Decision Making Analysis for an Integrated Risk Management Framework of Maritime Container Port Infrastructure and Transportation Systems

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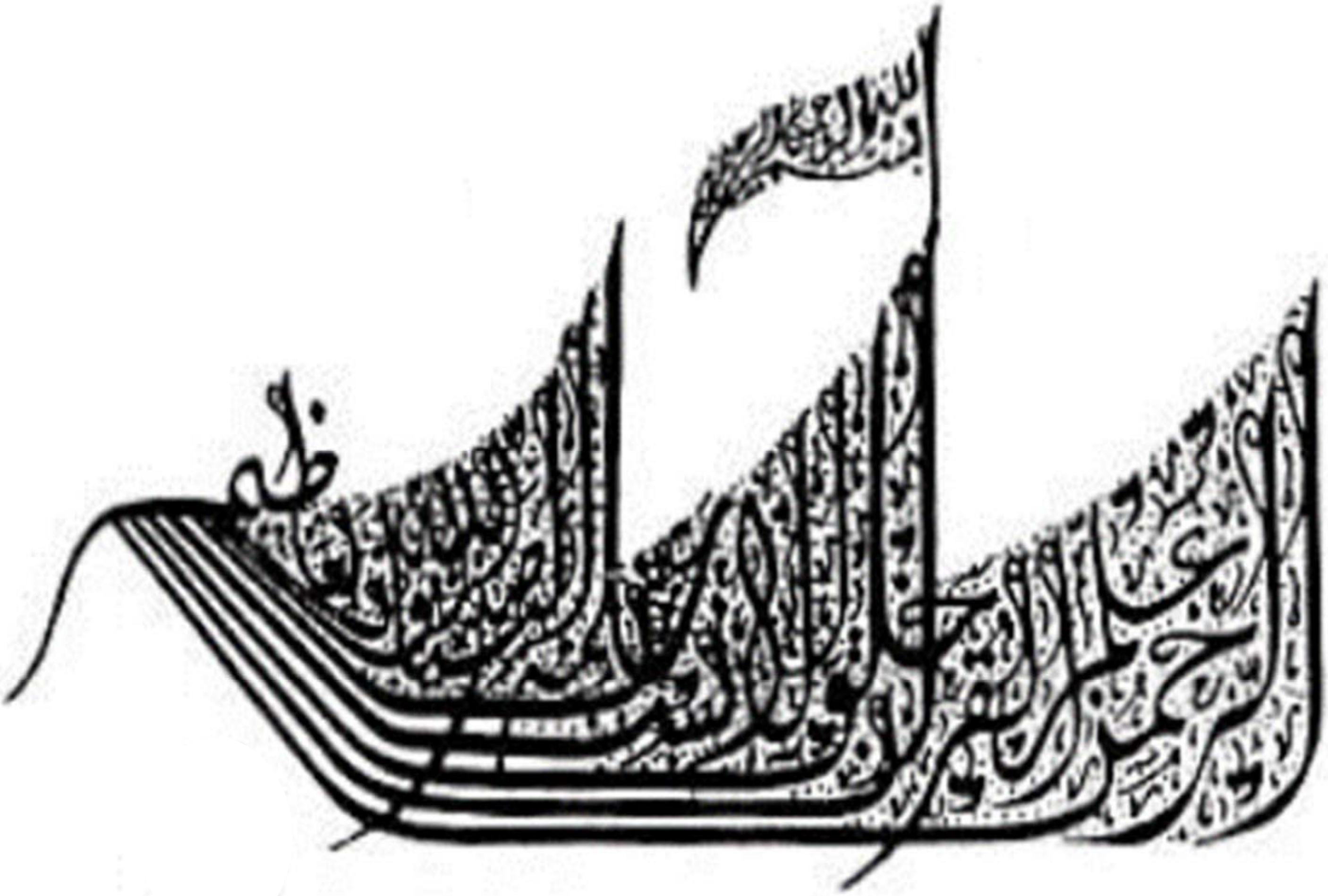
A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

November 2016



Abstract

This research proposes a risk management framework and develops generic risk-based decision-making, and risk-assessment models for dealing with potential Hazard Events (HEs) and risks associated with uncertainty for Operational Safety Performance (OSP) in container terminals and maritime ports. Three main sections are formulated in this study: Section 1: Risk Assessment, in the first phase, all HEs are identified through a literature review and human knowledge base and expertise. In the second phase, a Fuzzy Rule Base (FRB) is developed using the proportion method to assess the most significant HEs identified. The FRB leads to the development of a generic risk-based model incorporating the FRB and a Bayesian Network (BN) into a Fuzzy Rule Base Bayesian Network (FRBN) method using *Hugin* software to evaluate each HE individually and prioritise their specific risk estimations locally. The third phase demonstrated the FRBN method with a case study. The fourth phase concludes this section with a developed generic risk-based model incorporating FRBN and Evidential Reasoning to form an FRBER method using the Intelligence Decision System (*IDS*) software to evaluate all HEs aggregated collectively for their Risk Influence (RI) globally with a case study demonstration. In addition, a new sensitivity analysis method is developed to rank the HEs based on their True Risk Influence (TRI) considering their specific risk estimations locally and their RI globally. Section 2: Risk Models Simulations, the first phase explains the construction of the simulation model Bayesian Network Artificial Neural Networks (BNANNs), which is formed by applying Artificial Neural Networks (ANNs). In the second phase, the simulation model Evidential Reasoning Artificial Neural Networks (ERANNs) is constructed. The final phase in this section integrates the BNANNs and ERANNs that can predict the risk magnitude for HEs and provide a panoramic view on the risk inference in both perspectives, locally and globally. Section 3: Risk Control Options is the last link that finalises the risk management based methodology cycle in this study. The Analytical Hierarchal Process (AHP) method was used for determining the relative weights of all criteria identified in the first phase. The last phase develops a risk control options method by incorporating Fuzzy Logic (FL) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to form an FTOPSIS method. The novelty of this research provides an effective risk management framework for OSP in container terminals and maritime ports. In addition, it provides an efficient safety prediction tool that can ease all the processes in the methods and techniques used with the risk management framework by applying the ANN concept to simulate the risk models.

