.8333, 12.5, 26.6667, 51.6667	5.8333, 9.1667, 12.5, 23.3333, 49.1667	11.6667, 13.3333, 31.6667, 23.3333, 20
H9	2.5, 5.8333, 10, 13.3333, 63.3333	4.1667, 9.1667, 18.3333, 25.8333, 42.5	26.6667, 23.3333, 25, 18.3333, 6.6667
H10	3.3333, 6.6667, 14.1667, 30, 45.8333	6.6667, 9.1667, 15.8333, 23.3333, 45	11.6667, 16.6667, 31. 6667, 23.3333, 16.6667

Appendix 2.9: Analysis of Ship transportation hazards by Hugin software

Hs	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
H1	17.7776	21.6667	19.4444	20	21.1111
H2	11.6241	20.2068	23.4439	19.7333	24.9922
H3	12.9214	19.3613	17.4401	28.7881	21.4892
H4	17.037	21.2963	18.3333	19.2593	24.0741

H5	13.1481	13.8889	22.5926	26.2963	24.0741
H6	11.8365	13.3153	24.0505	29.2413	21.5564
H7	19.8148	17.5926	18.5185	27.963	16.1111
H8	17.1094	12.6319	19.5686	20.7687	29.8314
H9	16.1111	14.6296	19.0741	31.2963	18.8889
H10	15.7407	20	28.5185	20.1852	15.5555
H11	8.1481	15.3704	34.6296	27.963	13.8889
H12	18.148	15.7407	23.8889	22.5926	19.6296
H13	10.9259	13.1481	25.3704	25.3704	25.1852
H14	12.963	15.9259	27.037	23.5185	20.5555
H15	11.4815	20	23.3333	19.6296	25.5555
H16	11.8519	16.1111	24.6296	24.4444	22.9629
H17	13.7037	14.4444	16.1111	33.1482	22.5926
H18	13.8889	11.8518	22.7778	31.1111	20.3704
H19	14.4444	10.1852	19.6296	30.5556	25.1852
H20	18.1481	17.2222	18.7037	24.2593	21.6667
H21	15.7407	12.0370	18.7037	25.7407	27.7778
H22	11.4815	15.1852	22.7778	20.7407	29.8148
H23	13.5185	14.4444	25.1852	20.1852	26.6667
H24	14.0741	15.1852	30	23.3333	17.4074
H25	12.7776	13.7037	22.2222	28.1481	23.1481
H26	11.8518	16.1111	26.1111	28.8889	17.037
H27	15.5556	13.7037	18.3333	27.963	24.4444
H28	12.2222	17.4074	22.037	26.1111	22.2222
H29	12.4074	16.2963	17.963	22.0371	31.2963
H30	9.6296	15.3704	23.1481	31.4815	20.3704
H31	9.6296	22.2222	27.4074	22.5926	18.1482
H32	9.6296	20.9259	22.037	24.8148	22.5926
H33	10.7407	15.5556	21.4815	24.8148	27.4074
H34	10.7472	21.4815	25.1852	20.1852	22.4074
H35	11.4814	18.1482	22.5926	23.1482	24.6296
H36	13.7037	18.5185	20.1852	23.3333	24.2593
H37	11.8518	17.8889	18.963	28.3333	22.963
H38	13.3333	21.4815	24.2592	16.4815	24.4444
H39	14.0741	15.3704	20.7407	26.2963	23.5185
H40	10.7407	15.5556	17.2222	27.037	29.4444
H41	7.4074	17.4074	16.1111	23.1482	35.9256
H42	7.2222	9.0741	19.5185	25.6291	38.5555
H43	12.2222	16.6667	16.6667	22.0371	32.4074
H44	17.963	11.4815	14.8148	21.4815	34.2593
H45	8.8889	16.4815	17.4074	26.2963	30.9259
H46	8.5185	14.0741	23.8889	25	28.5185
H47	6.6667	13.7037	25.5556	25.1852	28.8889
H48	8.5185	13.3334	29.6296	23.1481	25.3703
H49	6.6667	12.963	20.3704	23.5185	36.4815
H50	7.037	25.926	20.7408	22.2221	24.0742
H51	7.037	18.8889	20	28.3333	25.7407

H52	7.7778	15.5556	18.1481	26.8519	31.6667
H53	6.6667	12.5926	17.5926	23.7037	39.4444
H54	8.5185	18.3333	23.3333	20.5555	29.2593
H55	8.8889	16.2963	23.1482	24.4444	27.2222
H56	8.1481	17.5926	22.037	23.1481	29.0741
H57	8.1481	11.4815	19.6296	30	30.7408
H58	5.9259	17.037	17.5926	35.7407	23.7037
H59	9.0741	19.4444	23.7037	26.4815	21.2963
H60	9.6296	22.5926	30	21.4815	16.2963
H61	6.2963	15.7407	20.5556	27.3333	30.0741

Appendix 2.10: Analysis of Pipeline transportation hazards by Hugin software

Hs	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
H1	12.2222	17.2222	18.6111	17.7778	34.1667
H2	8.0556	13.6111	16.9445	23.6111	37.7778
H3	9.4445	12.2222	16.6666	21.3889	40.2778
H4	18.3889	12.6667	13.6111	17.0556	38.2778
H5	5.6944	8.1945	36.9444	16.6667	32.5
H6	9.4445	14.4444	19.7222	18.6111	37.7778
H7	7.4926	11.5428	21.4453	26.0055	33.5138
H8	6.94444	9.4444	18.8889	24.4444	40.2778
H9	11.155	12.8801	17.9532	19.4006	38.6111
H10	7.2222	10.8333	20.5556	25.5555	35.8333

Appendix 2.11: Utility value of the 61 Ship transportation hazards

	Hs	Utility value	Ranking
H 1	Main Engine Failure (Collision)	48.75	3
H 2	Bridge Navigation Equipment Failure (Collision)	43.4344	17
H 3	Communication System Failure (Collision)	43.3594	18
H 4	Wrong use of Navigation Equipment (Collision)	46.9907	5
H 5	Lack of Communication (Collision)	41.4352	31
H 6	Failure to Follow Operational Procedure (Collision)	41.1586	33
H 7	Action To Avoid Collision (Collision)	49.2593	2
H 8	Human Inattention (Collision)	41.6048	30
H 9	Human Neglect (Collision)	44.4445	12
H 10	Human Fatigue (Collision)	50.0463	1
H 11	Human Skills (Collision)	43.9815	15
H 12	Weather Condition (Collision)	47.5463	4
H 13	Third Party Activity (Collision)	39.8148	37
H 14	Main Engine Failure (Grounding)	44.3056	13
H 15	Communication System Failure (Grounding)	43.0556	19
H 16	Bridge Navigation Equipment Failure (Grounding)	42.3611	24
H 17	Wrong use of Navigation Equipment (Grounding)	40.8796	34
H 18	Lack of Communication (Grounding)	41.9444	28

H 19	Failure to Follow Operational Procedure (Grounding)	39.5370	38
H 20	Rout Selection (Grounding)	46.4815	7
H 21	Using Inappropriate Chart (Grounding)	40.5556	36
H 22	Human Inattention (Grounding)	39.4445	39
H 23	Human Neglect (Grounding)	41.9908	24
H 24	Human Fatigue (Grounding)	46.2963	8
H 25	Human Skills (Grounding)	41.2037	32
H 26	Weather Condition (Grounding)	44.2129	14
H 27	Third Party Activity (Grounding)	41.9907	27
H 28	Water Depth (Grounding)	42.8241	20
H 29	Construction Failure (Hull Failure)	39.1204	42
H 30	Corrosion (Hull Failure)	40.6019	35
H 31	Maintenance Failure (Hull Failure)	45.6482	10
H 32	Stowage Planning Failure (Hull Failure)	42.5463	21
H 33	Collision (Hull Failure)	39.3519	40
H 34	Grounding (Hull Failure)	44.4907	11
H 35	Human Inattention (Fire/Explosion)	42.1759	25
H 36	Human Neglect (Fire/Explosion)	43.5185	16
H 37	Human Skills (Fire/Explosion)	41.8333	29
H 38	Inert Gas/Ventilation System Failure(Fire/Explosion)	45.6945	9
H 39	Electric Failure (Fire/Explosion)	42.5463	22
H 40	Pumping Room Failure (Fire/Explosion)	37.7778	49
H 41	Main Engine Failure (Fire/Explosion)	34.3055	56
H 42	Heating system Failure (Fire/Explosion)	30.1945	60
H 43	Spread of Fire From Other Object (Fire/Explosion)	38.5648	46
H 44	Sabotage (Fire/Explosion)	39.3518	41
H 45	Weather Condition (Fire/Explosion)	36.5278	51
H 46	Pipe Failure (Equipment Failure)	37.2685	50
H 47	Valve Failure (Equipment Failure)	36.0185	53
H 48	Pump Failure (Equipment Failure)	39.1204	43
H 49	Tank Gauging System (Equipment Failure)	32.4537	58
H 50	Manifold Failure (Equipment Failure)	42.4074	23
H 51	Power Failure (Equipment Failure)	38.2870	47
H 52	Heating System Failure (Equipment Failure)	35.2315	54
H 53	Loading Computer (Equipment Failure)	30.8333	59
H 54	Maintenance Error (Equipment Failure)	39.0741	44
H 55	Maintenance Omission (Equipment Failure)	38.7963	45
H 56	Lack of Communication (Equipment Failure)	38.1481	48
H 57	Procedural Failure (Equipment Failure)	34.0741	57
H 58	Human Inattention (Equipment Failure)	36.4352	52
H 59	Human Neglect (Equipment Failure)	42.1296	26
H 60	Human Fatigue (Equipment Failure)	46.9444	6
H 61	Human Skills (Equipment Failure)	35.213	61

Appendix 2.12: Utility value of the 10 pipeline transportation hazards

	Hs	Utility value	Ranking
H 1	Sabotage	38.8889	2
H 2	Workers Actions	32.6389	7
H 3	Weather Condition	32.2917	8
H 4	Geological Hazards	38.9583	1
H 5	Material Failure	34.4792	6
H 6	Construction Failure	34.7917	3
H 7	Maintenance Failure	34.651	4
H 8	Failure to Follow Procedure	29.5833	10
H 9	Internal Corrosion	34.6418	5
H 10	External Corrosion	32.0139	9

Questionnaire used for the purpose of Chapter 5

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Date :

Dear Sir,

My name is Ayman Fahad Alghanmi and I am a PhD student from Liverpool John Moores University. For my research project I am examining the risk factors that influence the operation at pipeline system that might lead to crude oil spill. The results of this study will be used to determine the factors that affect the operation at pipeline system. Because you are an expert in the petroleum transportation industry, I am inviting you to participate in this research study by completing the attached survey.

The following questionnaire will takes a maximum of 20 minutes of your time. There is no compensation for responding nor is there any known risk. In order to ensure that all information will remain confidential, please do not include your name. If you choose to participate in this project, please answer all questions as honestly as possible and e-mail me the completed questionnaires. Your participation in this project is entirely voluntary and you can withdraw from the study at any time.

Thank you for taking the time to assist me in my educational endeavours. If you require additional information or have questions, please contact me at the number/e-mail listed below.

Sincerely,

Ayman Fahad Alghanmi
Liverpool Logistics Offshore and Marine Research Institute (LOOM)
Liverpool John Moores University
Tel: 074 7720 0174
E-mail: A.F.Alghanmi@2013.ljmu.ac.uk

SECTION 1: PERSONAL DETAILS

- Please mark the appropriate answer for each question:

1. Please mark your age range:
   - A. Less than 30 years old
   - B. Between 30 and 40 years old
   - C. 40 years old or more
2. Please mark your appropriate qualification:
   - A. Diploma
   - B. BSc
   - C. MSc
   - D. PhD
3. Please mark your work experiences:
   - A. Work experience 1-5 Years
   - B. Work experience 6-10 Years
   - C. Work experience 11-15 Years
   - D. Work experience 16-20 Years
   - E. Work experience over 20 Years

SECTION 2: INTRODUCTION

The aim of the research is to develop a novel risk assessment methodology for estimating, controlling and monitoring the operational risks in petroleum transportation systems. To achieve the aim of this study the most important factor that influences pipeline operation should be identify. These factors are considered to affecting the operation at pipeline which leads to an oil spill. Therefore, the criteria, sub-criteria and sub-sub-criteria listed in Table 1 are the parameters that need to be evaluated by using a “Pair-wise Comparisons” technique.

Criteria	Sub-criteria	Sub-sub-criteria	Sub-sub-sub-criteria
Spill Due to Pipeline Failure	Internal Factors	Operator Failure	Maintenance Failure
			Failure to Follow Procedure
		Structural Failure	Material Failure
			Construction Failure
		Corrosion	Internal Corrosion
			External Corrosion
	External Factors	Natural Hazards	Weather Condition
			Geological Hazards
		Third Party Activity	Working Activity
			Sabotage

Table 1: The list of criteria, sub-criteria and sub-sub criteria that influence pipeline safety

Before proceeding with the “Pair-wise Comparisons” technique, an expert has to understand the ratio scale measurement used in this study (Table 2). This table contains two parts which describe the numerical assessment together with the linguistic meaning of each number. The first part is on the left side which explains “IMPORTANT”, while the right side is the second part of the table which describes “UNIMPORTANT”.

Numerical Assessment	Linguistic meaning
1	Equally important
3	A little important
5	Important
7	Very important
9	Extremely important
2,4,6,8	Intermediate values of importance

Numerical Assessment	Linguistic meaning
1	Equally important
1/3	A little unimportant
1/5	Unimportant
1/7	Very unimportant
1/9	Extremely unimportant
1/2, 1/4, 1/6, 1/8	Intermediate values of unimportance

Table 2: Ratio scale for pair-wise comparisons

SECTION 3: QUESTIONNAIRE EXAMPLE

An expert is required to give a possible judgment to all questions based on his/her expertise and experience in the pipeline industry. The judgement process has to be focussed on how to achieve the 21 respective goals (Part A until Part S). Please tick (/) accordingly the rate of importance of each criteria, sub-criteria and sub-sub-criteria in the given column. For instance:

***Goal**: To select the most important component of a computer*

1) Monitor

	Unimportant								**Equally Important**	**Important**							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the above goal, how important is the Monitor compared to the Keyboard?											/						
To achieve the above goal, how important is the Monitor compared to the Mouse?														/			
To achieve the above goal, how important is the Monitor compared to Central Processing Unit (CPU)?	/																

The explanation of the above example,

3. The monitor is 3 times more important than the keyboard. It is because we can still explore a computer by using a mouse. The only thing we cannot do without the keyboard is typing.
4. The monitor is 6 times more important that the mouse. We can still do a lot of things by using a keyboard such as to open files by using arrow and enter key.
5. The monitor is 1/9 times less unimportant than the CPU. The monitor is useless without the CPU.

SECTION 4: QUESTIONNAIRE

PLEASE REFER TABLE 1 BEFORE ANSWERING THE QUESTIONNAIRE

Part B: The most important factors that lead to Crude oil pipeline spill

Goal: *To select the most important Hazard that influence the* ***internal Safety of Pipeline operation***

1) Operator Failure

	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the above goal how important is the **Operator Failure** compared to the **Structural Failure**?																	
To achieve the above goal how important is the **Operator Failure** compared to the **Corrosion**?																	

2) Structural Failure

	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the above goal how important is the **Structural Failure** compared to the **Corrosion**?											/						