Acknowledgements

First and foremost, I praise and acknowledge Allah; all praise is due to Allah, the most gracious and the most merciful. Second, my humblest gratitude to the holy prophet Muhammad (peace be upon him), whose way of life has been a continuous source of guidance for me. This thesis appears in its current form due to the assistance and guidance of several people and organisations. I am delighted to convey my appreciation and sincere gratitude to them in my acknowledgement. They were always there when I needed them the most.

Acknowledgement is due to the Ministry of Higher Education of the Kingdom of Saudi Arabia, the Saudi Cultural Bureau in the United Kingdom, the Maritime Studies College at King Abdul Aziz University, the Liverpool Logistics, Offshore and Marine (LOOM) Research Institute at Liverpool John Moores University, Wuhan University of Technology in China, and EU projects for providing support to carry out this work.

I express my profound sense of reverence to my principal supervisor Prof. Zaili Yang for his continuous support; the motivation and untiring guidance he provided have made this dream come true. His vast knowledge, calm nature, and positive criticism motivated me to strive for significant and tangible results. I could always rely on him for support during the course of my Ph.D. Thanks to him for his patience and encouragement, which he exhibited even when I made mistakes or could not meet our deadlines. I am greatly indebted to him for having shown me how to conduct nothing less than the highest quality research. I feel privileged to have been associated with such a person during my life.

Equally important was the support of Prof. Jin Wang, who gave me the opportunity to perform this project by accepting me as a researcher in LOOM. During my initial days, I was apprehensive about my decision to join an institution where things were new to me. Prof. Wang came to my rescue and helped me sail through the initial fumbling stage. I am also greatly indebted to him for his intelligent ideas, thought-provoking discussions, and comprehensive understanding. Through his contributions, I was able to select an interesting and practical topic to research. His scientific inputs, personal help, and friendly nature has always made me feel at ease with him and has inspired me to strive for nothing short of excellence.

My special words of thanks should also go to my co-supervisors. Dr. Ramin Riahi was always available to encourage challenging discussions and to inspire me to take the next step. Thanks to him for his critical but valuable suggestions for my thesis and for his availability whenever I needed advice. I extend my sincere words of thanks to Dr. Steve Bonsall as well. I am grateful for the time he took to review my work and for his comments to improve the work presentation.

In science, you are never on your own. Therefore, I am grateful for the support of all co-authors who made contributions to my articles and their stimulating role in addressing the issues in this thesis. Heartfelt thanks to my senior and junior colleagues in the LOOM centre and Wuhan University of Technology. It was enjoyable and exciting to have them during my research and nice to exchange ideas and chat. Special thanks are due to the Saudi community in Liverpool for pleasant times on tours, parties, and family gatherings during festive seasons.

Words are bound and knowledge is limited to acknowledge my parents, brothers, and sisters for their constant support, prayers, and best wishes. In fact, to get a higher education was a wish of my father, who was the first inspiration for me, may his soul rest in peace. A sincere and profound gratitude is due to my mother for her great material and spiritual support, which always boosts my progress. Most sincerely, I would like to pay my warmest tribute to my beloved wife and my children. Their great patience, love, and strong emotional support made my life pleasant even in the hardest times. I would never have succeeded without their support.

Even all these acknowledgements fail to thank all who have supported me. Many people and organisations have helped me, and many good friends have shared experiences and thoughts with me throughout the past years. To all of them, if their names do not appear above, I would like to express my heartfelt gratitude.

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List of Abbreviations

AD	Axiomatic Design
AGVs	Automated Guided Vehicles
AHP	Analytical Hierarchal Process
ALARP	As Low As is Reasonably Practicable
ALVs	Automated Lifting Vehicles
AnBnEvR	ANNs Bayesian Networks Evidential Reasoning
ANNs	Artificial Neural Networks
ANP	Analytic Network Process
APM	Arnold Peter Møller – Maersk Group
ARIMA	Autoregressive Integrated Moving Average
BER	Bayesian Evidential Reasoning
BN	Bayesian Network
BNANNs	Bayesian Network ANNs
BP	Back-Propagation network
C	Consequences (i.e., severity)
CCA	Cause-Consequence Analysis
CCs	Closeness Coefficients
CR	Consistency Ratio
CTOS	Container Terminal Operation System
CTRE	Container Terminal Risk Evaluation
CTU	Code of Practice for Packing of Cargo Transport Units
D	Detection capability
DFT	Department of Transport
DMP	Decision Making Problems
DP	Dubai Ports International
D-S	Dempster-Shafer theory
EBITDA	Earnings Before Interest, Taxes, Depreciation, And Amortization
ECANSE	Environment for Computer Aided Neural Software Engineering
ED	Experimental Data
ES	Expert Systems
ESD	Event Sequence Diagrams
ETA	Event Tree Analysis
EvRANNs	Evidential Reasoning ANNs