Appendix Chapter 5

Appendix 3.1: Prior probability of P_l, S_c and D_p for petroleum port A hazards

	Hs	Degree of Belief (VH, H, M, L, VL)		
		Likelihood	**Consequences**	**Probability**
H1	MRHAA	8.3333, 16.6667, 23.3333, 33.3333, 18.3333	7.3333, 14.3333, 23.3333, 28.3333, 26.6667	5, 13.3333, 20, 31.6667, 30
H2	MRHAB	15, 20, 25, 26.6667, 13.3333	11.6667, 20, 28.3333, 23.3333, 16.6667	10,16.6667, 26.6667, 25, 21.6667
H3	MRHAC	6.6667, 23.3333, 28.3333, 26.6667, 15	11.6667, 25, 31.6667, 20, 11.6667	11.6667, 18.3333, 30, 28.3333, 11.6667
H4	MRHBA	13.3333, 31.6667, 26.6667, 20, 8.3333	18.3333, 20, 23.3333, 21.6667, 16.6667	10, 20 26.6667, 33.3333, 10
H5	MRHBB	13.3333, 21.6667, 26.6667, 30, 8.3333	15, 23.3333, 26.6667, 25, 10	10, 16.6667, 33.3333, 30, 10
H6	MRHBC	11.6667, 13.3333, 28.3333, 25, 21.6667	11.6667, 21.6667, 33.3333, 21.6667, 11.6667	8.3333, 15, 36.6667, 30, 10
H7	MRHBD	23.3333, 25, 30, 11.6667, 10	18.3333, 23.3333, 26.6667, 21.6667, 10	10, 11.6667, 28.3333, 35, 15
H8	MRHCA	15, 18.3333, 28.3333, 23.3333, 15	13.3333, 21.6667, 23.3333, 26.6667, 15	8.3333, 11.6667, 33.3333, 30, 16.6667
H9	MRHCB	12.3333, 23.3333, 25, 30, 8.3333	15, 23.3333, 30, 21.6667, 10	10, 16.6667, 23.3333, 31.6667, 18.3333
H10	MRHCC	10, 11.6667, 28.3333, 35, 15	13.3333, 23.3333, 30, 18.3333, 15	23.3333, 20, 30, 16.6667, 10
H11	MRHCD	10, 11.6667, 26.6667, 30, 21.6667	11.6667, 13.3333, 21.6667, 30, 23.3333	10, 11.6667, 30, 38.3333, 10
H12	MRHCE	8.3333, 11.6667, 26.6667, 35, 18.3333	13.3333, 23.3333, 28.3333, 25, 10	8.3333, 20, 26.6667, 33.3333, 11.6667
H13	MRHCFA	23.3333, 26, 23.3333, 20.6667, 6.6667	11.6667, 21.6667, 25, 23.3333, 18.3333	6.6667, 10, 26.6667, 36.6667, 20
H14	MRHCFB	16.6667, 25, 23.3333, 21.6667, 13.3333	11.6667, 30, 25, 23.3333, 10	10.6667, 18.3333, 29.3333, 28.3333, 13.3333
H15	MRHCFC	11.6667, 20, 25, 23.3333, 20	13.3333, 23.3333, 30, 23.3333, 10	6.6667, 16.6667, 20, 36.6667, 20
H16	MRHDA	10.6667, 11, 20, 20.6667, 37.6667	28.3333, 31.6667, 21.6667, 10, 8.3333	40, 35, 10, 8.3333, 6.6667
H17	MRHDB	8.3333, 11.6667, 21.6667, 23.3333, 35	28.3333, 31.6667, 21.6667, 10, 8.3333	10, 18.3333, 31.6667, 28.3333, 11.6667
H18	HRHAAC	16.6667, 18.333, 20, 23.3333, 21.6667	11.6667, 26.6667, 23.3333, 26.6667, 11.6667	8.3333, 18.3333, 28.3333, 33.3333, 11.6667
H19	HRHAAB	13.3333, 18.3333, 21.6667, 30, 16.6667	11.6667, 20, 31.6667, 25, 11.6667	10, 18.3333, 31.6667, 28.3333, 11.6667
H20	HRHAAA	15, 25, 21.6667, 23.3333, 15	11.6667, 26.6667, 23.3333, 26.6667, 11.6667	10, 11.6667, 38.3333, 28.3333, 11.6667
H21	HRHAB	10, 18.3333, 28.3333, 30, 13.3333	11.6667, 20, 31.6667, 25, 11.6667	13.3333, 16.6667, 33.3333, 26.6667, 10
H22	HRHBAA	23.3333, 25, 20, 18.3333, 13.3333	18.3333, 20, 31.6667, 18.3333, 11.6667	23.3333, 26.6667, 23.3333, 20, 6.6667
H23	HRHBAB	8.3333, 11.6667, 15, 36.6667, 28.3333	10, 13.3333, 30, 28.3333, 18.3333	11.6667, 18.3333, 26.6667, 30, 13.3333
H24	HRHBAC	6.6667, 11.6667, 20, 30, 31.6667	5, 8.3333, 25, 31.6667, 30	10, 26.6667, 38.3333, 16.6667, 8.3333
H25	HRHBAD	8.3333, 11.6667, 18.3333, 28.3333, 33.3333	15, 21.6667, 30, 23.3333, 10	8.3333, 11.6667, 26.6667, 40, 13.3333
H26	HRHBBA	26.6667, 30, 25, 10, 8.3333	10, 16.6667, 26.6667, 30, 16.6667	10, 13.3333, 36.6667, 28.3333, 11.6667
H27	HRHBBB	8.3333, 16.6667, 21.6667, 28.3333, 25	31.6667, 28.3333, 20, 11.6667, 8.3333	1.6667, 10, 21.6667, 63.3333, 3.3333

H28	HRHBBC	11.6667, 18.3333, 26.6667, 28.3333, 15	11.6667, 13.3333, 31.6667, 26.6667, 16.6667	5.3333, 8, 28.3333, 31.6667, 26.6667
H29	HRHBBD	8.3333, 11.6667, 26.6667, 36.6667, 16.6667	3.3333, 8.3333, 13.3333, 28.3333, 46.6667	6.6667, 7.6667, 16.6667, 35.6667, 33.3333
H30	HRHBBE	6.6667, 10, 23.3333, 31.6667, 28.3333	15, 26.6667, 31.6667, 16.6667, 10	36.6667, 30, 13.3333, 11.6667, 8.3333
H31	HRHBBF	11.6667, 21.6667, 28.3333, 25, 13.3333	13.3333, 28.3333, 31.6667, 16.6667, 10	20, 20, 28.3333, 23.3333, 8.3333
H32	HRHBBG	8.3333, 11.6667, 13.3333, 30, 36.6667	11.6667, 21.6667, 43.3333, 18.3333, 5	10, 10, 30, 30, 20
H33	HRHBBH	8.3333, 11.6667, 20, 43.3333, 16.6667	33.3333, 36.6667, 13.3333, 8.3333, 8.3333	3.3333, 13.3333, 26.6667, 35, 21.6667
H34	HRHBBI	8.3333, 18.3333, 26.6667, 30, 16.6667	15, 36.6667, 26.6667, 11.6667, 10	56.6667, 20, 13.3333, 10, 0
H35	NRHAA	6.6667, 11.6667, 20, 23.3333, 38.3333	6.6667, 15, 20, 26.6667, 31.6667	20, 43.3333, 36.6667, 0, 0
H36	NRHAB	1.6667, 10, 20, 30, 38.3333	11.6667, 16.6667, 26.6667, 21.6667, 23.3333	20, 43.3333, 36.6667, 0, 0
H37	NRHAC	0, 0, 0, 10, 90	5, 13.3333, 21.6667, 31.6667, 28.3333	20, 43.3333, 36, 6667, 0, 0
H38	NRHBA	1.6667, 5, 20, 28.3333, 45	6.6667, 16.6667, 20, 25, 31.6667	10, 20, 30, 33.3333, 6.6667
H39	NRHBC	3.3333, 10, 20, 38.3333, 28.3333	11.6667, 18.3333, 28.3333, 23.3333, 18.3333	0, 10, 33.3333, 50, 6.6667
H40	NRHBB	1.6667, 1.6667, 3.3333, 15, 78.3333	41.6667, 31.6667, 9.6667, 8.6667, 8.3333	1.6667, 10, 36.6667, 41.66667, 10
H41	NRHCA	1.6667, 1.6667, 6.6667, 21.6667, 68.3333	41.6667, 35, 11.6667, 10, 1.6667	0, 0, 46.6667, 50, 3.3333
H42	NRHCB	1.6667, 1.6667, 3.3333, 20, 73.3333	48.3333, 30, 10, 8.3333, 3.3333	0, 0, 46.6667, 50, 3.3333

Appendix 3.2: Prior probability of P_l, S_c and D_p for petroleum port C hazards

	Hs	**Degree of Belief (VH, H, M, L, VL)**		
		Likelihood	**Consequences**	**Probability**
H1	MRHAA	6.6667, 11.6667, 21.6667, 33.3333, 26.6667	8.3333, 11.6667, 23.3333, 30, 26.6667	10, 16.6667, 30, 26.6667, 16.6667
H2	MRHAB	11.6667, 20, 26.6667, 31.6667, 10	15, 20, 26.6667, 23.3333, 15	10, 15, 28.3333, 26.6667, 20
H3	MRHAC	11.6667, 21.6667, 23.3333, 28.3333, 15	13.3333, 23.3333, 30, 18.3333, 15	13.3333, 20, 28.3333, 25, 13.3333
H4	MRHBA	10, 23.3333, 25, 23.3333, 18.3333	16.6667, 18.3333, 28.3333, 26.6667, 10	8.3333, 16.6667, 30, 31.6667, 13.3333
H5	MRHBB	11.6667, 18.3333, 26.6667, 25, 18.3333	18.3333, 20, 28.3333, 23.3333, 10	10, 13.3333, 36.6667, 28.3333, 11.6667
H6	MRHBC	10, 13.3333, 20, 30, 26.6667	11.6667, 16.6667, 26.6667, 28.3333, 16.6667	10, 16.6667, 33.3333, 28.3333, 11.6667
H7	MRHBD	13.3333, 16.6667, 28.3333, 26.6667, 15	11.6667, 21.6667, 30, 23.3333, 13.3333	15, 16.6667, 28.3333, 26.6667, 13.3333,
H8	MRHCA	6.6667, 15, 21.6667, 38.3333, 18.3333	6.6667, 11.6667, 21.6667, 35, 25	6.6667, 10, 28.3333, 31.6667, 23.3333
H9	MRHCB	16.6667, 18.3333, 25, 28.3333, 11.6667	13.3333, 26.6667, 23.3333, 21.6667, 15	10, 16.6667, 25, 30, 18.3333
H10	MRHCC	6.6667, 13.3333, 28.3333, 30, 21.6667	11.6667, 20, 23.3333, 26.6667, 18.3333	15, 16.6667, 23.3333, 26.6667, 18.3333
H11	MRHCD	11.6667, 13.3333, 28.3333, 25, 21.6667	13.3333, 20, 28.3333, 23.3333, 15	8.3333, 10, 26.6667, 33.3333, 21.6667
H12	MRHCE	11.6667, 16.6667, 28.3333, 30, 13.3333,	13.3333, 23.3333, 33.3333, 21.6667, 8.3333	16.6667, 16.6667, 28.3333, 26.6667, 16.6667
H13	MRHCFA	18.3333, 23.3333, 26.6667, 25, 6.6667	11.6667, 25, 31.6667, 21.6667, 10	11.6667, 16.6667, 28.3333, 30, 13.3333

H14	MRHCFB	11.6667, 21.6667, 28.3333, 25, 13.3333	11.6667, 26.6667, 30, 21.6667, 10	11.6667, 20, 28.3333, 26.6667, 13.3333
H15	MRHCFC	13.3333, 20, 30, 23.3333, 13.3333	10, 23.3333, 31.6667, 25, 10	13.3333, 21.6667, 28.3333, 26.6667, 10
H16	MRHDA	5, 11.6667, 16.6667, 20, 46.6667	26.6667, 28.3333, 21.6667, 13.3333, 10	23.3333, 25, 21.6667, 18.3333, 11.6667
H17	MRHDB	6.6667, 10, 13.3333, 20, 50	25.26.6667, 21, 21.6667, 15, 11.6667,	28.3333, 26.6667, 21.6667, 18.3333, 8.3333
H18	HRHAAC	10, 11.6667, 21.6667, 33.3333, 23.3333	11.6667, 20, 25, 33.3333, 10	10, 18.3333, 26.6667, 31.6667, 13.3333
H19	HRHAAB	8.3333, 16.6667, 18.3333, 33.3333, 23.3333	11.6667, 16.6667, 28.3333, 33.3333, 10	10, 18.3333, 28.3333, 30, 13.3333
H20	HRHAAA	11.6667, 18.3333, 20, 28.3333, 21.6667	11.6667, 23.3333, 25, 26.6667, 13.3333	13.3333, 18.3333, 30, 28.3333, 10
H21	HRHAB	8.3333, 11.6667, 21.6667, 26.6667, 31.6667	11.6667, 20, 28.3333, 26.6667, 13.3333	13.3333, 15, 33.3333, 26.6667, 11.6667
H22	HRHBAA	16.6667, 20, 23.3333, 30, 10	11.6667, 23.3333, 25, 26.6667, 13.3333	13.3333, 15, 31.6667, 26.6667, 13.3333
H23	HRHBAB	3.3333, 5, 21.6667, 36.6667, 30	13.3333, 20, 28.3333, 23.3333, 15	20, 23.3333, 25, 23.3333, 8.3333
H24	HRHBAC	5, 6.6667, 18.3333, 38.3333, 31.6667	18.3333, 16.6667, 28.3333, 21.6667, 15	10, 18.3333, 26.6667, 31.6667, 13.3333,
H25	HRHBAD	8.3333, 6.6667, 23.3333, 30, 31.6667	8.3333, 13.3333, 28.3333, 33.3333, 16.6667	13.3333, 21.6667, 33.3333, 21.6667, 10
H26	HRHBBA	16.6667, 20, 23.3333, 30, 10	15, 21.6667, 28.3333, 25, 10	10, 15, 30, 35, 10
H27	HRHBBB	8.3333, 16.6667, 26.6667, 33.3333, 11.6667	18.3333, 20, 28.3333, 23.3333, 10	10, 15, 33.3333, 31.6667, 10
H28	HRHBBC	8.3333, 15, 26.6667, 33.3333, 16.6667	26.6667, 25, 21.6667, 16.6667, 10	6.6667, 15, 26.6667, 43.3333, 8.3333
H29	HRHBBD	8.3333, 11.6667, 26.6667, 36.6667, 16.6667	18.3333, 21.6667, 28.3333, 25, 6.6667	6.6667, 18.3333, 28.3333, 38.3333, 8.3333
H30	HRHBBE	8.3333, 15, 26.6667, 36.6667, 13.3333	11.6667, 16.6667, 20, 23.3333, 28.3333	6.6667, 8.3333, 26.6667, 38.3333, 20
H31	HRHBBF	8.3333, 15, 28.3333, 33.3333, 15	21.6667, 25, 28.3333, 15, 10	28.3333, 23.3333, 20, 18.3333, 10
H32	HRHBBG	3.3333, 8.3333, 15, 31.6667, 41.6667	18.3333, 20, 40, 13.3333, 8.3333	13.3333, 15, 28.3333, 35, 8.3333
H33	HRHBBH	6.6667, 10, 25, 41.6667, 16.6667	36.6667, 30, 16.6667, 10, 6.6667	3.3333. 3.3333. 26.6667. 43.3333, 23.3333
H34	HRHBBI	6.6667, 13.3333, 30, 33.3333, 16.6667	18.3333, 26.6667, 28.3333, 20, 6.6667	33.3333, 25, 18.3333, 15, 8.3333
H35	NRHAA	3.333, 6.6667, 21.6667, 30, 38.3333	11.6667, 13.3333, 25, 33.3333, 16.6667	5, 31.6667, 35, 16.6667, 11.6667
H36	NRHAB	0, 0, 6.6667, 18.3333, 75	10, 18.3333, 26.6667, 25, 20	5, 31.6667, 36.6667, 16.6667, 10
H37	NRHAC	0.6667, 1, 1.6667, 6.6667, 90	11.6667, 18.3333, 26.6667, 33.3333, 10	5, 31.6667, 35, 16.6667, 11.6667
H38	NRHBA	0, 5, 6.6667, 21.6667, 66.6667	11.6667, 16.6667, 26.6667, 30, 15	5, 8.3333, 31.6667, 36.6667, 18.3333
H39	NRHBC	1.6667, 5, 13.3333, 33.3333, 46.6667	13.3333, 15, 28.3333, 30.3333, 10	5, 6.6667, 35, 36.6667, 16.6667
H40	NRHBB	0, 1.6667, 3.3333, 11.6667, 83.3333	36.6667, 21.6667, 18.3333, 16.6667, 6.6667	5, 6.6667, 35, 36.6667, 16.6667
H41	NRHCA	0, 0, 3.3333, 10, 86.6667	40, 25, 16.6667, 11.6667, 6.6667	6.6667, 8.3333, 33.3333, 38.3333, 13.3333
H42	NRHCB	0, 0, 0, 11.6667, 88.3333	36.6667, 26.6667, 18.3333, 11.6667, 6.6667	6.6667, 8.3333, 33.3333, 38.3333, 13.3333

Appendix 3.3: Prior probability of P_l, S_c and D_p for petroleum port D hazards

	Hs	Degree of Belief (VH, H, M, L, VL)		
		Likelihood	Consequences	Probability
H1	MRHAA	8.3333, 13.3333, 21.6667, 38.3333, 18.3333	13.3333, 15, 26.6667, 25, 20	3.3333, 16.6667, 26.6667, 30, 23.3333
H2	MRHAB	11.6667, 20, 28.3333, 31.6667, 8.3333	13.3333, 15, 33.3333, 26.6667, 11.6667	10, 18.3333, 28.3333, 23.3333, 20
H3	MRHAC	13.3333, 21.6667, 23.3333, 31.6667, 10	15, 21.6667, 31.6667, 18.3333, 13.3333	10, 20, 28.3333, 31.6667, 10
H4	MRHBA	11.6667, 31.6667, 23.3333, 20, 13.3333	13.3333, 13.3333, 28.3333, 33.3333, 11.6667	10, 18.3333, 21.6667, 38.3333, 11.6667
H5	MRHBB	13.3333, 23.3333, 26.6667, 23.3333, 13.3333	15, 25, 26.6667, 23.3333, 10	10, 11.6667, 36.6667, 31.6667, 10
H6	MRHBC	11.6667, 15, 31.6667, 25, 16.6667	13.3333, 16.6667, 30, 31.6667, 8.3333	11.6667, 13.3333, 36.6667, 26.6667, 11.6667
H7	MRHBD	13.3333, 21.6667, 31.6667, 23.3333, 10	11.6667, 20, 31.6667, 23.3333, 13.3333	10, 11.6667, 28.3333, 38.3333, 11.6667
H8	MRHCA	10, 21.6667, 23.3333, 33.3333, 11.6667	15, 18.3333, 26.6667, 26.6667, 13.3333	8.3333, 11.6667, 38.3333, 30, 11.6667
H9	MRHCB	13.3333, 21.6667, 25, 31.6667, 8.3333	15, 23.3333, 28.3333, 21.6667, 11.6667	11.6667, 18.3333, 26.6667, 31.6667, 11.6667
H10	MRHCC	10, 11.6667, 28.3333, 35, 15	16.6667, 20, 28.3333, 20, 15	13.3333, 16.6667, 28.3333, 31.6667, 10
H11	MRHCD	10, 18.3333, 26.6667, 30, 15	11.6667, 21.6667, 30, 21.6667, 15	10, 11.6667, 28.3333, 38.3333, 11.6667
H12	MRHCE	8.3333, 13.3333, 26.6667, 35, 16.6667	18.3333, 20, 26.6667, 25, 10	13.3333, 16.6667, 31.6667, 28.3333, 10
H13	MRHCFA	21.6667, 25, 23.3333, 21.6667, 8.3333	18.3333, 21.6667, 26.6667, 25, 8.3333	8.3333, 11.6667, 28.3333, 40, 11.6667,
H14	MRHCFB	16.6667, 25, 21.6667, 23.3333, 13.3333	13.3333, 28.3333, 26.6667, 21.6667, 10	11.6667, 18.3333, 31.6667, 28.3333, 10
H15	MRHCFC	15.18.3333, 28.3333, 21.6667, 16.6667	16.6667, 20, 31.6667, 21.6667, 10	11.6667, 18.3333, 23.3333, 36.6667, 10
H16	MRHDA	10.6667, 11, 20, 20.6667, 37.6667	30, 30, 18.3333, 13.3333, 8.3333	36.6667, 38.3333, 13.3333, 6.6667, 5
H17	MRHDB	10.6667, 11, 18.3333, 21.6667, 38.3333	25, 31.6667, 25, 10, 8.3333	38.3333, 35, 13.3333, 10, 3.3333
H18	HRHAAC	11.6667, 16.6667, 21.6667, 26.6667, 23.3333	13.3333, 23.3333, 25, 26.6667, 11.6667	13.3333, 16.6667, 31.6667, 28.3333, 10
H19	HRHAAB	16.6667, 18.3333, 21.6667, 30, 13.3333	15.16.6667, 33.3333, 23.3333, 11.6667,	13.3333, 16.6667, 30, 28.3333, 11.6667
H20	HRHAAA	15.6667, 25.3333, 22.3333, 21.6667, 15	15, 23.3333, 26.66667, 23.3333, 11.6667	13.3333, 16.6667, 30, 28.3333, 10
H21	HRHAB	10, 18.3333, 28.3333, 30, 13.3333	15, 16.6667, 31.6667, 25, 11.6667	13.3333, 10, 36.6667, 30, 10
H22	HRHBAA	18.3333, 25, 23.3333, 21.6667, 11.6667	15, 18.3333, 26.6667, 28.3333, 11.6667	13.3333, 10, 36.6667, 30, 10
H23	HRHBAB	1.6667, 5, 28.3333, 36.6667, 28.3333	20, 21.6667, 28.3333, 18.3333, 11.6667	28.3333, 30, 21.6667, 18.3333, 1.6667
H24	HRHBAC	5, 11.66667, 20, 33.3333, 30	13.3333, 16.6667, 26.6667, 25, 18.3333	13.3333, 16.6667, 23.3333, 26.6667, 20
H25	HRHBAD	13.3333, 15, 26.6667, 23.3333, 21.6667	5, 6.6667, 25, 35, 28.3333	11.6667, 28.3333, 38.3333, 11.6667, 10
H26	HRHBBA	26.6667, 30, 25, 16.6667, 1.6667	16.6667, 18.3333, 30, 23.3333, 11.6667	11.6667, 13.3333, 26.6667, 36.6667, 11.6667
H27	HRHBBB	11.6667, 18.3333, 26.6667, 28.3333, 15	11.6667, 15, 26.6667, 30, 16.6667	10, 11.6667, 38.3333, 30, 10
H28	HRHBBC	10, 18.3333, 31.6667, 28.3333, 11	33.3333, 28.3333, 18.3333, 18.6667, 8.3333	3.3333, 13.3333, 23.3333, 56.6667, 3.3333
H29	HRHBBD	8.3333, 11.6667, 26.6667, 36.6667, 16.6667	18.3333, 21.6667, 30, 23.3333, 6.6667	3.3333, 13.3333, 28.3333, 46.6667, 8.3333

H30	HRHBBE	8.3333, 18.3333, 26.6667, 36.6667, 10	5, 6.6667, 21.6667, 23.3333, 43.3333	0, 0, 23.3333, 46.6667, 30
H31	HRHBBF	11.6667, 18.3333, 28.3333, 26.6667, 15	21.6667, 23.3333, 28.3333, 18.3333, 8.3333	38.3333, 31.6667, 13.3333, 10, 6.6667
H32	HRHBBG	1.6667, 11.6667, 20, 30, 36.6667	10, 15, 55, 13.3333, 6.6667	23.3333, 20, 26.6667, 30
H33	HRHBBH	8.3333, 11.6667, 20, 43.3333, 16.6667	36.6667, 40, 13.3333, 6.6667, 3.3333	1.6667, 3.3333, 26.6667, 56.6667, 11.6667
H34	HRHBBI	8.3333, 18.3333, 26.6667, 30, 16.6667	16.6667, 35, 30, 13.3333, 5	28.3333, 31.6667, 20, 18.3333, 1.6667
H35	NRHAA	8.3333, 10, 20, 23.3333, 38.3333	10, 18.3333, 21.6667, 23.3333, 26.6667	3.3333, 46.6667, 45, 3.3333, 1.6667
H36	NRHAB	1.6667, 3.3333, 6.6667, 16.6667, 71.6667	6.6667, 18.3333, 28.3333, 26.6667, 20	3.3333, 43.3333, 46.6667, 5, 1.6667
H37	NRHAC	1.6667. 3.3333. 5. 6.6667. 83.3333	8.3333, 16.6667, 25, 28.3333, 21.6667	5, 43.3333, 46.6667, 3.3333, 1.6667
H38	NRHBA	3.3333, 5, 18.3333, 28.3333, 45	8.3333, 18.3333, 24, 25, 24.3333	8.3333, 18.3333, 30, 38.3333, 5
H39	NRHBC	3.3333, 10, 20, 45, 21.6667	13.3333, 15, 26.6667, 31.6667, 13.3333	1.6667, 11.6667, 38.3333, 46.6667, 1.6667
H40	NRHBB	1.6667, 1.6667, 3.3333, 15, 78.3333	60, 23.3333, 9.6667, 3.6667, 3.3333	1.6667, 3.3333, 43.3333, 46.6667, 5
H41	NRHCA	1.6667, 1.6667, 3.3333, 6.6667, 86.6667	61. 6667, 26.6667, 6.6667, 3.3333, 1.6667	1.6667, 3.3333, 46.6667, 43.3333, 3.3333
H42	NRHCB	1.6667, 1.6667, 3.3333, 5, 88.3333	61. 6667, 26.6667, 6.6667, 3.3333, 1.6667	1.6667, 3.3333, 46.6667, 43.3333, 3.3333

Appendix 3.4: Prior Probability of L, C and P for Shipping Route A hazards (Collision)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H1	2.5, 20, 21.6667, 26.6667, 29.1667	28.3333, 20.8333, 15.8333, 13.3333, 21.6667	23.3333, 24.1667, 16.6667, 20.8333, 15
H2	5, 10.8333, 18.3333, 20, 45.83333	35, 22.5, 20, 12.1667, 10.3333	10, 13.3333, 29.1667, 24.1667, 23.3333
H3	3.3333, 7.5, 13.3333, 40.83333, 35	13.3333, 29.1667, 21.6667, 22.1667, 13.6667	23.3333, 24.1667, 19.1667, 17.5, 15.8333
H4	6.6667, 16.6667, 21.6667, 20, 35	26.6667, 35, 16.6667, 15, 6.6667	16.6667, 16.6667, 21.6667, 18.3333, 26.6667
H5	3.3333, 3.3333, 16.6667, 35, 41.6667	22.5, 19.1667, 26.6667, 18.3333, 13.3333	10, 17.5, 25, 28.3333, 19.1667
H6	5, 6.6667, 21.6667, 35.8333, 30.8333	17.5, 20, 25, 18.3333, 19.1667	13.3333, 12.5, 24.1667, 28.3333, 21.6667
H7	10, 8.3333, 22.5, 35.83333, 23.3333	41.6667, 30, 15, 10, 3.3333	8.3333, 16.6667, 15, 35, 25
H8	5, 6.6667, 21.6667, 27.5, 39.1667	39.1667, 23.3333, 15, 14.1667, 8.3333	6.6667, 10, 23.3333, 22.5, 37.5
H9	4.1667, 6.6667, 25, 39.1667, 25	38.3333, 23.3333, 16.6667, 15.8333, 5.8333	6.6667, 15, 18.3333, 32.5, 27.5
H10	6.6667, 18.3333, 36.6667, 20.8333, 17.5	34.1667, 26.6667, 14.1667, 19.1667, 5.8333	6.6667, 13.3333, 33.3333, 20.8333, 25.8333
H11	5.8333, 8.3333, 36.6667, 34.1667, 15	7.5, 31.6667, 35, 18.3333, 7.5	13.3333, 9.1667, 30.8333, 27.5, 19.1667
H12	5, 9.1667, 30.8333, 29.1667, 25.8333	30, 22.5, 17.5, 18.3333, 11.6667	13.3333, 15, 30, 21.6667, 20
H13	3.3333, 5, 18.3333, 38.3333, 35	18.3333, 20, 18.3333, 19.1667, 24.1667	6.6667, 15, 35, 20, 23.3333

Appendix 3.5: Prior Probability of L, C and P for Shipping Route A hazards (Grounding)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H14	5, 10, 28.3333, 29.1667, 27.5	23.3333, 21.6667, 23.3333, 16.6667, 15	6.6667, 16.6667, 31.6667, 25.8333, 19.1667
H15	3.3333, 8.3333, 28.3333, 19.1667, 40.83333	20, 31.6667, 18.3333, 16.6667, 13.3333	10, 20, 25.8333, 22.5, 21.6667
H16	3.3333, 6.6667, 30, 26.6667, 33.3333	20, 30, 21.6667, 15, 13.3333	8.3333, 11.6667, 26.6667, 30, 23.3333
H17	3.3333, 5, 13.3333, 43.3333, 35	20, 25, 21.6667, 15, 18.3333	11.6667, 14.1667, 19.1667, 36.6667, 18.3333
H18	3.3333, 5, 20, 23.3333, 48.3333	25.8333, 20, 22.5, 15, 16.6667	6.6667, 10, 35, 21.6667, 26.6667
H19	3.3333, 5.8333, 16.6667, 55.8333, 18.3333	26.6667, 16.6667, 25, 15.8333, 15.8333	8.3333, 9.1667, 25, 20, 37.5
H20	2.5, 15, 15, 32.5, 35	38.3333, 25, 15.9.1667, 12.5	13.3333, 15.8333, 24.1667, 30, 16.6667
H21	3.3333, 3.3333, 13.3333, 38.3333, 41.6667	34.1667, 24.1667, 20.8333, 12.5, 8.3333	5.8333, 10.8333, 24.1667, 27.5, 31.6667
H22	3.3333, 6.6667, 22.5, 27.5, 40	25.8333, 27.5, 20.8333, 10.8333, 15	5, 11.6667, 25, 25.8333, 32.5
H23	6.6667, 5, 29.1667, 19.1667, 40	28.3333, 25, 21.6667, 15, 10	5, 12.5, 27.5, 25, 30
H24	6.6667, 6.6667, 36.6667, 31.6667, 18.3333	31.6667, 23.3333, 21.6667, 13.3333, 10	5, 15, 31.6667, 25, 23.3333
H25	3.3333, 5, 25, 31.6667, 35	23.3333, 25, 20.8333, 19.1667, 11.6667	7.5, 14.1667, 21.6667, 30.8333, 25.8333
H26	8.3333, 8.3333, 28.3333, 38.3333, 16.6667	16.6667, 25, 20.8333, 27.5, 10	11.6667, 13.3333, 32.5, 19.1667, 23.3333
H27	3.3333, 5, 15, 40, 36.6667	28.3333, 20.8333, 20, 19.1667, 11.6667	10, 17.5, 23.3333, 24.1667, 25
H28	5.8333, 6.6667, 30.8333, 29.1667, 27.5	24.1667, 34.1667, 16.6667, 15, 10	5.8333, 12.5, 20, 34.1667, 27.5

Appendix 3.6: Prior Probability of L, C and P for Shipping Route A hazards (Hull Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H29	3.3333, 3.3333, 8.3333, 25, 60	26.6667, 33.3333, 20, 13.3333, 6.6667	10.8333, 11.6667, 24.1667, 27.5, 25.83333
H30	8.3333, 10, 15, 36.6667, 30	10, 23.3333, 33.3333, 21.6667, 11.6667	8.3333, 9.1667, 29.1667, 35, 18.3333
H31	6.6667, 20, 21.6667, 20, 31.6667	13.3333, 23.3333, 30, 23.3333, 10	8.3333, 24.1667, 35.8333, 23.3333, 8.3333
H32	5, 11.6667, 24.1667, 29.1667, 30	16.6667, 45, 17.5, 15.8333, 5	6.6667, 11.6667, 35, 26.6667, 20
H33	3.3333, 6.6667, 10, 33.3333, 46.6667	21.6667, 28.3333, 26.6667, 15, 8.3333	8.3333, 11.6667, 28.3333, 25, 26.6667
H34	5, 18.3333, 17.5, 22.5, 36.6667	21.6667, 33.3333, 21.6667, 16.6667, 6.6667	6.6667, 10, 36.6667, 22.5, 24.1667

Appendix 3.7: Prior Probability of L, C and P for Shipping Route A hazards (Fire/Explosion)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H35	4.1667, 8.3333, 23.3333, 36.6667, 27.5	26.6667, 30, 18.3333, 9.1667, 15.8333	6.6667, 16.6667, 28.3333, 20, 28.3333
H36	5.83333, 8.3333, 17.5, 35.8333, 32.5	25, 28.3333, 21.6667, 12.5, 12.5	15, 20, 24.1667, 17.5, 23.3333
H37	5, 8.3333, 15, 31.6667, 40	26.6667, 30, 20, 15, 8.3333	6.6667, 17.1667, 23.6667, 28.3333, 24.1667
H38	7.5, 11.6667, 18.3333, 20, 42.5	25, 28.3333, 24.1667, 12.5, 10	8.3333, 26.6667, 30, 18.3333, 16.6667
H39	8.3333, 8.3333, 20, 33.3333, 30	26.6667, 30, 20.8333, 12.5, 10	6.6667, 9.1667, 26.6667, 31.6667, 25.8333
H40	1.6667, 5.8333, 15, 33.3333, 44.1667	23.3333, 25, 17.5, 19.1667, 15	6.6667, 17.5, 23.3333, 25, 27.5
H41	3.3333, 6.6667, 11.6667, 30, 48.3333	6.6667, 25, 18.33333, 18.3333, 31.6667	8.3333, 20.8333, 20.8333, 20.8333, 29.1667
H42	3.3333, 5.8333, 10.83333, 26.6667, 53.3333	10, 8.3333, 26.6667, 21.6667, 33.3333	5, 10, 27.8333, 25.3333, 31.8333
H43	3.3333, 8.3333, 14.1667, 20.8333, 53.3333	16.6667, 26.6667, 25, 20, 11.6667	13.3333, 18.3333, 16.6667, 23.3333, 28.3333
H44	3.3333, 3.3333, 8.3333, 21.6667, 63.3333	33.3333, 18.3333, 13.3333, 10, 25	14.1667, 15, 21.6667, 22.5, 26.6667
H45	3.3333, 5, 11.6667, 33.3333, 46.6667	10, 35, 20.83333, 18.3333, 15.83333	8.3333, 10.8333, 21.6667, 30, 29.1667

Appendix 3.8: Prior Probability of L, C and P for Shipping Route A hazards (Equipment Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H46	3.3333, 6.6667, 18.3333, 29.1667, 42.5	15, 21.6667, 22.5, 19.1667, 21.6667	6.6667, 13.3333, 33.3333, 26.6667, 20
H47	3.3333, 8.3333, 20.83333, 26.6667, 40.8333	6.6667, 18.3333, 28.3333, 21.6667, 25	6.6667, 13.3333, 27.5, 25.8333, 26.6667
H48	3.3333, 8.3333, 25, 25.8333, 37.5	8.3333, 16.6667, 25, 21.6667, 28.3333	10, 15, 38.3333, 23.3333, 13.3333
H49	3.3333, 6.6667, 18.3333, 29.1667, 42.5	6.6667, 23.3333, 15.8333, 14.1667, 40	6.6667, 11.6667, 32.5, 27.5, 21.6667
H50	5, 18.3333, 20, 25.8333, 30.8333	6.6667, 36.6667, 15, 15, 26.6667	6.6667, 20, 31.6667, 25, 16.6667
H51	5, 9.1667, 13.3333, 36.6667, 35.8333	6.6667, 28.3333, 23.3333, 18.3333, 23.3333	7.5, 18.3333, 22.5, 29.1667, 22.5
H52	3.3333, 7.5, 15, 29.1667, 45	10, 25, 18.3333, 25, 21.6667	6.6667, 11.6667, 21.6667, 29.1667, 30.8333
H53	3.3333, 6.6667, 8.3333, 19.1667, 62.5	6.6667, 16.6667, 30, 21.6667, 25	6.6667, 13.3333, 16.6667, 30.8333, 32.5
H54	3.3333, 8.3333, 18.3333, 25, 45	11.6667, 26.6667, 31.6667, 15, 15	8.3333, 19.1667, 25.8333, 24.1667, 22.5
H55	3.3333, 8.3333, 16.6667, 28.3333, 43.3333	6.6667, 25, 30, 23.3333, 15	15, 17.5, 25.8333, 18.3333, 23.3333
H56	3.3333, 10, 20.83333, 28.3333, 37.5	10, 28.3333, 23.3333, 16.6667, 21.6667	8.3333, 18.3333, 26.6667, 23.3333, 23.3333
H57	5, 8.3333, 20, 29.1667, 37.5	11.6667, 8.3333, 25, 31.6667, 23.3333	6.6667, 16.6667, 18.3333, 28.3333, 30

H58	5, 10, 16.6667, 44.1667, 24.1667	6.6667, 29.1667, 22.5, 25, 16.6667	4.1667, 19.1667, 20, 30.8333, 25.8333
H59	3.3333, 6.6667, 21.6667, 35, 33.3333	15, 34.1667, 26.6667, 14.1667, 10	10.8333, 18.3333, 22.5, 27.5, 20.83333
H60	10, 21.6667, 26.6667, 23.3333, 18.3333	11.6667, 20, 33.3333, 18.3333, 16.6667	8.3333, 23.3333, 31.6667, 20, 16.6667
H61	5, 8.3333, 20, 32.5, 34.1667	8.3333, 27.5, 20.8333, 20, 23.3333	5, 12.5, 28.3333, 26.3333, 27.83333