FL	Fuzzy logic
FMEA	Failure Modes and Effects Analysis
FMEANNs	Failure Modes and Effects Analysis ANNs
FMECA	Failure Mode Effects and Criticality Analysis
FNIS	Fuzzy Negative Ideal Solutions
FPIS	Fuzzy Positive Ideal Solutions
FRB	Fuzzy Rule Base
FRBER	FRBN and Evidential Reasoning approach
FRBN	FRB and Bayesian Network approach
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
FTOPSIS	Fuzzy Technique for Order Preference
GCH	Guidance on Container Handling
GDP	Gross domestic product
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HEs	Hazard Events
HHLA	Hamburger Hafen und Logistik AG
HPH	Hutchison Port Holdings
HRA	Human Reliability Analysis
HRI	High Risk Inference
HSE	Health and Safety Executive
I	Impact of a failure to the resilience of port operational systems
ICHCA	International Cargo Handling Co-ordination Association
ICS	the International Chamber of Shipping
ICTOS	Internal Container Terminal Operation Safety
ICTSI	International Container Terminal Services
IDS	Intelligence Decision System
ILO	International Labour Organization
IMO	International Maritime Organization
L	Likelihood or occurrence probability
logsig	logarithmic sigmoid
LRI	Low Risk Inference
MADM	Multiple Attribute Decision Making

MARPOL	International Convention for the Prevention of Pollution
MCDM	Multiple Criteria Decision Making
MLD	Master Logic Diagrams
MODM	Multiple Objective Decision Making
MPM	Maritime Policy & Management
MSA	Marine Safety Agency
MSC	Maritime Safety Committee
MSE	Minimum Mean Squared Errors
OSP	Operational Safety Performance
PEMA	Port Equipment Manufacturers Association
PHA	Preliminary Hazard Analysis
PRA	Probabilistic risk analysis
PRN	Risk Priority Numbers
PSA	Probabilistic Safety Analysis
PSN	Port of Singapore
purelin	Linear Transfer Function
QC	Quay Crane
QRA	Quantitative Risk Assessment
R2	Regression
RBD	Reliability Block Diagrams
RCOs	Risk Control Options
RE	Risk Estimation
RI	Risk Influence
RIx	Random Index
RMG	Rail-Mounted Gantry
RoS	Risk level of the System
RS	Reach Stackers
RSGT	Red Sea Gateway Terminal co.
RTG	Rubber-Tired Gantry
SC	Straddle Carriers
SIPG	Shanghai International Port Group
SMS	Safety Management System
SOLAS	Safety of Life at Sea
SWIFT	Structured What-If Technique

TA	Task Analysis
tansig	Tangent Sigmoid Transfer Function
TEU	Twenty Feet Equivalent Unit
TFN	Triangular Fuzzy Numbers
trainlm	Levenberg–Marquardt
TRI	True Risk Influence
TT Club	Through Transport Mutual Insurance Association Limited
UNCTAD	United Nations Conferences on Trade and Development
UNECE	United Nations Economic Commission for Europe
USGAO	United States Government Accountability Office
WSC	World Shipping Council

Chapter 1 — Introduction

Summary

This chapter introduces the research background analysis followed by the discussion of the research aim and objectives. The challenges of conducting the research, the research methodology, and the scope of the thesis are also described. The objectives and hypotheses of this thesis set out a logical platform aimed at addressing the outlined problems. The structure of the thesis is outlined to show how the study addresses the risk-based methodologies for decision support of maritime ports and risk management of maritime container terminals' operations.

1.1. Background

The impact of maritime activities on the economy is significant for any coastal state. Container terminals are critical and costly engineering systems that enable economic development through the transfer of goods and services between national and international destinations (Vis & de Koster, 2003). Ports are gearing up to meet the challenge of handling mega-vessels capable of carrying 10,000–12,000 Twenty-Feet Equivalent Unit (TEU) and above (Baird, 2006). Accordingly, a container terminal must advance its operational and managerial technology basis (Kang et al., 2008) in order to cope with such progressive developments. Container terminal infrastructure is characterised by large investments, tight time schedules, and evolving technology, sometimes through unproven conditions (Koster et al., 2009). These challenges result in high-risk exposure along with more opportunities to be exploited in terms of risk management. Inland container terminals are, due to their operational business and environmental conditions, exposed to several risks having different consequences (Stahlbock & Voß, 2008).

Research and subsequent improvements in related areas including operational, organisational, economic, business, and natural conditions that affect seaports and marine terminals have been carried out for many years, which is evident in major maritime academic journals such as the Journals of Maritime Policy and Management, Marine Science and Technology, Marine Policy, Offshore Engineering, Offshore Technology, Maritime Economic, Maritime Economic and Logistics, Marine Pollution Bulletin, Transport Management, Transportation Research, Research in Transportation Economics, and Environmental Impact Assessment Review. Improvements based on research can also be seen in other academic journals such as the Journals of Operational Research, Hazardous Materials, Reliability Engineering System Safety, Business Continuity and Risk Management, Economics and Business, World Development, Productivity Analysis, Industrial Economics, Industrial Engineering, Fuzzy Sets and Systems, and Expert Systems with Applications. In addition, international bodies involved in the maritime industry such as the International Maritime Organization (IMO), United Nations Conferences on Trade and Development (UNCTAD), World Bank, European Commission, and Asian Development Bank have been contributing towards the improvement within the five major areas mentioned previously. Current risk assessment methods for maritime container terminals are gradually taking into account dramatic events in security issues such as terrorist attacks. However, the impact on safety aspects has not been addressed adequately in research (Lois et al., 2004; Shang & Lu, 2009).