Appendix 3.9: Prior Probability of L, C and P for Shipping Route B hazards (Collision)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H1	2.5, 20, 21.6667, 26.6667, 29.1667	28.3333, 20.8333, 15.8333, 13.3333, 21.6667	23.3333, 24.1667, 16.6667, 20.8333, 15
H2	5, 10.8333, 18.3333, 20, 45.83333	35, 22.5, 20, 12.1667, 10.3333	10, 13.3333, 29.1667, 24.1667, 23.3333
H3	3.3333, 7.5, 13.3333, 40.83333, 35	13.3333, 29.1667, 21.6667, 22.1667, 13.6667	23.3333, 24.1667, 19.1667, 17.5, 15.8333
H4	6.6667, 8.333, 17.5, 29.1667, 38.3333	26.6667, 35, 16.6667, 15, 6.6667	16.6667, 16.6667, 21.6667, 18.3333, 26.6667
H5	3.3333, 3.3333, 16.6667, 35, 41.6667	22.5, 19.1667, 26.6667, 18.3333, 13.3333	10, 17.5, 25, 28.3333, 19.1667
H6	3.3333, 6.6667, 21.6667, 37.5, 30.8333	17.5, 20, 25, 18.3333, 19.1667	13.3333, 12.5, 24.1667, 28.3333, 21.6667
H7	4.1667, 6.6667, 23.3333, 37.5, 28.3333	41.6667, 30, 15, 10, 3.3333	8.3333, 16.6667, 15, 35, 25
H8	5, 6.6667, 21.6667, 27.5, 39.1667	39.1667, 23.3333, 15, 14.1667, 8.3333	6.6667, 10, 23.3333, 22.5, 37.5
H9	4.1667, 6.6667, 25, 39.1667, 25	38.3333, 23.3333, 16.6667, 15.8333, 5.8333	6.6667, 15, 18.3333, 32.5, 27.5
H10	6.6667, 18.3333, 36.6667, 20.8333, 17.5	34.1667, 26.6667, 14.1667, 19.1667, 5.8333	6.6667, 13.3333, 33.3333, 20.8333, 25.8333
H11	5.8333, 8.3333, 36.6667, 34.1667, 15	7.5, 31.6667, 35, 18.3333, 7.5	13.3333, 9.1667, 30.8333, 27.5, 19.1667
H12	5, 9.1667, 25.8333, 30.8333, 29.1667	30, 22.5, 17.5, 18.3333, 11.6667	13.3333, 15, 30, 21.6667, 20
H13	3.3333, 5, 18.3333, 38.3333, 35	18.3333, 20, 18.3333, 19.1667, 24.1667	6.6667, 15, 35, 20, 23.3333

Appendix 3.10: Prior Probability of L, C and P for Shipping Route B hazards (Grounding)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H14	5, 10, 28.3333, 29.1667, 27.5	23.3333, 21.6667, 23.3333, 16.6667, 15	6.6667, 16.6667, 31.6667, 25.8333, 19.1667
H15	3.3333, 8.3333, 28.3333, 19.1667, 40.83333	20, 31.6667, 18.3333, 16.6667, 13.3333	10, 20, 25.8333, 22.5, 21.6667
H16	3.3333, 6.6667, 30, 26.6667, 33.3333	20, 30, 21.6667, 15, 13.3333	8.3333, 11.6667, 26.6667, 30, 23.3333
H17	3.3333, 5, 13.3333, 43.3333, 35	20, 25, 21.6667, 15, 18.3333	11.6667, 14.1667, 19.1667, 36.6667, 18.3333
H18	3.3333, 5, 20, 23.3333, 48.3333	25.8333, 20, 22.5, 15, 16.6667	6.6667, 10, 35, 21.6667, 26.6667

H19	3.3333, 4.1667, 16.6667, 55.8333, 20	26.6667, 16.6667, 25, 15.8333, 15.8333	8.3333, 9.1667, 25, 20, 37.5
H20	2.5, 10.8333, 15.8333, 34.1667, 36.6667	38.3333, 25, 15.9.1667, 12.5	13.3333, 15.8333, 24.1667, 30, 16.6667
H21	3.3333, 3.3333, 13.3333, 38.3333, 41.6667	34.1667, 24.1667, 20.8333, 12.5, 8.3333	5.8333, 10.8333, 24.1667, 27.5, 31.6667
H22	3.3333, 6.6667, 22.5, 27.5, 40	25.8333, 27.5, 20.8333, 10.8333, 15	5, 11.6667, 25, 25.8333, 32.5
H23	6.6667, 5, 29.1667, 19.1667, 40	28.3333, 25, 21.6667, 15, 10	5, 12.5, 27.5, 25, 30
H24	6.6667, 6.6667, 36.6667, 31.6667, 18.3333	31.6667, 23.3333, 21.6667, 13.3333, 10	5, 15, 31.6667, 25, 23.3333
H25	3.3333, 5, 25, 31.6667, 35	23.3333, 25, 20.8333, 19.1667, 11.6667	7.5, 14.1667, 21.6667, 30.8333, 25.8333
H26	5.8333, 7.5, 27.5, 38.3333, 20.8333	16.6667, 25, 20.8333, 27.5, 10	11.6667, 13.3333, 32.5, 19.1667, 23.3333
H27	3.3333, 4.1667, 14.1667, 40, 38.3333	28.3333, 20.8333, 20, 19.1667, 11.6667	10, 17.5, 23.3333, 24.1667, 25
H28	5.8333, 6.6667, 30.8333, 29.1667, 27.5	24.1667, 34.1667, 16.6667, 15, 10	5.8333, 12.5, 20, 34.1667, 27.5

Appendix 3.11: Prior Probability of L, C and P for Shipping Route B hazards (Hull Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H29	3.3333, 3.3333, 8.3333, 25, 60	26.6667, 33.3333, 20, 13.3333, 6.6667	10.8333, 11.6667, 24.1667, 27.5, 25.83333
H30	8.3333, 10, 15, 36.6667, 30	10, 23.3333, 33.3333, 21.6667, 11.6667	8.3333, 9.1667, 29.1667, 35, 18.3333
H31	6.6667, 20, 21.6667, 20, 31.6667	13.3333, 23.3333, 30, 23.3333, 10	8.3333, 24.1667, 35.8333, 23.3333, 8.3333
H32	5, 10.8333, 20.8333, 26.6667, 36.6667	16.6667, 45, 17.5, 15.8333, 5	6.6667, 11.6667, 35, 26.6667, 20
H33	3.3333, 6.6667, 10, 33.3333, 46.6667	21.6667, 28.3333, 26.6667, 15, 8.3333	8.3333, 11.6667, 28.3333, 25, 26.6667
H34	5, 18.3333, 17.5, 22.5, 36.6667	21.6667, 33.3333, 21.6667, 16.6667, 6.6667	6.6667, 10, 36.6667, 22.5, 24.1667

Appendix 3.12: Prior Probability of L, C and P for Shipping Route B hazards (Fire/Explosion)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H35	4.1667, 8.3333, 23.3333, 36.6667, 27.5	26.6667, 30, 18.3333, 9.1667, 15.8333	6.6667, 16.6667, 28.3333, 20, 28.3333
H36	5.83333, 8.3333, 17.5, 35.8333, 32.5	25, 28.3333, 21.6667, 12.5, 12.5	15, 20, 24.1667, 17.5, 23.3333
H37	5, 8.3333, 15, 31.6667, 40	26.6667, 30, 20, 15, 8.3333	6.6667, 17.1667, 23.6667, 28.3333, 24.1667
H38	7.5, 11.6667, 18.3333, 20, 42.5	25, 28.3333, 24.1667, 12.5, 10	8.3333, 26.6667, 30, 18.3333, 16.6667
H39	5.8333, 10.8333, 17.5, 34.1667, 31.6667	26.6667, 30, 20.8333, 12.5, 10	6.6667, 9.1667, 26.6667, 31.6667, 25.8333
H40	1.6667, 5, 13.3333, 34.1667, 45.8333	23.3333, 25, 17.5, 19.1667, 15	6.6667, 17.5, 23.3333, 25, 27.5

H41	3.3333, 5.8333, 11.6667, 30, 49.1667	6.6667, 25, 18.33333, 18.3333, 31.6667	8.3333, 20.8333, 20.8333, 20.8333, 29.1667
H42	3.3333, 5.8333, 10.83333, 26.6667, 53.3333	10, 8.3333, 26.6667, 21.6667, 33.3333	5, 10, 27.8333, 25.3333, 31.8333
H43	3.33335, 12.5, 21.6667, 57.5	16.6667, 26.6667, 25, 20, 11.6667	13.3333, 18.3333, 16.6667, 23.3333, 28.3333
H44	2.5, 3.3333, 8.3333, 21.6667, 64.1667	33.3333, 18.3333, 13.3333, 10, 25	14.1667, 15, 21.6667, 22.5, 26.6667
H45	3.3333, 5, 11.6667, 30.8333, 49.1667	10, 35, 20.83333, 18.3333, 15.83333	8.3333, 10.8333, 21.6667, 30, 29.1667

Appendix 3.13: Prior Probability of L, C and P for Shipping Route B hazards (Equipment Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H46	3.3333, 6.6667, 18.3333, 29.1667, 42.5	15, 21.6667, 22.5, 19.1667, 21.6667	6.6667, 13.3333, 33.3333, 26.6667, 20
H47	3.3333, 8.3333, 20.83333, 26.6667, 40.8333	6.6667, 18.3333, 28.3333, 21.6667, 25	6.6667, 13.3333, 27.5, 25.8333, 26.6667
H48	3.3333, 8.3333, 25, 25.8333, 37.5	8.3333, 16.6667, 25, 21.6667, 28.3333	10, 15, 38.3333, 23.3333, 13.3333
H49	3.3333, 6.6667, 18.3333, 29.1667, 42.5	6.6667, 23.3333, 15.8333, 14.1667, 40	6.6667, 11.6667, 32.5, 27.5, 21.6667
H50	5, 18.3333, 20, 25.8333, 30.8333	6.6667, 36.6667, 15, 15, 26.6667	6.6667, 20, 31.6667, 25, 16.6667
H51	5, 9.1667, 13.3333, 36.6667, 35.8333	6.6667, 28.3333, 23.3333, 18.3333, 23.3333	7.5, 18.3333, 22.5, 29.1667, 22.5
H52	3.3333, 7.5, 15, 29.1667, 45	10, 25, 18.3333, 25, 21.6667	6.6667, 11.6667, 21.6667, 29.1667, 30.8333
H53	3.3333, 6.6667, 8.3333, 19.1667, 62.5	6.6667, 16.6667, 30, 21.6667, 25	6.6667, 13.3333, 16.6667, 30.8333, 32.5
H54	3.3333, 8.3333, 18.3333, 25, 45	11.6667, 26.6667, 31.6667, 15, 15	8.3333, 19.1667, 25.8333, 24.1667, 22.5
H55	3.3333, 8.3333, 16.6667, 28.3333, 43.3333	6.6667, 25, 30, 23.3333, 15	15, 17.5, 25.8333, 18.3333, 23.3333
H56	3.3333, 10, 20.83333, 28.3333, 37.5	10, 28.3333, 23.3333, 16.6667, 21.6667	8.3333, 18.3333, 26.6667, 23.3333, 23.3333
H57	5, 8.3333, 20, 29.1667, 37.5	11.6667, 8.3333, 25, 31.6667, 23.3333	6.6667, 16.6667, 18.3333, 28.3333, 30
H58	5, 10, 16.6667, 44.1667, 24.1667	6.6667, 29.1667, 22.5, 25, 16.6667	4.1667, 19.1667, 20, 30.8333, 25.8333
H59	3.3333, 6.6667, 21.6667, 35, 33.3333	15, 34.1667, 26.6667, 14.1667, 10	10.8333, 18.3333, 22.5, 27.5, 20.83333
H60	10, 21.6667, 26.6667, 23.3333, 18.3333	11.6667, 20, 33.3333, 18.3333, 16.6667	8.3333, 23.3333, 31.6667, 20, 16.6667
H61	5, 8.3333, 20, 32.5, 34.1667	8.3333, 27.5, 20.8333, 20, 23.3333	5, 12.5, 28.3333, 26.3333, 27.83333

Appendix 3.14: Prior Probability of L, C and P for Shipping Route C hazards (Collision)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H1	2.5, 20, 21.6667, 26.6667, 29.1667	28.3333, 20.8333, 15.8333, 13.3333, 21.6667	23.3333, 24.1667, 16.6667, 20.8333, 15

H2	5, 10.8333, 18.3333, 20, 45.83333	35, 22.5, 20, 12.1667, 10.3333	10, 13.3333, 29.1667, 24.1667, 23.3333
H3	3.3333, 7.5, 13.3333, 40.83333, 35	13.3333, 29.1667, 21.6667, 22.1667, 13.6667	23.3333, 24.1667, 19.1667, 17.5, 15.8333
H4	6.6667, 16.6667, 21.6667, 20, 35	26.6667, 35, 16.6667, 15, 6.6667	16.6667, 16.6667, 21.6667, 18.3333, 26.6667
H5	3.3333, 3.3333, 16.6667, 35, 41.6667	22.5, 19.1667, 26.6667, 18.3333, 13.3333	10, 17.5, 25, 28.3333, 19.1667
H6	5, 6.6667, 21.6667, 35.8333, 30.8333	17.5, 20, 25, 18.3333, 19.1667	13.3333, 12.5, 24.1667, 28.3333, 21.6667
H7	10, 8.3333, 22.5, 35.83333, 23.3333	41.6667, 30, 15, 10, 3.3333	8.3333, 16.6667, 15, 35, 25
H8	5, 6.6667, 21.6667, 27.5, 39.1667	39.1667, 23.3333, 15, 14.1667, 8.3333	6.6667, 10, 23.3333, 22.5, 37.5
H9	4.1667, 6.6667, 25, 39.1667, 25	38.3333, 23.3333, 16.6667, 15.8333, 5.8333	6.6667, 15, 18.3333, 32.5, 27.5
H10	6.6667, 18.3333, 36.6667, 20.8333, 17.5	34.1667, 26.6667, 14.1667, 19.1667, 5.8333	6.6667, 13.3333, 33.3333, 20.8333, 25.8333
H11	5.8333, 8.3333, 36.6667, 34.1667, 15	7.5, 31.6667, 35, 18.3333, 7.5	13.3333, 9.1667, 30.8333, 27.5, 19.1667
H12	5, 9.1667, 30.8333, 29.1667, 25.8333	30, 22.5, 17.5, 18.3333, 11.6667	13.3333, 15, 30, 21.6667, 20
H13	3.3333, 5, 18.3333, 38.3333, 35	18.3333, 20, 18.3333, 19.1667, 24.1667	6.6667, 15, 35, 20, 23.3333

Appendix 3.15: Prior Probability of L, C and P for Shipping Route C hazards (Grounding)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H14	5, 10, 28.3333, 29.1667, 27.5	23.3333, 21.6667, 23.3333, 16.6667, 15	6.6667, 16.6667, 31.6667, 25.8333, 19.1667
H15	3.3333, 8.3333, 28.3333, 19.1667, 40.83333	20, 31.6667, 18.3333, 16.6667, 13.3333	10, 20, 25.8333, 22.5, 21.6667
H16	3.3333, 6.6667, 30, 26.6667, 33.3333	20, 30, 21.6667, 15, 13.3333	8.3333, 11.6667, 26.6667, 30, 23.3333
H17	3.3333, 5, 13.3333, 43.3333, 35	20, 25, 21.6667, 15, 18.3333	11.6667, 14.1667, 19.1667, 36.6667, 18.3333
H18	3.3333, 5, 20, 23.3333, 48.3333	25.8333, 20, 22.5, 15, 16.6667	6.6667, 10, 35, 21.6667, 26.6667
H19	3.3333, 5.8333, 16.6667, 55.8333, 18.3333	26.6667, 16.6667, 25, 15.8333, 15.8333	8.3333, 9.1667, 25, 20, 37.5
H20	2.5, 15, 15, 32.5, 35	38.3333, 25, 15.9.1667, 12.5	13.3333, 15.8333, 24.1667, 30, 16.6667
H21	3.3333, 3.3333, 13.3333, 38.3333, 41.6667	34.1667, 24.1667, 20.8333, 12.5, 8.3333	5.8333, 10.8333, 24.1667, 27.5, 31.6667
H22	3.3333, 6.6667, 22.5, 27.5, 40	25.8333, 27.5, 20.8333, 10.8333, 15	5, 11.6667, 25, 25.8333, 32.5
H23	6.6667, 5, 29.1667, 19.1667, 40	28.3333, 25, 21.6667, 15, 10	5, 12.5, 27.5, 25, 30
H24	6.6667, 6.6667, 36.6667, 31.6667, 18.3333	31.6667, 23.3333, 21.6667, 13.3333, 10	5, 15, 31.6667, 25, 23.3333
H25	3.3333, 5, 25, 31.6667, 35	23.3333, 25, 20.8333, 19.1667, 11.6667	7.5, 14.1667, 21.6667, 30.8333, 25.8333
H26	8.3333, 8.3333, 28.3333, 38.3333, 16.6667	16.6667, 25, 20.8333, 27.5, 10	11.6667, 13.3333, 32.5, 19.1667, 23.3333

H27	3.3333, 5, 15, 40, 36.6667	28.3333, 20.8333, 20, 19.1667, 11.6667	10, 17.5, 23.3333, 24.1667, 25
H28	5.8333, 6.6667, 30.8333, 29.1667, 27.5	24.1667, 34.1667, 16.6667, 15, 10	5.8333, 12.5, 20, 34.1667, 27.5

Appendix 3.16: Prior Probability of L, C and P for Shipping Route C hazards (Hull Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H29	3.3333, 3.3333, 8.3333, 25, 60	26.6667, 33.3333, 20, 13.3333, 6.6667	10.8333, 11.6667, 24.1667, 27.5, 25.83333
H30	8.3333, 10, 15, 36.6667, 30	10, 23.3333, 33.3333, 21.6667, 11.6667	8.3333, 9.1667, 29.1667, 35, 18.3333
H31	6.6667, 20, 21.6667, 20, 31.6667	13.3333, 23.3333, 30, 23.3333, 10	8.3333, 24.1667, 35.8333, 23.3333, 8.3333
H32	5, 11.6667, 24.1667, 29.1667, 30	16.6667, 45, 17.5, 15.8333, 5	6.6667, 11.6667, 35, 26.6667, 20
H33	3.3333, 6.6667, 10, 33.3333, 46.6667	21.6667, 28.3333, 26.6667, 15, 8.3333	8.3333, 11.6667, 28.3333, 25, 26.6667
H34	5, 18.3333, 17.5, 22.5, 36.6667	21.6667, 33.3333, 21.6667, 16.6667, 6.6667	6.6667, 10, 36.6667, 22.5, 24.1667

Appendix 3.17: Prior Probability of L, C and P for Shipping Route C hazards (Fire/Explosion)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H35	4.1667, 8.3333, 23.3333, 36.6667, 27.5	26.6667, 30, 18.3333, 9.1667, 15.8333	6.6667, 16.6667, 28.3333, 20, 28.3333
H36	5.83333, 8.3333, 17.5, 35.8333, 32.5	25, 28.3333, 21.6667, 12.5, 12.5	15, 20, 24.1667, 17.5, 23.3333
H37	5, 8.3333, 15, 31.6667, 40	26.6667, 30, 20, 15, 8.3333	6.6667, 17.1667, 23.6667, 28.3333, 24.1667
H38	7.5, 11.6667, 18.3333, 20, 42.5	25, 28.3333, 24.1667, 12.5, 10	8.3333, 26.6667, 30, 18.3333, 16.6667
H39	8.3333, 8.3333, 20, 33.3333, 30	26.6667, 30, 20.8333, 12.5, 10	6.6667, 9.1667, 26.6667, 31.6667, 25.8333
H40	1.6667, 5.8333, 15, 33.3333, 44.1667	23.3333, 25, 17.5, 19.1667, 15	6.6667, 17.5, 23.3333, 25, 27.5
H41	3.3333, 6.6667, 11.6667, 30, 48.3333	6.6667, 25, 18.33333, 18.3333, 31.6667	8.3333, 20.8333, 20.8333, 20.8333, 29.1667
H42	3.3333, 5.8333, 10.83333, 26.6667, 53.3333	10, 8.3333, 26.6667, 21.6667, 33.3333	5, 10, 27.8333, 25.3333, 31.8333
H43	3.3333, 8.3333, 14.1667, 20.8333, 53.3333	16.6667, 26.6667, 25, 20, 11.6667	13.3333, 18.3333, 16.6667, 23.3333, 28.3333
H44	3.3333, 3.3333, 8.3333, 21.6667, 63.3333	33.3333, 18.3333, 13.3333, 10, 25	14.1667, 15, 21.6667, 22.5, 26.6667
H45	3.3333, 5, 11.6667, 33.3333, 46.6667	10, 35, 20.83333, 18.3333, 15.83333	8.3333, 10.8333, 21.6667, 30, 29.1667

Appendix 3.18: Prior Probability of L, C and P for Shipping Route C hazards (Equipment Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H46	3.3333, 6.6667, 18.3333, 29.1667, 42.5	15, 21.6667, 22.5, 19.1667, 21.6667	6.6667, 13.3333, 33.3333, 26.6667, 20
H47	3.3333, 8.3333, 20.83333, 26.6667, 40.8333	6.6667, 18.3333, 28.3333, 21.6667, 25	6.6667, 13.3333, 27.5, 25.8333, 26.6667
H48	3.3333, 8.3333, 25, 25.8333, 37.5	8.3333, 16.6667, 25, 21.6667, 28.3333	10, 15, 38.3333, 23.3333, 13.3333
H49	3.3333, 6.6667, 18.3333, 29.1667, 42.5	6.6667, 23.3333, 15.8333, 14.1667, 40	6.6667, 11.6667, 32.5, 27.5, 21.6667
H50	5, 18.3333, 20, 25.8333, 30.8333	6.6667, 36.6667, 15, 15, 26.6667	6.6667, 20, 31.6667, 25, 16.6667
H51	5, 9.1667, 13.3333, 36.6667, 35.8333	6.6667, 28.3333, 23.3333, 18.3333, 23.3333	7.5, 18.3333, 22.5, 29.1667, 22.5
H52	3.3333, 7.5, 15, 29.1667, 45	10, 25, 18.3333, 25, 21.6667	6.6667, 11.6667, 21.6667, 29.1667, 30.8333
H53	3.3333, 6.6667, 8.3333, 19.1667, 62.5	6.6667, 16.6667, 30, 21.6667, 25	6.6667, 13.3333, 16.6667, 30.8333, 32.5
H54	3.3333, 8.3333, 18.3333, 25, 45	11.6667, 26.6667, 31.6667, 15, 15	8.3333, 19.1667, 25.8333, 24.1667, 22.5
H55	3.3333, 8.3333, 16.6667, 28.3333, 43.3333	6.6667, 25, 30, 23.3333, 15	15, 17.5, 25.8333, 18.3333, 23.3333
H56	3.3333, 10, 20.83333, 28.3333, 37.5	10, 28.3333, 23.3333, 16.6667, 21.6667	8.3333, 18.3333, 26.6667, 23.3333, 23.3333
H57	5, 8.3333, 20, 29.1667, 37.5	11.6667, 8.3333, 25, 31.6667, 23.3333	6.6667, 16.6667, 18.3333, 28.3333, 30
H58	5, 10, 16.6667, 44.1667, 24.1667	6.6667, 29.1667, 22.5, 25, 16.6667	4.1667, 19.1667, 20, 30.8333, 25.8333
H59	3.3333, 6.6667, 21.6667, 35, 33.3333	15, 34.1667, 26.6667, 14.1667, 10	10.8333, 18.3333, 22.5, 27.5, 20.83333
H60	10, 21.6667, 26.6667, 23.3333, 18.3333	11.6667, 20, 33.3333, 18.3333, 16.6667	8.3333, 23.3333, 31.6667, 20, 16.6667
H61	5, 8.3333, 20, 32.5, 34.1667	8.3333, 27.5, 20.8333, 20, 23.3333	5, 12.5, 28.3333, 26.3333, 27.83333

Appendix 3.19: Prior Probability of L, C and P for Shipping Route D hazards (Collision)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H1	2.5, 20, 21.6667, 26.6667, 29.1667	28.3333, 20.8333, 15.8333, 13.3333, 21.6667	23.3333, 24.1667, 16.6667, 20.8333, 15
H2	5, 10.8333, 18.3333, 20, 45.83333	35, 22.5, 20, 12.1667, 10.3333	10, 13.3333, 29.1667, 24.1667, 23.3333
H3	3.3333, 7.5, 13.3333, 40.83333, 35	13.3333, 29.1667, 21.6667, 22.1667, 13.6667	23.3333, 24.1667, 19.1667, 17.5, 15.8333
H4	6.6667, 8.333, 17.5, 29.1667, 38.3333	26.6667, 35, 16.6667, 15, 6.6667	16.6667, 16.6667, 21.6667, 18.3333, 26.6667
H5	3.3333, 3.3333, 16.6667, 35, 41.6667	22.5, 19.1667, 26.6667, 18.3333, 13.3333	10, 17.5, 25, 28.3333, 19.1667
H6	3.3333, 6.6667, 21.6667, 37.5, 30.8333	17.5, 20, 25, 18.3333, 19.1667	13.3333, 12.5, 24.1667, 28.3333, 21.6667
H7	4.1667, 6.6667, 23.3333, 37.5, 28.3333	41.6667, 30, 15, 10, 3.3333	8.3333, 16.6667, 15, 35, 25

H8	5, 6.6667, 21.6667, 27.5, 39.1667	39.1667, 23.3333, 15, 14.1667, 8.3333	6.6667, 10, 23.3333, 22.5, 37.5
H9	4.1667, 6.6667, 25, 39.1667, 25	38.3333, 23.3333, 16.6667, 15.8333, 5.8333	6.6667, 15, 18.3333, 32.5, 27.5
H10	6.6667, 18.3333, 36.6667, 20.8333, 17.5	34.1667, 26.6667, 14.1667, 19.1667, 5.8333	6.6667, 13.3333, 33.3333, 20.8333, 25.8333
H11	5.8333, 8.3333, 36.6667, 34.1667, 15	7.5, 31.6667, 35, 18.3333, 7.5	13.3333, 9.1667, 30.8333, 27.5, 19.1667
H12	5, 9.1667, 25.8333, 30.8333, 29.1667	30, 22.5, 17.5, 18.3333, 11.6667	13.3333, 15, 30, 21.6667, 20
H13	3.3333, 5, 18.3333, 38.3333, 35	18.3333, 20, 18.3333, 19.1667, 24.1667	6.6667, 15, 35, 20, 23.3333

Appendix 3.20: Prior Probability of L, C and P for Shipping Route D hazards (Grounding)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H14	5, 10, 28.3333, 29.1667, 27.5	23.3333, 21.6667, 23.3333, 16.6667, 15	6.6667, 16.6667, 31.6667, 25.8333, 19.1667
H15	3.3333, 8.3333, 28.3333, 19.1667, 40.83333	20, 31.6667, 18.3333, 16.6667, 13.3333	10, 20, 25.8333, 22.5, 21.6667
H16	3.3333, 6.6667, 30, 26.6667, 33.3333	20, 30, 21.6667, 15, 13.3333	8.3333, 11.6667, 26.6667, 30, 23.3333
H17	3.3333, 5, 13.3333, 43.3333, 35	20, 25, 21.6667, 15, 18.3333	11.6667, 14.1667, 19.1667, 36.6667, 18.3333
H18	3.3333, 5, 20, 23.3333, 48.3333	25.8333, 20, 22.5, 15, 16.6667	6.6667, 10, 35, 21.6667, 26.6667
H19	3.3333, 4.1667, 16.6667, 55.8333, 20	26.6667, 16.6667, 25, 15.8333, 15.8333	8.3333, 9.1667, 25, 20, 37.5
H20	2.5, 10.8333, 15.8333, 34.1667, 36.6667	38.3333, 25, 15.9.1667, 12.5	13.3333, 15.8333, 24.1667, 30, 16.6667
H21	3.3333, 3.3333, 13.3333, 38.3333, 41.6667	34.1667, 24.1667, 20.8333, 12.5, 8.3333	5.8333, 10.8333, 24.1667, 27.5, 31.6667
H22	3.3333, 6.6667, 22.5, 27.5, 40	25.8333, 27.5, 20.8333, 10.8333, 15	5, 11.6667, 25, 25.8333, 32.5
H23	6.6667, 5, 29.1667, 19.1667, 40	28.3333, 25, 21.6667, 15, 10	5, 12.5, 27.5, 25, 30
H24	6.6667, 6.6667, 36.6667, 31.6667, 18.3333	31.6667, 23.3333, 21.6667, 13.3333, 10	5, 15, 31.6667, 25, 23.3333
H25	3.3333, 5, 25, 31.6667, 35	23.3333, 25, 20.8333, 19.1667, 11.6667	7.5, 14.1667, 21.6667, 30.8333, 25.8333
H26	5.8333, 7.5, 27.5, 38.3333, 20.8333	16.6667, 25, 20.8333, 27.5, 10	11.6667, 13.3333, 32.5, 19.1667, 23.3333
H27	3.3333, 4.1667, 14.1667, 40, 38.3333	28.3333, 20.8333, 20, 19.1667, 11.6667	10, 17.5, 23.3333, 24.1667, 25
H28	5.8333, 6.6667, 30.8333, 29.1667, 27.5	24.1667, 34.1667, 16.6667, 15, 10	5.8333, 12.5, 20, 34.1667, 27.5

Appendix 3.21: Prior Probability of L, C and P for Shipping Route D hazards (Hull Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H29	3.3333, 3.3333, 8.3333, 25, 60	26.6667, 33.3333, 20, 13.3333, 6.6667	10.8333, 11.6667, 24.1667, 27.5, 25.83333

H30	8.3333, 10, 15, 36.6667, 30	10, 23.3333, 33.3333, 21.6667, 11.6667	8.3333, 9.1667, 29.1667, 35, 18.3333
H31	6.6667, 20, 21.6667, 20, 31.6667	13.3333, 23.3333, 30, 23.3333, 10	8.3333, 24.1667, 35.8333, 23.3333, 8.3333
H32	5, 10.8333, 20.8333, 26.6667, 36.6667	16.6667, 45, 17.5, 15.8333, 5	6.6667, 11.6667, 35, 26.6667, 20
H33	3.3333, 6.6667, 10, 33.3333, 46.6667	21.6667, 28.3333, 26.6667, 15, 8.3333	8.3333, 11.6667, 28.3333, 25, 26.6667
H34	5, 18.3333, 17.5, 22.5, 36.6667	21.6667, 33.3333, 21.6667, 16.6667, 6.6667	6.6667, 10, 36.6667, 22.5, 24.1667

Appendix 3.22: Prior Probability of L, C and P for Shipping Route D hazards (Fire/Explosion)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H35	4.1667, 8.3333, 23.3333, 36.6667, 27.5	26.6667, 30, 18.3333, 9.1667, 15.8333	6.6667, 16.6667, 28.3333, 20, 28.3333
H36	5.83333, 8.3333, 17.5, 35.8333, 32.5	25, 28.3333, 21.6667, 12.5, 12.5	15, 20, 24.1667, 17.5, 23.3333
H37	5, 8.3333, 15, 31.6667, 40	26.6667, 30, 20, 15, 8.3333	6.6667, 17.1667, 23.6667, 28.3333, 24.1667
H38	7.5, 11.6667, 18.3333, 20, 42.5	25, 28.3333, 24.1667, 12.5, 10	8.3333, 26.6667, 30, 18.3333, 16.6667
H39	5.8333, 10.8333, 17.5, 34.1667, 31.6667	26.6667, 30, 20.8333, 12.5, 10	6.6667, 9.1667, 26.6667, 31.6667, 25.8333
H40	1.6667, 5, 13.3333, 34.1667, 45.8333	23.3333, 25, 17.5, 19.1667, 15	6.6667, 17.5, 23.3333, 25, 27.5
H41	3.3333, 5.8333, 11.6667, 30, 49.1667	6.6667, 25, 18.33333, 18.3333, 31.6667	8.3333, 20.8333, 20.8333, 20.8333, 29.1667
H42	3.3333, 5.8333, 10.83333, 26.6667, 53.3333	10, 8.3333, 26.6667, 21.6667, 33.3333	5, 10, 27.8333, 25.3333, 31.8333
H43	3.33335, 12.5, 21.6667, 57.5	16.6667, 26.6667, 25, 20, 11.6667	13.3333, 18.3333, 16.6667, 23.3333, 28.3333
H44	2.5, 3.3333, 8.3333, 21.6667, 64.1667	33.3333, 18.3333, 13.3333, 10, 25	14.1667, 15, 21.6667, 22.5, 26.6667
H45	3.3333, 5, 11.6667, 30.8333, 49.1667	10, 35, 20.83333, 18.3333, 15.83333	8.3333, 10.8333, 21.6667, 30, 29.1667

Appendix 3.23: Prior Probability of L, C and P for D Shipping Route hazards (Equipment Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H46	3.3333, 6.6667, 18.3333, 29.1667, 42.5	15, 21.6667, 22.5, 19.1667, 21.6667	6.6667, 13.3333, 33.3333, 26.6667, 20
H47	3.3333, 8.3333, 20.83333, 26.6667, 40.8333	6.6667, 18.3333, 28.3333, 21.6667, 25	6.6667, 13.3333, 27.5, 25.8333, 26.6667
H48	3.3333, 8.3333, 25, 25.8333, 37.5	8.3333, 16.6667, 25, 21.6667, 28.3333	10, 15, 38.3333, 23.3333, 13.3333
H49	3.3333, 6.6667, 18.3333, 29.1667, 42.5	6.6667, 23.3333, 15.8333, 14.1667, 40	6.6667, 11.6667, 32.5, 27.5, 21.6667
H50	5, 18.3333, 20, 25.8333, 30.8333	6.6667, 36.6667, 15, 15, 26.6667	6.6667, 20, 31.6667, 25, 16.6667
H51	5, 9.1667, 13.3333, 36.6667, 35.8333	6.6667, 28.3333, 23.3333, 18.3333, 23.3333	7.5, 18.3333, 22.5, 29.1667, 22.5

H52	3.3333, 7.5, 15, 29.1667, 45	10, 25, 18.3333, 25, 21.6667	6.6667, 11.6667, 21.6667, 29.1667, 30.8333
H53	3.3333, 6.6667, 8.3333, 19.1667, 62.5	6.6667, 16.6667, 30, 21.6667, 25	6.6667, 13.3333, 16.6667, 30.8333, 32.5
H54	3.3333, 8.3333, 18.3333, 25, 45	11.6667, 26.6667, 31.6667, 15, 15	8.3333, 19.1667, 25.8333, 24.1667, 22.5
H55	3.3333, 8.3333, 16.6667, 28.3333, 43.3333	6.6667, 25, 30, 23.3333, 15	15, 17.5, 25.8333, 18.3333, 23.3333
H56	3.3333, 10, 20.83333, 28.3333, 37.5	10, 28.3333, 23.3333, 16.6667, 21.6667	8.3333, 18.3333, 26.6667, 23.3333, 23.3333
H57	5, 8.3333, 20, 29.1667, 37.5	11.6667, 8.3333, 25, 31.6667, 23.3333	6.6667, 16.6667, 18.3333, 28.3333, 30
H58	5, 10, 16.6667, 44.1667, 24.1667	6.6667, 29.1667, 22.5, 25, 16.6667	4.1667, 19.1667, 20, 30.8333, 25.8333
H59	3.3333, 6.6667, 21.6667, 35, 33.3333	15, 34.1667, 26.6667, 14.1667, 10	10.8333, 18.3333, 22.5, 27.5, 20.83333
H60	10, 21.6667, 26.6667, 23.3333, 18.3333	11.6667, 20, 33.3333, 18.3333, 16.6667	8.3333, 23.3333, 31.6667, 20, 16.6667
H61	5, 8.3333, 20, 32.5, 34.1667	8.3333, 27.5, 20.8333, 20, 23.3333	5, 12.5, 28.3333, 26.3333, 27.83333