The IMO as a regulatory body since 1958 has proposed many instruments, guidelines and codes related to the maritime industry such as the use of a risk assessment method, including offshore operators, in order to mitigate the risk (Trbojevic & Carr, 2000). This method contributed to the adoption of a Formal Safety Assessment (FSA) (IMO, 2002). Since the adoption of FSA, many parties have been encouraged to contribute evolving developments to perform risk assessment such as maritime ports, and classification societies (HSE, 2001) because risk assessment emerges as an important engineering discipline in the maritime and port industries (Wang & Ruxton, 1998).

The FSA methodology can provide desirable results by mitigating risk and enhancing maritime safety because it has a systematic mechanism that enables decision-making based on risk assessment and, more importantly, the cost-benefit analysis of the risk controlling option (Wang & Trbojevic, 2007). The FSA principles have been widely used by many maritime related industries (Pillay and Wang, 2003a; Bai and Jin, 2016) and other industries involved with risk management. Therefore, in this study, the FSA method will be adopted towards container terminal infrastructure and transportation systems safety to offer a clear and justifiable rationale for a risk management based methodology. Moreover, this research is an in-depth investigation of the risks associated with container terminal infrastructure and transportation systems on operational safety aspects, as well as a description of how to effectively implement the risk management based methodology.

Risk assessment techniques in general are a creative practice which benefits the decision-making mechanism (Wang, 2002). Decision makers often encounter the problem of selecting a solution from a given set of alternatives. The chosen alternative is the one that meets certain predefined objectives/goals (Liu et al., 2008a). The criteria of container terminal infrastructure and transportation systems' decision making are slightly more than alternative choices of risk mitigation options; these criteria also exist to evaluate the resilience and flexibility of strategies aimed at dealing with any disturbances throughout the systems' lifecycle. Therefore, the challenge for decision-makers is to select the most suitable set of alternatives based on reliability, availability and cost-benefit criteria (Martorell et al., 2010). This research classifies decision problems that arise in container terminal infrastructure and transportation systems in order to develop a risk management framework that applies systemic thinking, logic, and a variety of approaches and tools to frame and potentially solve complex safety issues.

1.2. Justification for the Research and Statement of the Problem

This research is motivated by the lack of an appropriate risk management framework addressing the Operational Safety Performance (OSP) in container terminals and maritime ports that are linked directly to the business functions and decision-making processes within marine ports, especially for the purpose of their operations and management. Furthermore, the problem facing container terminal stakeholders is a lack of research upon which to base safety measures for the stakeholders' complex terminal activities; a general lack of a model that approximates the risk management realities of the terminal; and confusion over uncertainty, terminology, approaches, and methods in the discipline. There is an imperative need to form a generic model that can highlight the safety issues facing container terminal stakeholders including risk managers, human resource managers, site control managers, safety officers, and port facility security officers.

A gap in knowledge exists concerning the applications of risk management in container terminals and marine port operations. Similarly, there is a need for more practical research at the academic level to improve the best practice of risk management methods, to ensure proper implementation of the methods in these logistics infrastructures, and to cope with potential requirements in the future.

The following guiding questions have been generated to ensure that the objectives of this research are met and to provide a base for conducting this research.

- ❖ What are the hazards or risk sources with uncertainties associated within container terminals and maritime ports affecting safety performance, and how can they be identified?

Hazard, risk, and uncertainty are different terms that need to be distinguished. There are different types and categories of hazards that can endanger a container terminal and/or a maritime port, including personnel, facilities technologies, and environment. While there are different methods and techniques for hazard identification, there are a number of common features of importance.

- ❖ What are the risk parameters that each hazard would have the greatest impact upon? How would the impact affect the performance safety of container terminals and maritime ports operations, and how can these risk parameters be identified?

Risk (R) is a simple value of Likelihood or occurrence probability (L), the Consequences (i.e., severity) (C), and Detection incapability (D) that can be presented as follows (O'Connor, 2001; Braglia et al., 2003; Berg, 2010):

$$R = L \times C \times D \tag{1.1}$$

The higher the R for any hazard, the more important it is that corrective action should be taken. However, are there any other risk parameters that can be included for the container terminals and maritime ports operations to improve safety performance?

- ❖ What are the most appropriate and useful tools for evaluating each risk factor individually (i.e., locally) and for evaluating all risk factors aggregated collectively (i.e., globally) with associated uncertainties for container terminal and maritime port OSP in real practises, and how can these tools be applied?

In any risk-based model application (i.e., risk factors identified and ranked accordingly), human judgement is inevitable, especially when uncertainties are involved. Each risk factor should be evaluated individually for its specific risk estimation locally and its Risk Influence (RI) to a port's safety system globally. There is a variety of techniques and tools-based software for analysing knowledge-based decision support systems that can be used.