Appendix 3.24 Prior Probability of L, C and P for Shipping Route E hazards (Collision)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H1	2.5, 20, 21.6667, 26.6667, 29.1667	28.3333, 20.8333, 15.8333, 13.3333, 21.6667	23.3333, 24.1667, 16.6667, 20.8333, 15
H2	5, 10.8333, 18.3333, 20, 45.83333	35, 22.5, 20, 12.1667, 10.3333	10, 13.3333, 29.1667, 24.1667, 23.3333
H3	3.3333, 7.5, 13.3333, 40.83333, 35	13.3333, 29.1667, 21.6667, 22.1667, 13.6667	23.3333, 24.1667, 19.1667, 17.5, 15.8333
H4	6.6667, 16.6667, 21.6667, 20, 35	26.6667, 35, 16.6667, 15, 6.6667	16.6667, 16.6667, 21.6667, 18.3333, 26.6667
H5	3.3333, 3.3333, 16.6667, 35, 41.6667	22.5, 19.1667, 26.6667, 18.3333, 13.3333	10, 17.5, 25, 28.3333, 19.1667
H6	5, 6.6667, 21.6667, 35.8333, 30.8333	17.5, 20, 25, 18.3333, 19.1667	13.3333, 12.5, 24.1667, 28.3333, 21.6667
H7	10, 8.3333, 22.5, 35.83333, 23.3333	41.6667, 30, 15, 10, 3.3333	8.3333, 16.6667, 15, 35, 25
H8	5, 6.6667, 21.6667, 27.5, 39.1667	39.1667, 23.3333, 15, 14.1667, 8.3333	6.6667, 10, 23.3333, 22.5, 37.5
H9	4.1667, 6.6667, 25, 39.1667, 25	38.3333, 23.3333, 16.6667, 15.8333, 5.8333	6.6667, 15, 18.3333, 32.5, 27.5
H10	6.6667, 18.3333, 36.6667, 20.8333, 17.5	34.1667, 26.6667, 14.1667, 19.1667, 5.8333	6.6667, 13.3333, 33.3333, 20.8333, 25.8333
H11	5.8333, 8.3333, 36.6667, 34.1667, 15	7.5, 31.6667, 35, 18.3333, 7.5	13.3333, 9.1667, 30.8333, 27.5, 19.1667
H12	5, 9.1667, 30.8333, 29.1667, 25.8333	30, 22.5, 17.5, 18.3333, 11.6667	13.3333, 15, 30, 21.6667, 20
H13	3.3333, 5, 18.3333, 38.3333, 35	18.3333, 20, 18.3333, 19.1667, 24.1667	6.6667, 15, 35, 20, 23.3333

Appendix 3.25: Prior Probability of L, C and P for Shipping Route E hazards (Grounding)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H14	5, 10, 28.3333, 29.1667, 27.5	23.3333, 21.6667, 23.3333, 16.6667, 15	6.6667, 16.6667, 31.6667, 25.8333, 19.1667
H15	3.3333, 8.3333, 28.3333, 19.1667, 40.83333	20, 31.6667, 18.3333, 16.6667, 13.3333	10, 20, 25.8333, 22.5, 21.6667
H16	3.3333, 6.6667, 30, 26.6667, 33.3333	20, 30, 21.6667, 15, 13.3333	8.3333, 11.6667, 26.6667, 30, 23.3333
H17	3.3333, 5, 13.3333, 43.3333, 35	20, 25, 21.6667, 15, 18.3333	11.6667, 14.1667, 19.1667, 36.6667, 18.3333
H18	3.3333, 5, 20, 23.3333, 48.3333	25.8333, 20, 22.5, 15, 16.6667	6.6667, 10, 35, 21.6667, 26.6667
H19	3.3333, 5.8333, 16.6667, 55.8333, 18.3333	26.6667, 16.6667, 25, 15.8333, 15.8333	8.3333, 9.1667, 25, 20, 37.5
H20	2.5, 15, 15, 32.5, 35	38.3333, 25, 15.9.1667, 12.5	13.3333, 15.8333, 24.1667, 30, 16.6667
H21	3.3333, 3.3333, 13.3333, 38.3333, 41.6667	34.1667, 24.1667, 20.8333, 12.5, 8.3333	5.8333, 10.8333, 24.1667, 27.5, 31.6667
H22	3.3333, 6.6667, 22.5, 27.5, 40	25.8333, 27.5, 20.8333, 10.8333, 15	5, 11.6667, 25, 25.8333, 32.5
H23	6.6667, 5, 29.1667, 19.1667, 40	28.3333, 25, 21.6667, 15, 10	5, 12.5, 27.5, 25, 30
H24	6.6667, 6.6667, 36.6667, 31.6667, 18.3333	31.6667, 23.3333, 21.6667, 13.3333, 10	5, 15, 31.6667, 25, 23.3333
H25	3.3333, 5, 25, 31.6667, 35	23.3333, 25, 20.8333, 19.1667, 11.6667	7.5, 14.1667, 21.6667, 30.8333, 25.8333
H26	8.3333, 8.3333, 28.3333, 38.3333, 16.6667	16.6667, 25, 20.8333, 27.5, 10	11.6667, 13.3333, 32.5, 19.1667, 23.3333
H27	3.3333, 5, 15, 40, 36.6667	28.3333, 20.8333, 20, 19.1667, 11.6667	10, 17.5, 23.3333, 24.1667, 25
H28	5.8333, 6.6667, 30.8333, 29.1667, 27.5	24.1667, 34.1667, 16.6667, 15, 10	5.8333, 12.5, 20, 34.1667, 27.5

Appendix 3.26: Prior Probability of L, C and P for Shipping Route E hazards (Hull Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H29	3.3333, 3.3333, 8.3333, 25, 60	26.6667, 33.3333, 20, 13.3333, 6.6667	10.8333, 11.6667, 24.1667, 27.5, 25.83333
H30	8.3333, 10, 15, 36.6667, 30	10, 23.3333, 33.3333, 21.6667, 11.6667	8.3333, 9.1667, 29.1667, 35, 18.3333
H31	6.6667, 20, 21.6667, 20, 31.6667	13.3333, 23.3333, 30, 23.3333, 10	8.3333, 24.1667, 35.8333, 23.3333, 8.3333
H32	5, 11.6667, 24.1667, 29.1667, 30	16.6667, 45, 17.5, 15.8333, 5	6.6667, 11.6667, 35, 26.6667, 20
H33	3.3333, 6.6667, 10, 33.3333, 46.6667	21.6667, 28.3333, 26.6667, 15, 8.3333	8.3333, 11.6667, 28.3333, 25, 26.6667
H34	5, 18.3333, 17.5, 22.5, 36.6667	21.6667, 33.3333, 21.6667, 16.6667, 6.6667	6.6667, 10, 36.6667, 22.5, 24.1667

Appendix 3.27: Prior Probability of L, C and P for Shipping Route E hazards (Fire/Explosion)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H35	4.1667, 8.3333, 23.3333, 36.6667, 27.5	26.6667, 30, 18.3333, 9.1667, 15.8333	6.6667, 16.6667, 28.3333, 20, 28.3333
H36	5.83333, 8.3333, 17.5, 35.8333, 32.5	25, 28.3333, 21.6667, 12.5, 12.5	15, 20, 24.1667, 17.5, 23.3333
H37	5, 8.3333, 15, 31.6667, 40	26.6667, 30, 20, 15, 8.3333	6.6667, 17.1667, 23.6667, 28.3333, 24.1667
H38	7.5, 11.6667, 18.3333, 20, 42.5	25, 28.3333, 24.1667, 12.5, 10	8.3333, 26.6667, 30, 18.3333, 16.6667
H39	8.3333, 8.3333, 20, 33.3333, 30	26.6667, 30, 20.8333, 12.5, 10	6.6667, 9.1667, 26.6667, 31.6667, 25.8333
H40	1.6667, 5.8333, 15, 33.3333, 44.1667	23.3333, 25, 17.5, 19.1667, 15	6.6667, 17.5, 23.3333, 25, 27.5
H41	3.3333, 6.6667, 11.6667, 30, 48.3333	6.6667, 25, 18.33333, 18.3333, 31.6667	8.3333, 20.8333, 20.8333, 20.8333, 29.1667
H42	3.3333, 5.8333, 10.83333, 26.6667, 53.3333	10, 8.3333, 26.6667, 21.6667, 33.3333	5, 10, 27.8333, 25.3333, 31.8333
H43	3.3333, 8.3333, 14.1667, 20.8333, 53.3333	16.6667, 26.6667, 25, 20, 11.6667	13.3333, 18.3333, 16.6667, 23.3333, 28.3333
H44	3.3333, 3.3333, 8.3333, 21.6667, 63.3333	33.3333, 18.3333, 13.3333, 10, 25	14.1667, 15, 21.6667, 22.5, 26.6667
H45	3.3333, 5, 11.6667, 33.3333, 46.6667	10, 35, 20.83333, 18.3333, 15.83333	8.3333, 10.8333, 21.6667, 30, 29.1667

Appendix 3.28: Prior Probability of L, C and P for Shipping Route E hazards (Equipment Failure)

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H46	3.3333, 6.6667, 18.3333, 29.1667, 42.5	15, 21.6667, 22.5, 19.1667, 21.6667	6.6667, 13.3333, 33.3333, 26.6667, 20
H47	3.3333, 8.3333, 20.83333, 26.6667, 40.8333	6.6667, 18.3333, 28.3333, 21.6667, 25	6.6667, 13.3333, 27.5, 25.8333, 26.6667
H48	3.3333, 8.3333, 25, 25.8333, 37.5	8.3333, 16.6667, 25, 21.6667, 28.3333	10, 15, 38.3333, 23.3333, 13.3333
H49	3.3333, 6.6667, 18.3333, 29.1667, 42.5	6.6667, 23.3333, 15.8333, 14.1667, 40	6.6667, 11.6667, 32.5, 27.5, 21.6667
H50	5, 18.3333, 20, 25.8333, 30.8333	6.6667, 36.6667, 15, 15, 26.6667	6.6667, 20, 31.6667, 25, 16.6667
H51	5, 9.1667, 13.3333, 36.6667, 35.8333	6.6667, 28.3333, 23.3333, 18.3333, 23.3333	7.5, 18.3333, 22.5, 29.1667, 22.5
H52	3.3333, 7.5, 15, 29.1667, 45	10, 25, 18.3333, 25, 21.6667	6.6667, 11.6667, 21.6667, 29.1667, 30.8333
H53	3.3333, 6.6667, 8.3333, 19.1667, 62.5	6.6667, 16.6667, 30, 21.6667, 25	6.6667, 13.3333, 16.6667, 30.8333, 32.5
H54	3.3333, 8.3333, 18.3333, 25, 45	11.6667, 26.6667, 31.6667, 15, 15	8.3333, 19.1667, 25.8333, 24.1667, 22.5
H55	3.3333, 8.3333, 16.6667, 28.3333, 43.3333	6.6667, 25, 30, 23.3333, 15	15, 17.5, 25.8333, 18.3333, 23.3333
H56	3.3333, 10, 20.83333, 28.3333, 37.5	10, 28.3333, 23.3333, 16.6667, 21.6667	8.3333, 18.3333, 26.6667, 23.3333, 23.3333
H57	5, 8.3333, 20, 29.1667, 37.5	11.6667, 8.3333, 25, 31.6667, 23.3333	6.6667, 16.6667, 18.3333, 28.3333, 30

H58	5, 10, 16.6667, 44.1667, 24.1667	6.6667, 29.1667, 22.5, 25, 16.6667	4.1667, 19.1667, 20, 30.8333, 25.8333
H59	3.3333, 6.6667, 21.6667, 35, 33.3333	15, 34.1667, 26.6667, 14.1667, 10	10.8333, 18.3333, 22.5, 27.5, 20.83333
H60	10, 21.6667, 26.6667, 23.3333, 18.3333	11.6667, 20, 33.3333, 18.3333, 16.6667	8.3333, 23.3333, 31.6667, 20, 16.6667
H61	5, 8.3333, 20, 32.5, 34.1667	8.3333, 27.5, 20.8333, 20, 23.3333	5, 12.5, 28.3333, 26.3333, 27.83333

Appendix 3.29: Prior Probability of L, C and P for Pipelines Transportation hazards

	Degree of Belief (VH, H, M, L, VL)		
	Likelihood	Consequences	Probability
H1	3.3333, 5, 8.3333, 10.8333, 72	13.3333, 18.3333, 16.6667, 20, 31.6667	30, 7.6667, 17, 21.3333, 24
H2	4.1667, 10.8333, 15, 20.8333, 49.1667	6.6667, 10, 16.6667, 23.3333, 43.3333	18.3333, 10, 18.3333, 23.3333, 30
H3	4.1667, 7.5, 10.8333, 20.8333, 56.6667	9.1667, 12.5, 14.1667, 21.6667, 42.5	21.6667, 15, 18.3333, 18.3333, 26.6666
H4	1.8333, 2.8333, 3.8333, 10,6667, 80.8333	10,6667, 14.6667, 17, 9.3333, 48.3333	36.6667, 11, 12, 14.6667, 25.6667
H5	3.3333, 6.6667, 14.1667, 30, 45.8333	6.6667, 10, 15, 23.3333, 45	20, 20, 28.3333, 23.3333, 8.3333
H6	4.1667, 7.5, 10, 13.3333, 65	7.5, 12.5, 17.5, 22.5, 40	18.3333, 15, 26.6667, 23.3333, 16.6667
H7	6.6667, 10, 22.5, 28.3333, 32.5	5.8333, 9.1667, 13.3333, 22.5, 49.1667	11.6667, 16.6667, 31.6667, 28.3333, 11.6667
H8	3.3333, 5.8333, 12.5, 26.6667, 51.6667	5.8333, 9.1667, 12.5, 23.3333, 49.1667	18.3333, 11.6667, 26.6667, 23.3333, 20
H9	2.5, 5.8333, 10, 13.3333, 68.3333	3.3333, 8.3333, 15, 25, 48.3333	26.6667, 23.3333, 25, 18.3333, 6.6667
H10	3.3333, 6.6667, 13.3333, 23.3333, 53.3333	6.6667, 8.3333, 15, 20, 50	18.3333, 15, 26.6667, 23.3333, 16.6667

Appendix 3.30: Analysis of petroleum port A hazards by HUGIN software

	Hs	Degree of Belief (VH, H, M, L, VL)				
		VH	H	M	L	VL
H1	MRHAA	0.0689	0.1478	0.2222	0.3111	0.2500
H2	MRHAB	0.1222	0.1889	0.2667	0.2500	0.1722
H3	MRHAC	0.1000	0.2222	0.3000	0.2500	0.1278
H4	MRHBA	0.1389	0.2389	0.2556	0.2500	0.1167
H5	MRHBB	0.1278	0.2056	0.2889	0.2833	0.0944
H6	MRHBC	0.1056	0.1667	0.3278	0.2556	0.1444
H7	MRHBD	0.1722	0.2000	0.2833	0.2278	0.1167
H8	MRHCA	0.1222	0.1722	0.2833	0.2667	0.1556
H9	MRHCB	0.1278	0.2111	0.2611	0.2778	0.1222
H10	MRHCC	0.1556	0.1833	0.2944	0.2333	0.1333
H11	MRHCD	0.1056	0.1222	0.2611	0.3278	0.1833
H12	MRHCE	0.1000	0.1833	0.2722	0.3111	0.1333
H13	MRHCFA	0.1389	0.1922	0.2500	0.2689	0.1500

H14	MRHCFB	0.1300	0.2444	0.2589	0.2444	0.1222
H15	MRHCFC	0.1056	0.2000	0.2500	0.2778	0.1667
H16	MRHDA	0.2633	0.2589	0.1722	0.1300	0.1756
H17	MRHDB	0.2500	0.2611	0.1833	0.1389	0.1667
H18	HRHAAA	0.1222	0.2333	0.2556	0.2611	0.1278
H19	HRHAAB	0.1111	0.1889	0.2722	0.2944	0.1333
H20	HRHAAC	0.1278	0.2111	0.2500	0.2611	0.1500
H21	HRHAB	0.1056	0.1667	0.3278	0.2778	0.1222
H22	HRHBAA	0.1611	0.2111	0.2556	0.2556	0.1167
H23	HRHBAB	0.1667	0.1944	0.2333	0.2500	0.1556
H24	HRHBAC	0.0944	0.1444	0.2556	0.2944	0.2111
H25	HRHBAD	0.0778	0.1556	0.2722	0.2556	0.2389
H26	HRHBBA	0.1667	0.2111	0.2722	0.2444	0.1056
H27	HRHBBB	0.1500	0.1889	0.2278	0.3444	0.0889
H28	HRHBBC	0.0844	0.1100	0.2889	0.3167	0.2000
H29	HRHBBD	0.0556	0.0867	0.1778	0.3189	0.3611
H30	HRHBBE	0.2111	0.2611	0.2444	0.1778	0.1056
H31	HRHBBF	0.1389	0.2000	0.2444	0.2333	0.1833
H32	HRHBBG	0.1500	0.2056	0.2000	0.2889	0.1556
H33	HRHBBH	0.2667	0.2500	0.2222	0.1722	0.0889
H34	HRHBBI	0.0944	0.1556	0.2833	0.2889	0.1778
H35	NRHAA	0.1111	0.2333	0.2556	0.1667	0.2333
H36	NRHAB	0.1111	0.2333	0.2778	0.1722	0.2056
H37	NRHAC	0.0833	0.1889	0.1944	0.1389	0.3944
H38	NRHBA	0.0611	0.1389	0.2333	0.2889	0.2778
H39	NRHBB	0.1500	0.1444	0.1656	0.2178	0.3222
H40	NRHBC	0.0500	0.1278	0.2722	0.3722	0.1778
H41	NRHCA	0.1444	0.1222	0.2167	0.2722	0.2444
H42	NRHCB	0.1667	0.1056	0.2000	0.2611	0.2667