- How can the identified hazards or risk factors be prioritised and ranked?

The prioritisation of hazards or risk factors is a fundamental step of any safety analysis. All risk factors are ranked locally and globally. Accordingly, there are various approaches that can be used depending on the risk factors under consideration and the particular methodology being employed.

- What are the most effective tools to analyse the causes and effects of the most significant identified risk factors, and how can they be employed?

Each risk factor needs to be investigated individually by carrying out a cause and effect analysis, and that analysis should not be limited to known causes; it should also address the potential causes that have not happened yet but that may lead to total or partial loss in the future. All the effects should be identified, taking into account the ones that have occurred. Therefore, a careful analysis is required to ensure that all the potential causes and effects for each risk factor are listed and acknowledged. There are numerous tools and techniques to perform such an analysis.

- How can a risk management based methodology and strategy be mapped and implemented for the most significant risk factors locally and globally?

Risk management based methodologies and approaches can be implemented on any system or organisation including container terminals and maritime ports. However, an effective and efficient risk management based methodology and strategy can be applied if an appropriate and detailed safety analysis is done at each step of the process and properly conducted with sufficient knowledge of the system or organisation.

- How can the identified hazards or risk factors be mitigated and controlled?

The last link to close the risk management based methodology cycle is assigning a proper decision-making tool or technique to select the best available strategies in order to mitigate and control the risk factors. There is no single correct technique for a particular decision problem, but some techniques are more suitable than others based on a wide range of elements related to infrastructural design, planning, and management that help to optimise the operational efficiency of the system or organisation.

1.3. Research Objectives and Relevant Hypothesis

1.3.1. Aim of the investigation

This study aims to develop a risk management framework with uncertainty treatment based decision-making analysis methodology that can support the selection of cost effective risk measures for container terminal infrastructure and transportation systems at both the operational and managerial levels on a safety basis.

1.3.2. Research objectives

The main objectives are defined as follows:

I. Analyse the complex activities in the lifecycle of container terminal operations in order to identify the Hazard Events (HEs), (i.e., failure modes in which an equipment or machine failure can occur, also, human error including managerial and container handling procedures). While Hazard is the basic material or behaviour that results in failure.

II. Review the risk assessment and decision-making techniques (quantitative and qualitative) that have been widely developed and applied in safety analysis and engineering design systems, particularly those capable of dealing with uncertainty and incompleteness of risk data records.

III. Develop a risk management framework and the associated supporting modelling techniques to solve complicated safety aspects in container terminals with various types of uncertainties.

IV. Design a risk-based decision-making support system that offers a systemic approach to improve the OSP and decision-making process of container terminals and their implementation in the port industry.

V. Demonstrate the above framework using real test cases.

1.4. Research Achievements

The research hypothesis develops an advanced, novel framework for the assessment of risks and vulnerability within container terminals on a safety basis that enables industrial stakeholders to identify, assess, and mitigate the risk factors with uncertainties that affect container terminal and maritime port OSP. In addition, this research is directed towards a risk-based decision-making analysis methodology for container terminal infrastructure that demonstrates the theory of the strategic risk management approach and reveals the effective implementation of the risk management principle and integration into all functions and processes in complex container terminal and maritime port operations.

The objectives of the hypothesis rely on widely used application for uncertainty treatment such as Fuzzy Logic (FL), Bayesian Network (BN), Evidential Reasoning (ER), Analytical Hierarchy Process (AHP), FL and Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS), and Artificial Neural Networks (ANNs). The proposed models are intended to provide practical tools in the application and study of container terminal and maritime port OSP.

1.5. Research Methodology and Scope of the Thesis

The Research methodology formulates the course for solving the research problem in a systematic and rational manner. A Risk management based methodology is an ongoing process to identify, assess, and mitigate risk factors for any system or organisation by setting plans and strategies to control all potential sources of risks associated with uncertainties. The proposed framework affects the effectiveness of risk management based methodology by its ability to re-evaluate the system or organisation and to adjust the mitigation strategy in order to determine the best practice and implementation, even with changed circumstances or environment. Therefore, various methods and techniques to be used throughout the implementation of the methodology are consistently taken into account.

The detailed research methodology is as follows:

Section 1: Risk Assessment

Phase 1: Identify hazards through an appropriate literature review and brainstorming session with various experts involved in container terminals and maritime port operations.

Phase 2: Develop a Fuzzy Rule Base (FRB) in order to assess the most significant HEs identified.

Phase 3: Develop a generic risk-based method by incorporating an FRB and BN to form an FRBN method using *Hugin* software. The FRBN method should be capable of helping container terminals and maritime port stakeholders to assess each risk factor (i.e., HE) individually for its specific, local risk estimations.

Phase 4: Develop a generic risk-based method by incorporating an FRB and ER to form an FRBER method using the *IDS* software to assess all risk factors (i.e., HEs) aggregated collectively for their global Risk Influence (RI). More importantly, the new sensitivity analysis method was developed and carried out to rank HEs by taking into account their specific local risk estimations and their RI to a port's system safety.

Section 2: Risk Models Simulations

Phase 1: Construct a simulation model BNANNs based on the generic risk method FRBN by employing the ANNs concepts using *Matlab* software.

Phase 2: Construct a simulation model ERANNs based on the generic risk method FRBER by employing the ANNs concepts using *Matlab* software.

Phase 3: Construct the AnBnEvR model by integrating BNANNs and EvRANNs models that enable the prediction of the risk magnitude for HEs locally and globally.

The complexity of handling a large amount of data dealing with two different methodologies (i.e., FRBN and FRBER) with reference to its software would burden the stakeholders with non-user-friendly processes to measure, predict, and improve their system safety and reliability performance, motions, and planning of actions. Therefore, two models simulating FRBN and FRBER are constructed.

The constructed models in the simulation section present a high-quality representative model in terms of accuracy and reliability assurance that can provide a favourable solution in the risk evaluation process. The model can help to predict the risk magnitude, explain the real safety performance, and develop a continuous risk management strategy for complex systems such as container terminals and maritime ports. More importantly, it can significantly overcome the mathematical complexity involved in the algorithms of the fuzzy BNs and ER in Section 1 and realise the integrity of BN and ER using ANN.

Section 3: Risk Control Options

Phase 1: Use the Analytical Hierarchy Process (AHP) method for determining the relative weights of all criteria identified.

Phase 2: Develop a risk control options model (FTOPSIS) by incorporating Fuzzy Logic and TOPSIS.

The best risk mitigation strategies were introduced and evaluated in the form of ideal solutions for mitigating the identified risk factors by offering the preferred safety control measures. These measures, such as automation solutions, had to be capable of addressing both operational efficiency and risk reduction in container terminals.

1.6. Structure of Thesis

Figure 1.1 gives a visual model of the thesis structure that leads the reader to the stated research methodology in Section 1.5. A brief description of each chapter presented in the thesis is as follows.

Chapter 1 corresponds to the research background and justifies conducting this research. Research questions are generated to ensure that the research objectives are met. At the end of the chapter, the risk management framework and structure of the thesis are described.

Chapter 2 reviews the maritime container terminals market to exhibit the impact magnitude of containerisation on container terminal operation. The operational lifecycle of a container terminal operation is described, followed by a careful analysis of the widely applied risk management based methodologies with reference to container terminal safety legislations introduced by national and international parties. Risk, hazard, and uncertainty, all three of which are important terms in the risk management process, are defined and distinguished.

Chapter 3 starts with the first phase of section 1, Risk Assessment, by identifying the most significant HEs in container terminal operation followed by the development of an FRB as the second phase. The third phase is the end of this chapter, where a generic risk-based method (FRBN) is developed in order to assess the most significant HEs identified individually for their specific risk local estimations.

Chapter 4, as the last phase in section 1, concludes the risk assessment process by developing a generic risk-based method (FRBER) to assess all risk factors (i.e., HEs) aggregated collectively for their RI for container terminals and maritime port safety system globally. In addition, a new sensitivity analysis method is developed and carried out to rank the HEs by taking into account their specific risk estimations locally and their RI globally.

Chapter 5 is the first phase of section 2, Risk Models Simulations, and the chapter includes the construction of the simulation model BNANNs for the FRBN method. This simulation model is followed by the second phase of the construction of the simulation model ERANNs for the FRBER method using Artificial Neural Networks (ANNs). The final phase in this section entails integrating the BNANNs and ERANNs in order to construct AnBnEvR, which enables the prediction of the risk magnitude for HEs locally and globally.

Chapter 6 uses the AHP method for determining the relative weights of all criteria identified in the first phase of section 3, Risk Control Options. It is followed by the last phase, which develops a risk control options model using FTOPSIS.

Chapter 7 draws the conclusions and contributes to the knowledge concerning risk management for container terminals and maritime port safety systems. Additional suggestions for further research are recommended.