Appendix 3.31: Analysis of petroleum port C hazards by HUGIN software

	Hs	Degree of Belief (VH, H, M, L, VL)				
		VH	H	M	L	VL
H1	MRHAA	0.0833	0.1333	0.2500	0.3000	0.2333
H2	MRHAB	0.1222	0.1833	0.2722	0.2722	0.1500
H3	MRHAC	0.1278	0.2167	0.2722	0.2389	0.1444
H4	MRHBA	0.1167	0.1944	0.2778	0.2722	0.1389
H5	MRHBB	0.1333	0.1722	0.3056	0.2556	0.1333
H6	MRHBC	0.1056	0.1556	0.2667	0.2889	0.1833
H7	MRHBD	0.1333	0.1833	0.2889	0.2556	0.1389
H8	MRHCA	0.0667	0.1222	0.2389	0.3500	0.2222

H9	MRHCB	0.1333	0.2056	0.2444	0.2667	0.1500
H10	MRHCC	0.1111	0.1667	0.2500	0.2778	0.1944
H11	MRHCD	0.1111	0.1444	0.2778	0.2722	0.1944
H12	MRHCE	0.1222	0.1889	0.3000	0.2611	0.1278
H13	MRHCFA	0.1389	0.2167	0.2889	0.2556	0.1000
H14	MRHCFB	0.1167	0.2278	0.2889	0.2444	0.1222
H15	MRHCFC	0.1222	0.2167	0.3000	0.2500	0.1111
H16	MRHDA	0.1833	0.2167	0.2000	0.1722	0.2278
H17	MRHDB	0.1970	0.2082	0.1866	0.1758	0.2324
H18	HRHAAA	0.1222	0.2000	0.2500	0.2778	0.1500
H19	HRHAAB	0.1000	0.1722	0.2500	0.3222	0.1556
H20	HRHAAC	0.1056	0.1667	0.2444	0.3278	0.1556
H21	HRHAB	0.1111	0.1556	0.2778	0.2667	0.1889
H22	HRHBAA	0.1389	0.1944	0.2667	0.2778	0.1222
H23	HRHBAB	0.1226	0.1617	0.2525	0.2820	0.1812
H24	HRHBAC	0.1111	0.1389	0.2444	0.3056	0.2000
H25	HRHBAD	0.1000	0.1389	0.2833	0.2833	0.1944
H26	HRHBBA	0.1389	0.1889	0.2722	0.3000	0.1000
H27	HRHBBB	0.1389	0.1833	0.2500	0.3111	0.1167
H28	HRHBBC	0.1111	0.1722	0.2778	0.3333	0.1056
H29	HRHBBD	0.0889	0.1333	0.2444	0.3278	0.2056
H30	HRHBBE	0.1944	0.2111	0.2556	0.2222	0.1167
H31	HRHBBF	0.1167	0.1444	0.2778	0.2667	0.1944
H32	HRHBBG	0.1556	0.1444	0.2278	0.3167	0.1556
H33	HRHBBH	0.1944	0.2167	0.2556	0.2278	0.1056
H34	HRHBBI	0.1232	0.1741	0.2975	0.2983	0.1069
H35	NRHAA	0.0667	0.1722	0.2722	0.2667	0.2222
H36	NRHAB	0.0500	0.1667	0.2333	0.2000	0.3500
H37	NRHAC	0.0578	0.1700	0.2111	0.1889	0.3722
H38	NRHBA	0.0556	0.1000	0.2222	0.2889	0.3333
H39	NRHBB	0.1389	0.1000	0.1889	0.2167	0.3556
H40	NRHBC	0.0667	0.0944	0.2444	0.3444	0.2500
H41	NRHCA	0.1556	0.1111	0.1778	0.2000	0.3556
H42	NRHCB	0.1444	0.1167	0.1722	0.2056	0.3611

Appendix 3.32: Analysis of petroleum port D hazards by HUGIN software

	Hs	Degree of Belief (VH, H, M, L, VL)				
		VH	H	M	L	VL
H1	MRHAA	0.0833	0.1500	0.2500	0.3111	0.2056
H2	MRHAB	0.1167	0.1778	0.3000	0.2722	0.1333
H3	MRHAC	0.1278	0.2111	0.2778	0.2722	0.1111

H4	MRHBA	0.1167	0.2111	0.2444	0.3056	0.1222
H5	MRHBB	0.1278	0.2000	0.3000	0.2611	0.1111
H6	MRHBC	0.1222	0.1500	0.3278	0.2778	0.1222
H7	MRHBD	0.1167	0.1778	0.3056	0.2833	0.1167
H8	MRHCA	0.1111	0.1722	0.2944	0.3000	0.1222
H9	MRHCB	0.1333	0.2111	0.2667	0.2833	0.1056
H10	MRHCC	0.1333	0.1611	0.2833	0.2889	0.1333
H11	MRHCD	0.1056	0.1722	0.2833	0.3000	0.1389
H12	MRHCE	0.1333	0.1667	0.2833	0.2944	0.1222
H13	MRHCFA	0.1611	0.1944	0.2611	0.2889	0.0944
H14	MRHCFB	0.1389	0.2389	0.2667	0.2444	0.1111
H15	MRHCFC	0.1444	0.1889	0.2778	0.2667	0.1222
H16	MRHDA	0.2578	0.2644	0.1722	0.1356	0.1700
H17	MRHDB	0.2467	0.2589	0.1889	0.1389	0.1667
H18	HRHAAA	0.1474	0.2187	0.2650	0.2460	0.1228
H19	HRHAAB	0.1500	0.1722	0.2833	0.2722	0.1222
H20	HRHAAC	0.1278	0.1889	0.2611	0.2722	0.1500
H21	HRHAB	0.1278	0.1500	0.3222	0.2833	0.1167
H22	HRHBAA	0.1556	0.1778	0.2889	0.2667	0.1111
H23	HRHBAB	0.1130	0.1315	0.2370	0.2963	0.2222
H24	HRHBAC	0.1056	0.1500	0.2333	0.2833	0.2278
H25	HRHBAD	0.1000	0.1667	0.3000	0.2333	0.2000
H26	HRHBBA	0.1833	0.2056	0.2722	0.2556	0.0833
H27	HRHBBB	0.1556	0.2000	0.2444	0.3222	0.0778
H28	HRHBBC	0.1000	0.1556	0.2833	0.3556	0.1056
H29	HRHBBD	0.0444	0.0833	0.2389	0.3556	0.2778
H30	HRHBBE	0.2389	0.2444	0.2333	0.1833	0.1000
H31	HRHBBF	0.1167	0.1556	0.3389	0.2444	0.1444
H32	HRHBBG	0.1556	0.1833	0.2000	0.3556	0.1056
H33	HRHBBH	0.1778	0.2833	0.2556	0.2056	0.0778
H34	HRHBBI	0.1111	0.1500	0.3056	0.2944	0.1389
H35	NRHAA	0.0722	0.2500	0.2889	0.1667	0.2222
H36	NRHAB	0.0389	0.2167	0.2722	0.1611	0.3111
H37	NRHAC	0.0667	0.1056	0.1944	0.2444	0.3889
H38	NRHBA	0.0667	0.1389	0.2411	0.3056	0.2478
H39	NRHBB	0.2111	0.0944	0.1878	0.2178	0.2889
H40	NRHBC	0.0611	0.1222	0.2833	0.4111	0.1222
H41	NRHCA	0.2168	0.1057	0.1915	0.1802	0.3057
H42	NRHCB	0.2168	0.1057	0.1915	0.1747	0.3113

Appendix 3.33: Analysis of Shipping Route A hazards by Hugin software

Hs	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
H1	0.0944	0.2083	0.2556	0.2361	0.2056
H2	0.1111	0.1556	0.2167	0.2444	0.2722
H3	0.1111	0.2056	0.2528	0.2056	0.2250
H4	0.0889	0.1417	0.2583	0.3111	0.2000
H5	0.1361	0.1611	0.1750	0.2194	0.3083
H6	0.0944	0.2250	0.2917	0.2222	0.1667
H7	0.1806	0.2167	0.1806	0.2028	0.2194
H8	0.1333	0.2028	0.1806	0.2683	0.2150
H9	0.1667	0.1556	0.2250	0.1878	0.2650
H10	0.1667	0.2000	0.1861	0.2083	0.2389
H11	0.1194	0.1333	0.2278	0.2722	0.2472
H12	0.1139	0.1306	0.2361	0.2806	0.2389
H13	0.1806	0.1778	0.1778	0.2750	0.1889
H14	0.1583	0.1944	0.2806	0.2028	0.1639
H15	0.0889	0.1639	0.3417	0.2667	0.1389
H16	0.1639	0.1500	0.2000	0.2917	0.1944
H17	0.1694	0.1333	0.2000	0.2139	0.2833
H18	0.1333	0.1611	0.2556	0.2417	0.2083
H19	0.0944	0.1333	0.2389	0.2583	0.2750
H20	0.1167	0.1611	0.2778	0.2389	0.2056
H21	0.1111	0.2000	0.2417	0.1944	0.2528
H22	0.1056	0.1611	0.2611	0.2389	0.2333
H23	0.1167	0.1472	0.1806	0.3167	0.2389
H24	0.1194	0.1167	0.2583	0.2000	0.3056
H25	0.1278	0.1000	0.2222	0.3056	0.2444
H26	0.1583	0.1778	0.1889	0.2500	0.2250
H27	0.1444	0.1278	0.1944	0.2611	0.2722
H28	0.1444	0.1500	0.3000	0.2333	0.1722
H29	0.1139	0.1472	0.2250	0.2722	0.2417
H30	0.1333	0.1417	0.2611	0.1972	0.2667
H31	0.1139	0.1528	0.2278	0.2139	0.2917
H32	0.1139	0.1528	0.2694	0.2833	0.1806
H33	0.1389	0.1417	0.1917	0.2778	0.2500
H34	0.1194	0.1778	0.2250	0.2611	0.2167
H35	0.1278	0.1850	0.1956	0.2500	0.2417
H36	0.1528	0.1889	0.2111	0.2194	0.2278
H37	0.1250	0.1833	0.2333	0.2194	0.2389
H38	0.1361	0.2222	0.2417	0.1694	0.2306

H39	0.1306	0.1667	0.2167	0.2611	0.2250
H40	0.0611	0.0806	0.2178	0.2456	0.3950
H41	0.1056	0.1611	0.1861	0.2583	0.2889
H42	0.0611	0.1750	0.1694	0.2306	0.3639
H43	0.0722	0.1694	0.1806	0.2722	0.3056
H44	0.1111	0.1667	0.1806	0.2167	0.3250
H45	0.1667	0.1222	0.1444	0.1806	0.3861
H46	0.0833	0.1389	0.2472	0.2500	0.2806
H47	0.0556	0.1333	0.2556	0.2472	0.3083
H48	0.0722	0.1333	0.2944	0.2361	0.2639
H49	0.0556	0.1389	0.2222	0.2361	0.3472
H50	0.0611	0.2500	0.2222	0.2194	0.2472
H51	0.0639	0.1861	0.1972	0.2806	0.2722
H52	0.0667	0.1472	0.1833	0.2778	0.3250
H53	0.0556	0.1222	0.1833	0.2389	0.4000
H54	0.0778	0.1806	0.2528	0.2139	0.2750
H55	0.0833	0.1694	0.2417	0.2333	0.2722
H56	0.0722	0.1889	0.2361	0.2278	0.2750
H57	0.0778	0.1111	0.2111	0.2972	0.3028
H58	0.1000	0.2167	0.3056	0.2056	0.1722
H59	0.0611	0.1611	0.2306	0.2628	0.2844
H60	0.0972	0.1972	0.2361	0.2556	0.2139
H61	0.0528	0.1944	0.1972	0.3333	0.2222

Appendix 3.34: Analysis of Shipping Route B hazards by Hugin software

Hs	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
H1	0.1806	0.2167	0.1806	0.2028	0.2194
H2	0.1333	0.2028	0.1806	0.2683	0.2150
H3	0.1667	0.1556	0.2250	0.1878	0.2650
H4	0.1667	0.2278	0.2000	0.1778	0.2278
H5	0.1194	0.1333	0.2278	0.2722	0.2472
H6	0.1194	0.1306	0.2361	0.2750	0.2389
H7	0.2000	0.1833	0.1750	0.2694	0.1722
H8	0.1583	0.1944	0.2806	0.2028	0.1639
H9	0.0889	0.1639	0.3417	0.2667	0.1389
H10	0.1639	0.1500	0.2000	0.2917	0.1944
H11	0.1694	0.1333	0.2000	0.2139	0.2833
H12	0.1333	0.1611	0.2722	0.2361	0.1972
H13	0.0944	0.1333	0.2389	0.2583	0.2750
H14	0.1167	0.1611	0.2778	0.2389	0.2056

H15	0.1111	0.2000	0.2417	0.1944	0.2528
H16	0.1056	0.1611	0.2611	0.2389	0.2333
H17	0.1167	0.1472	0.1806	0.3167	0.2389
H18	0.1194	0.1167	0.2583	0.2000	0.3056
H19	0.1278	0.1056	0.2222	0.3056	0.2389
H20	0.1583	0.1917	0.1861	0.2444	0.2194
H21	0.1444	0.1278	0.1944	0.2611	0.2722
H22	0.1444	0.1500	0.3000	0.2333	0.1722
H23	0.1139	0.1472	0.2250	0.2722	0.2417
H24	0.1333	0.1417	0.2611	0.1972	0.2667
H25	0.1139	0.1528	0.2278	0.2139	0.2917
H26	0.1222	0.1556	0.2722	0.2833	0.1667
H27	0.1389	0.1444	0.1944	0.2778	0.2444
H28	0.1194	0.1778	0.2250	0.2611	0.2167
H29	0.0944	0.2111	0.2667	0.2444	0.1833
H30	0.1111	0.1556	0.2167	0.2444	0.2722
H31	0.1111	0.2056	0.2528	0.2056	0.2250
H32	0.0889	0.1417	0.2583	0.3111	0.2000
H33	0.1361	0.1611	0.1750	0.2194	0.3083
H34	0.0944	0.2250	0.2917	0.2222	0.1667
H35	0.1278	0.1850	0.1956	0.2500	0.2417
H36	0.1528	0.1889	0.2111	0.2194	0.2278
H37	0.1250	0.1833	0.2333	0.2194	0.2389
H38	0.1361	0.2222	0.2417	0.1694	0.2306
H39	0.1389	0.1583	0.2250	0.2583	0.2194
H40	0.0611	0.0806	0.2178	0.2456	0.3950
H41	0.1056	0.1611	0.1861	0.2583	0.2889
H42	0.0611	0.1750	0.1694	0.2306	0.3639
H43	0.0722	0.1694	0.1806	0.2722	0.3056
H44	0.1111	0.1778	0.1861	0.2139	0.3111
H45	0.1694	0.1222	0.1444	0.1806	0.3833
H46	0.0833	0.1389	0.2472	0.2500	0.2806
H47	0.0556	0.1333	0.2556	0.2472	0.3083
H48	0.0722	0.1333	0.2944	0.2361	0.2639
H49	0.0556	0.1389	0.2222	0.2361	0.3472
H50	0.0611	0.2500	0.2222	0.2194	0.2472
H51	0.0639	0.1861	0.1972	0.2806	0.2722
H52	0.0667	0.1472	0.1833	0.2778	0.3250
H53	0.0556	0.1222	0.1833	0.2389	0.4000
H54	0.0778	0.1806	0.2528	0.2139	0.2750
H55	0.0833	0.1694	0.2417	0.2333	0.2722

H56	0.0722	0.1889	0.2361	0.2278	0.2750
H57	0.0778	0.1111	0.2111	0.2972	0.3028
H58	0.1000	0.2167	0.3056	0.2056	0.1722
H59	0.0611	0.1611	0.2306	0.2628	0.2844
H60	0.0972	0.1972	0.2361	0.2556	0.2139
H61	0.0528	0.1944	0.1972	0.3333	0.2222

Appendix 3.35: Analysis of Shipping Route C hazards by Hugin software

Hs	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
H1	0.0944	0.2083	0.2556	0.2361	0.2056
H2	0.1111	0.1556	0.2167	0.2444	0.2722
H3	0.1111	0.2056	0.2528	0.2056	0.2250
H4	0.0889	0.1417	0.2583	0.3111	0.2000
H5	0.1361	0.1611	0.1750	0.2194	0.3083
H6	0.0944	0.2250	0.2917	0.2222	0.1667
H7	0.1806	0.2167	0.1806	0.2028	0.2194
H8	0.1333	0.2028	0.1806	0.2683	0.2150
H9	0.1667	0.1556	0.2250	0.1878	0.2650
H10	0.1667	0.2000	0.1861	0.2083	0.2389
H11	0.1194	0.1333	0.2278	0.2722	0.2472
H12	0.1139	0.1306	0.2361	0.2806	0.2389
H13	0.1806	0.1778	0.1778	0.2750	0.1889
H14	0.1583	0.1944	0.2806	0.2028	0.1639
H15	0.0889	0.1639	0.3417	0.2667	0.1389
H16	0.1639	0.1500	0.2000	0.2917	0.1944
H17	0.1694	0.1333	0.2000	0.2139	0.2833
H18	0.1333	0.1611	0.2556	0.2417	0.2083
H19	0.0944	0.1333	0.2389	0.2583	0.2750
H20	0.1167	0.1611	0.2778	0.2389	0.2056
H21	0.1111	0.2000	0.2417	0.1944	0.2528
H22	0.1056	0.1611	0.2611	0.2389	0.2333
H23	0.1167	0.1472	0.1806	0.3167	0.2389
H24	0.1194	0.1167	0.2583	0.2000	0.3056
H25	0.1278	0.1000	0.2222	0.3056	0.2444
H26	0.1583	0.1778	0.1889	0.2500	0.2250
H27	0.1444	0.1278	0.1944	0.2611	0.2722
H28	0.1444	0.1500	0.3000	0.2333	0.1722
H29	0.1139	0.1472	0.2250	0.2722	0.2417
H30	0.1333	0.1417	0.2611	0.1972	0.2667
H31	0.1139	0.1528	0.2278	0.2139	0.2917