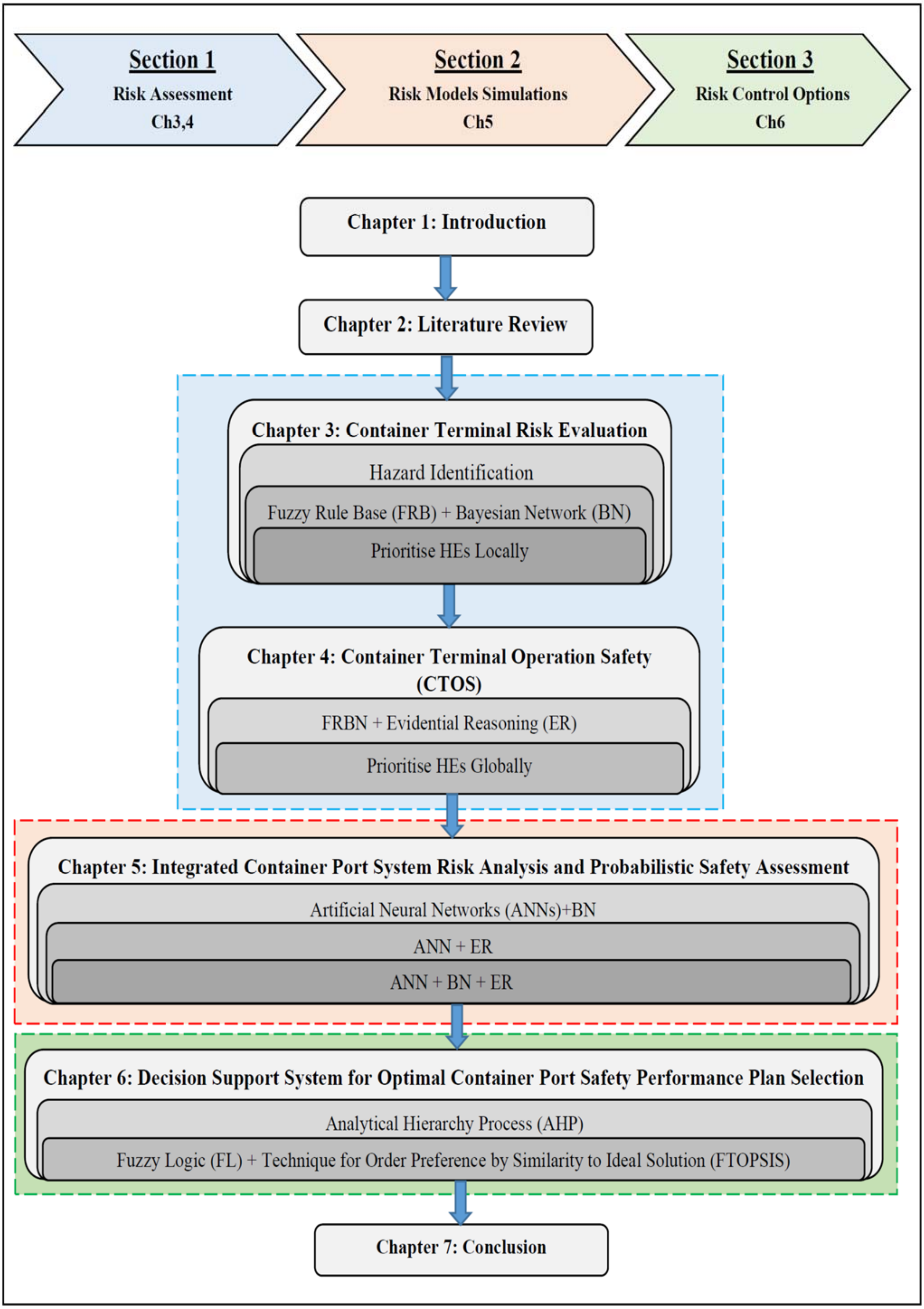

Figure 1.1: Research methodology

Chapter 2 — Literature Review

Summary

This chapter reviews the fundamental elements that influenced and contributed to this research. It commences by highlighting the impact of containerisation growth on maritime container terminals operation taking into account the direct and indirect effects on terminal operation safety including container ships, terminal facilities, technology overview, rules and regulations, and handling equipment interfacing. Also discussed is the range of the comprehensive literature related to container terminal safety and a critical analysis of risk management process in maritime ports.

2.1. Introduction

Containerisation was first introduced in the 1960s, and has subsequently become the most common method for transporting industrial and consumer products seaborne. Consequently, the containerisation development process has cause major transformation among port terminals. Container transportation began in the United States in 1920 with Pennsylvania Railways. Then container transportation expanded to Europe, where McLean Industry Ltd established and developed a connecting system of piggyback and marine transport in 1955. Pan Atlantic Shipping Lines began the first container shipping transportation between New York and Houston in 1956 and later launched Gateway City, the first full container vessel, into operation for the route in 1957 (Inamura et al., 1997). Container shipping is performed by companies that operate frequently scheduled liner services with pre-determined port calls, using a number of owned or chartered vessels of a particular size to achieve an appropriate frequency and utilisation level for each service (Heejung et al., 2015).

Maritime container transportation occupies an increasingly important position in world trade and is the fastest growing sector of international shipping, benefiting from a shift towards unitisation in cargo transport, as well as from world trade developments. The share of containerised trade in the total volume of global trade steadily rose from 11% in 2000 to 14% in 2010 (Drewry, 2009).

Containerisation has a number of advantages compared with other shipping methods, including:

- Less cargo handling: once the contents of a container are loaded into secure containers, they are not directly handled until reaching the final destination.

- Efficient port turnaround: container ships are loaded and unloaded in significantly less time and at a lower cost than other cargo vessels, using quay cranes and other terminal handling equipment.

- Highly developed intermodal network: the intermodal industry has developed sophisticated and intelligent modes to support container transportation, such as physical integration of the container with other intermodal transportation equipment, including the staging or storage areas, to final destinations.

As this thesis focuses on container terminal port operations safety, it is necessary first to review and discuss the existing risks outlined in maritime shipping industry literature as a whole, then to concentrate on container terminal port operations safety.

2.2. Container Terminal Market Overview

Ports are characterised by their geographical and operational settings. Each port may have several terminals, and each terminal is operated by one or many operators (Yip et al., 2011). The advent of global terminal operators is a profound organisational change in the development of container terminals. Container terminal operators are firms that operate one or several container terminals at a port. Regulatory requirements, limited land availability, and steep capital requirements for building container terminal capacity all impose high barriers on the container terminal market features (Pawlik et al., 2011). The cost of building infrastructure is highly dependent on the region and type of construction required. Constructing a new container terminal on existing infrastructure can cost several tens of millions GBP (British Pound), whereas the construction of an offshore port can cost several billion GBP.

Many projects involve local governments providing terminal infrastructure, with long-term concessions delegated to the most attractive terminal operators. The development of new terminals is often constrained by national planning procedures and legislation, involving many stakeholders throughout the planning process; this system contributes to long lead times, and sometimes results in significant implementation and execution delays. As a result, global growth in new container capacity lags behind growth in container trade (Global Ports, 2011).