H32	0.1139	0.1528	0.2694	0.2833	0.1806
H33	0.1389	0.1417	0.1917	0.2778	0.2500
H34	0.1194	0.1778	0.2250	0.2611	0.2167
H35	0.1278	0.1850	0.1956	0.2500	0.2417
H36	0.1528	0.1889	0.2111	0.2194	0.2278
H37	0.1250	0.1833	0.2333	0.2194	0.2389
H38	0.1361	0.2222	0.2417	0.1694	0.2306
H39	0.1306	0.1667	0.2167	0.2611	0.2250
H40	0.0611	0.0806	0.2178	0.2456	0.3950
H41	0.1056	0.1611	0.1861	0.2583	0.2889
H42	0.0611	0.1750	0.1694	0.2306	0.3639
H43	0.0722	0.1694	0.1806	0.2722	0.3056
H44	0.1111	0.1667	0.1806	0.2167	0.3250
H45	0.1667	0.1222	0.1444	0.1806	0.3861
H46	0.0833	0.1389	0.2472	0.2500	0.2806
H47	0.0556	0.1333	0.2556	0.2472	0.3083
H48	0.0722	0.1333	0.2944	0.2361	0.2639
H49	0.0556	0.1389	0.2222	0.2361	0.3472
H50	0.0611	0.2500	0.2222	0.2194	0.2472
H51	0.0639	0.1861	0.1972	0.2806	0.2722
H52	0.0667	0.1472	0.1833	0.2778	0.3250
H53	0.0556	0.1222	0.1833	0.2389	0.4000
H54	0.0778	0.1806	0.2528	0.2139	0.2750
H55	0.0833	0.1694	0.2417	0.2333	0.2722
H56	0.0722	0.1889	0.2361	0.2278	0.2750
H57	0.0778	0.1111	0.2111	0.2972	0.3028
H58	0.1000	0.2167	0.3056	0.2056	0.1722
H59	0.0611	0.1611	0.2306	0.2628	0.2844
H60	0.0972	0.1972	0.2361	0.2556	0.2139
H61	0.0528	0.1944	0.1972	0.3333	0.2222

Appendix 3.36: Analysis of Shipping Route D hazards by Hugin software

Hs	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
H1	0.1806	0.2167	0.1806	0.2028	0.2194
H2	0.1333	0.2028	0.1806	0.2683	0.2150
H3	0.1667	0.1556	0.2250	0.1878	0.2650
H4	0.1667	0.2278	0.2000	0.1778	0.2278
H5	0.1194	0.1333	0.2278	0.2722	0.2472
H6	0.1194	0.1306	0.2361	0.2750	0.2389
H7	0.2000	0.1833	0.1750	0.2694	0.1722

H8	0.1583	0.1944	0.2806	0.2028	0.1639
H9	0.0889	0.1639	0.3417	0.2667	0.1389
H10	0.1639	0.1500	0.2000	0.2917	0.1944
H11	0.1694	0.1333	0.2000	0.2139	0.2833
H12	0.1333	0.1611	0.2722	0.2361	0.1972
H13	0.0944	0.1333	0.2389	0.2583	0.2750
H14	0.1167	0.1611	0.2778	0.2389	0.2056
H15	0.1111	0.2000	0.2417	0.1944	0.2528
H16	0.1056	0.1611	0.2611	0.2389	0.2333
H17	0.1167	0.1472	0.1806	0.3167	0.2389
H18	0.1194	0.1167	0.2583	0.2000	0.3056
H19	0.1278	0.1056	0.2222	0.3056	0.2389
H20	0.1583	0.1917	0.1861	0.2444	0.2194
H21	0.1444	0.1278	0.1944	0.2611	0.2722
H22	0.1444	0.1500	0.3000	0.2333	0.1722
H23	0.1139	0.1472	0.2250	0.2722	0.2417
H24	0.1333	0.1417	0.2611	0.1972	0.2667
H25	0.1139	0.1528	0.2278	0.2139	0.2917
H26	0.1222	0.1556	0.2722	0.2833	0.1667
H27	0.1389	0.1444	0.1944	0.2778	0.2444
H28	0.1194	0.1778	0.2250	0.2611	0.2167
H29	0.0944	0.2111	0.2667	0.2444	0.1833
H30	0.1111	0.1556	0.2167	0.2444	0.2722
H31	0.1111	0.2056	0.2528	0.2056	0.2250
H32	0.0889	0.1417	0.2583	0.3111	0.2000
H33	0.1361	0.1611	0.1750	0.2194	0.3083
H34	0.0944	0.2250	0.2917	0.2222	0.1667
H35	0.1278	0.1850	0.1956	0.2500	0.2417
H36	0.1528	0.1889	0.2111	0.2194	0.2278
H37	0.1250	0.1833	0.2333	0.2194	0.2389
H38	0.1361	0.2222	0.2417	0.1694	0.2306
H39	0.1389	0.1583	0.2250	0.2583	0.2194
H40	0.0611	0.0806	0.2178	0.2456	0.3950
H41	0.1056	0.1611	0.1861	0.2583	0.2889
H42	0.0611	0.1750	0.1694	0.2306	0.3639
H43	0.0722	0.1694	0.1806	0.2722	0.3056
H44	0.1111	0.1778	0.1861	0.2139	0.3111
H45	0.1694	0.1222	0.1444	0.1806	0.3833
H46	0.0833	0.1389	0.2472	0.2500	0.2806
H47	0.0556	0.1333	0.2556	0.2472	0.3083
H48	0.0722	0.1333	0.2944	0.2361	0.2639

H49	0.0556	0.1389	0.2222	0.2361	0.3472
H50	0.0611	0.2500	0.2222	0.2194	0.2472
H51	0.0639	0.1861	0.1972	0.2806	0.2722
H52	0.0667	0.1472	0.1833	0.2778	0.3250
H53	0.0556	0.1222	0.1833	0.2389	0.4000
H54	0.0778	0.1806	0.2528	0.2139	0.2750
H55	0.0833	0.1694	0.2417	0.2333	0.2722
H56	0.0722	0.1889	0.2361	0.2278	0.2750
H57	0.0778	0.1111	0.2111	0.2972	0.3028
H58	0.1000	0.2167	0.3056	0.2056	0.1722
H59	0.0611	0.1611	0.2306	0.2628	0.2844
H60	0.0972	0.1972	0.2361	0.2556	0.2139
H61	0.0528	0.1944	0.1972	0.3333	0.2222

Appendix 3.37: Analysis of Shipping Route E hazards by Hugin software

Hs	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
H1	0.0944	0.2111	0.2667	0.2444	0.1833
H2	0.1111	0.1556	0.2167	0.2444	0.2722
H3	0.1111	0.2056	0.2528	0.2056	0.2250
H4	0.0889	0.1417	0.2583	0.3111	0.2000
H5	0.1361	0.1611	0.1750	0.2194	0.3083
H6	0.0944	0.2250	0.2917	0.2222	0.1667
H7	0.1806	0.2167	0.1806	0.2028	0.2194
H8	0.1333	0.2028	0.1806	0.2683	0.2150
H9	0.1667	0.1556	0.2250	0.1878	0.2650
H10	0.1667	0.2278	0.2000	0.1778	0.2278
H11	0.1194	0.1333	0.2278	0.2722	0.2472
H12	0.1194	0.1306	0.2361	0.2750	0.2389
H13	0.2000	0.1833	0.1750	0.2694	0.1722
H14	0.1583	0.1944	0.2806	0.2028	0.1639
H15	0.0889	0.1639	0.3417	0.2667	0.1389
H16	0.1639	0.1500	0.2000	0.2917	0.1944
H17	0.1694	0.1333	0.2000	0.2139	0.2833
H18	0.1333	0.1611	0.2722	0.2361	0.1972
H19	0.0944	0.1333	0.2389	0.2583	0.2750
H20	0.1167	0.1611	0.2778	0.2389	0.2056
H21	0.1111	0.2000	0.2417	0.1944	0.2528
H22	0.1056	0.1611	0.2611	0.2389	0.2333
H23	0.1167	0.1472	0.1806	0.3167	0.2389
H24	0.1194	0.1167	0.2583	0.2000	0.3056

H25	0.1278	0.1056	0.2222	0.3056	0.2389
H26	0.1583	0.1917	0.1861	0.2444	0.2194
H27	0.1444	0.1278	0.1944	0.2611	0.2722
H28	0.1444	0.1500	0.3000	0.2333	0.1722
H29	0.1139	0.1472	0.2250	0.2722	0.2417
H30	0.1333	0.1417	0.2611	0.1972	0.2667
H31	0.1139	0.1528	0.2278	0.2139	0.2917
H32	0.1222	0.1556	0.2722	0.2833	0.1667
H33	0.1389	0.1444	0.1944	0.2778	0.2444
H34	0.1194	0.1778	0.2250	0.2611	0.2167
H35	0.1278	0.1850	0.1956	0.2500	0.2417
H36	0.1528	0.1889	0.2111	0.2194	0.2278
H37	0.1250	0.1833	0.2333	0.2194	0.2389
H38	0.1361	0.2222	0.2417	0.1694	0.2306
H39	0.1389	0.1583	0.2250	0.2583	0.2194
H40	0.0611	0.0806	0.2178	0.2456	0.3950
H41	0.1056	0.1611	0.1861	0.2583	0.2889
H42	0.0611	0.1750	0.1694	0.2306	0.3639
H43	0.0722	0.1694	0.1806	0.2722	0.3056
H44	0.1111	0.1778	0.1861	0.2139	0.3111
H45	0.1694	0.1222	0.1444	0.1806	0.3833
H46	0.0833	0.1389	0.2472	0.2500	0.2806
H47	0.0556	0.1333	0.2556	0.2472	0.3083
H48	0.0722	0.1333	0.2944	0.2361	0.2639
H49	0.0556	0.1389	0.2222	0.2361	0.3472
H50	0.0611	0.2500	0.2222	0.2194	0.2472
H51	0.0639	0.1861	0.1972	0.2806	0.2722
H52	0.0667	0.1472	0.1833	0.2778	0.3250
H53	0.0556	0.1222	0.1833	0.2389	0.4000
H54	0.0778	0.1806	0.2528	0.2139	0.2750
H55	0.0833	0.1694	0.2417	0.2333	0.2722
H56	0.0722	0.1889	0.2361	0.2278	0.2750
H57	0.0778	0.1111	0.2111	0.2972	0.3028
H58	0.1000	0.2167	0.3056	0.2056	0.1722
H59	0.0611	0.1611	0.2306	0.2628	0.2844
H60	0.0972	0.1972	0.2361	0.2556	0.2139
H61	0.0528	0.1944	0.1972	0.3333	0.2222

Appendix 3.38: Analysis of Pipelines hazards by Hugin software

Hs	Degree of Belief (VH, H, M, L, VL)				
	VH	H	M	L	VL
H1	0.1600	0.1067	0.1478	0.1833	0.4022
H2	0.1000	0.1056	0.1722	0.2278	0.3944
H3	0.1167	0.1167	0.1500	0.1889	0.4278
H4	0.1656	0.0956	0.1089	0.1333	0.4967
H5	0.1000	0.1222	0.1889	0.2333	0.3556
H6	0.1056	0.1167	0.1722	0.1944	0.4111
H7	0.0778	0.1167	0.2333	0.2556	0.3167
H8	0.0889	0.0833	0.1667	0.2556	0.4056
H9	0.1056	0.1222	0.1667	0.1889	0.4167
H10	0.0944	0.1000	0.1889	0.2444	0.3722

Appendix 3.39: Weight of Ship Transportation Main Criteria

	Weight
H1	0.1950
H2	0.8050
H3	0.6217
H4	0.3783
H5	0.6591
H6	0.3409
H7	0.6025
H8	0.3975
H9	0.2701
H10	0.7299
H11	0.5273
H12	0.2277
H13	0.2450
H14	0.3727
H15	0.6273
H16	0.7017
H17	0.2983

Appendix 3.40: Weight of pipeline transportation Hazards Criteria

	Weight
H1	0.2124
H2	0.1985
H3	0.2221
H4	0.2047
H5	0.2047

Appendix 3.41: Weight of Hull failure Criteria

	Weight
H1	0.3977
H2	0.3578
H3	0.2446
H4	0.3391
H5	0.4033
H6	0.2577
H7	0.3211
H8	0.6789

Appendix 3.42: Weight of Collision Criteria

	Weight
H1	0.4320
H2	0.2535
H3	0.3145
H4	0.2922
H5	0.1688
H6	0.1971
H7	0.3418
H8	0.3581
H9	0.2478
H10	0.1902
H11	0.2038
H12	0.2421
H13	0.7579
H14	0.4142
H15	0.5858
H16	0.4820
H17	0.5180
H18	0.7006
H19	0.2994

Appendix 3.43: Weight of Grounding Criteria

	Weight
H1	0.3593
H2	0.2529
H3	0.3878
H4	0.2866
H5	0.1306
H6	0.1776
H7	0.1933
H8	0.2119
H9	0.2902
H10	0.2639
H11	0.2181

H12	0.2278
H13	0.2636
H14	0.2888
H15	0.4476
H16	0.6101
H17	0.3899
H18	0.5253
H19	0.4747
H20	0.7882
H21	0.2118

Appendix 3.44: Weight of Fire/explosion Criteria

	Weight
H1	0.3170
H2	0.4683
H3	0.2146
H4	0.2528
H5	0.2244
H6	0.2110
H7	0.1582
H8	0.1537
H9	0.2515
H10	0.3843
H11	0.3643
H12	0.2252
H13	0.7748
H14	0.8333
H15	0.1667

Appendix 3.45: Weight of Equipment failure Criteria

	Weight
H1	0.1066
H2	0.1402
H3	0.1496
H4	0.1027
H5	0.1507
H6	0.1314
H7	0.1094
H8	0.1093
H9	0.4430
H10	0.5570
H11	0.2695
H12	0.7305
H13	0.3333
H14	0.1667
H15	0.3333

H16	0.1667
H17	0.3333
H18	0.6667
H19	0.3899
H20	0.6101
H21	0.4142
H22	0.5858

Questionnaire used for the purpose of Chapter 6

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Date :

Dear Sir,

My name is Ayman Fahad Alghanmi and I am a PhD student from Liverpool John Moores University. For my research project I am mitigating the hazard (i.e. human procedural failure during ship/port interference) that influence on the port operation which lead to crude oil spill. The results of this study will be used to eliminating and/or mitigating the operational risk of human procedural failure during ship/port interference (i.e. loading/unloading operation). Because you are an expert, I am inviting you to participate in this research study by completing this survey.

The following questionnaire will takes a maximum of 20 minutes of your time. There is no compensation for responding nor is there any risk. In order to ensure that all information will remain confidential, please do not include your name. If you choose to participate in this project, please answer all questions as honestly as possible. Your participation in this project is entirely voluntary and you can withdraw from the study at any time.

Sincerely,

Ayman Fahad Alghanmi
Liverpool Logistics Offshore and Marine Research Institute (LOOM)
Liverpool John Moores University
Tel: 074 7720 0174
E-mail: A.F.Alghanmi@2013.ljmu.ac.uk

SECTION 1: PERSONAL DETAILS

- Please mark the appropriate answer for each question:

1. Please mark your age range:
    - A. Less than 30 years old
    - B. Between 30 and 40 years old
    - C. 40 years old or more
2. Please mark your appropriate qualification:
    - A. Diploma
    - B. BSc
    - C. MSc
    - D. PhD
3. Please mark your work experiences:
    - A. Work experience 1-5 Years
    - B. Work experience 6-10 Years
    - C. Work experience 11-15 Years
    - D. Work experience 16-20 Years
    - E. Work experience over 20 Years

SECTION 2: INTRODUCTION

The aim of the research is to develop a novel safety assessment methodology for estimating, controlling and monitoring the operational risks. To achieve the aim of this study the most important factors that influences on mitigating the hazard (i.e. human procedural failure during ship/port interference) should be identify. Therefore, the criteria, and solutions (alternatives) listed in Table 1 are the parameters that need to be evaluated.

Level number	**Criteria/ Alternatives**	**Explanation**
Level 1 (Criteria)	Operating Safety	Safety level that offered by applying any of the Alternatives
	Operating Costs	Cost of applying any of the Alternatives (e.g. Labour cost, Training cost, Maintenance cost, Equipment cost)
	Operating Time	Time takes for operation after applying any of the Alternatives
	Operating Quality	Quality of operation from applying any of the Alternatives
Level 2 (Alternatives)	Hiring qualified labour	Raising the minimum qualifications a new employee is required to have before being hired
	Hiring highly qualified labour	Hiring only specialists who are competent and have over 7 years' experience and multiple certifications
	Labour training programme	Implementing training programmes that new and current workers are required to take to improve their knowledge, skills and experience
	Enhancing work force capacity	Increasing the number of workers involved in the operation
	Requiring Loading/discharging terminal supervision officer	Posting an operator (port representative) from the port side to represent the port on the ship during ship-board operations to

		ensure the safety of the loading and unloading operation
	Intensive regulation for safety and security checks	Requiring an intensive checklist before, during, and after the operating process to ensure the safety of the loading and unloading operation
	Apply new equipment	Renewing the equipment (Loading Arm/SBM) involved in the loading/unloading process
	Regulate an intensive maintenance program	Implementing an intensive maintenance plan to ensure the safety and quality operation of the equipment
	Requiring visual operating signs	Implementing visual guides in to assist the workers during the operation process

Table 1: The list of criteria and alternatives that influences on the mitigating the hazard

SECTION 3: QUESTIONNAIRE

Part 1 Goal: *Select the best alternative that eliminate and/or mitigate the hazard of human procedural during ship/port interference (i.e. loading/unloading operation).*

What would be the *operating safety* in order to apply the following alternatives?

	0 Low	1	2	3	4	5 Medium	6	7	8	9	10 High
Hiring highly qualified employee											
Hiring qualified employee											
Regulating training programmes for employee											
Increase the number of employees that participate during the operation process											
An operator from the port side represent the port on ship and involve during the operation on ship side for insuring the safety of the operation process.											
Regulating intensive safety and security checks before, while and after the operation											
Regulating intensive maintenance programme											
Renew the operating equipment (Loading Arm/SBM)											
Requiring visual operating signs											