Logically, shipping lines are the main customers of container terminal operators. Both of them (i.e., shipping lines and container terminal operators), consequently, are mainly dependent on the level of world seaborne trade and the corresponding demand for container terminal services that the level generates.

Increased participation of private investors in managing container ports and the establishment of new ports have both increased pressures on port efficiency (Bergantino et al., 2013). Container terminal operators are compelled to provide high-quality service levels at competitive prices (Araujo De Souza et al., 2003). They should invest in facilities, service, and management systems to gain and sustain competitiveness. They should also increase expenditure to improve crane capacities, information technology efficiency, and transhipment facilities, as well as shorten vessel turnaround movements (Notteboom, 2002).

In 2013, the global container fleet reached 320.9 million Twenty-Feet Equivalent Unit (TEU). A variety of container types make up this fleet. Dry containers are the majority; historically, they comprised about 93% of the fleet, but they decreased to 89% in 2012. While, the other 7% was split between insulated reefer containers and tanks; the latter made up approximately 0.75% for transporting various liquids, and the former occupied the remaining 6.25% of the global fleet. Based on these ratios, the size of the dry container fleet in 2012 was approximately 290.3 million TEU. Reefer containers filled out about 20.1 million TEU of the global fleet, and tank containers comprised about 9.6 million. Subsequently, the global container fleet is set to grow another 1.6 billion TEU in 2013, that made the global container fleet about 421.5 million TEU (WSCa, 2015).

2.2.1. Global containerisation market

Many elements determine terminal performance, including labour relations, numbers and types of cargo handling equipment, quality of backhaul areas, port access channels, landside access, and customs efficiency, as well as potential concessions to international terminal operators. In 2009, terminal operators faced extraordinary challenges posed by the economic crisis, substantially affecting volumes. However, most of the global container terminal operators sustained and returned to a healthy volume growth in 2010 (UNCTAD, 2011).

DSC (2012) attested that average terminal utilisation (i.e. increase the transhipments and the handled container between maritime container ports) grade was generally increasing, and operators were increasing their Earnings Before Interest, Taxes, Depreciation, And Amortisation (EBITDA) compared with 2009; also, EBITDA margins in percentage terms were largely maintained, as shown in Table 2.1, with percentage forecasting up to 2016. As an example, Hutchison Port Holdings (HPH) was the most profitable global container terminal operator, with an EBITDA of over 2 billion U.S. dollars, up from 1.8 billion in 2009. Port of Singapore (PSN) achieved an EBITDA of around 1.3 billion U.S., and Dubai Ports International (DP) World achieved an increased EBITDA of 1.24 billion U.S. compared with 1.1 billion the previous year. International Container Terminal Services (ICTSI), PSN, HPH, DP World, and Hamburger Hafen und Logistik AG (HHLA) achieved an EBITDA margin in excess of 40% in 2010. Arnold Peter Møller – Maersk Group (APM Terminals), meanwhile, increased its margin to just over 20%.

Table 2.1: Average regional container terminal utilisation 2010 and 2016 forecast
Source: Drewry Shipping Consultants (2012)

Region	2010 Actual Utilisation	2016 Forecast Utilisation
Far East	69.3%	97.8%
South East Asia	72.2 %	93.5%
South America	66.3%	87%
Middle East	76%	88.6%
Central America	67.3%	83.2%
Africa	70.4%	78.9%
North America	54.1%	67.1%
North Europe	60.2%	66.2%
South Asia	76.4%	61.2%
World	**66.5%**	**84.2%**

The main international terminal operators broadly maintained their TEU positions in 2010, and those with significant interests in Chinese ports achieved particularly high growth. The international terminal operators' EBITDA margins remain in a 20–45% range, and the 2014 financial performance was similar to that in previous years, showing the consistency and reliability of container terminal operators' profitability. However, it is difficult to maintain these margins in the face of the demands from larger container ship deployments, combined with the creation of larger shipping line alliances. These interrelated factors are stimulating significantly greater demands on ports and terminals and have far-reaching consequences, driving up operating costs and capital expenditure requirements (Drewry, 2015).

As a result, by 2013, most shipping companies increased orders of large vessels to improve efficiency and reduce operational costs per TEU. The containership order book grew from 41 million dwt at the beginning of 2013 to 43 million at the beginning of 2014, representing about 20% of the fleet in service (UNCTAD, 2014).

DSC (2012) analyses, as shown in Table 2.2, nominated PSN as the leading global container terminal operator in 2010, with an equity adjusted throughput of 51.3 million TEU, approximately 14% higher than in 2009. Hutchison Ports is ranked second, with 36 million TEU, followed by DP World with 32.6 million TEU, APM Terminals with 31.6 million TEU, and Shanghai International Port Group (SIPG) in fifth with 13.6 million TEU. This shows a steady upward worldwide trend among the leading container operators.

Table 2.2: World container terminal ownership ranking, 2010
Source: DSC (2012)

No.	Operator	Million TEU	Share percentage
1.	PSN	51.3	9.4%
2.	HPH	36	6.6%
3.	DPW	32.6	6%
4.	APMT	31.6	5.8%
5.	SIPG	19.5	3.6%
6.	China Merchants Holding International	17.3	3.2%
7.	COSCO	13.6	2.5%
8.	MSC	9.9	1.8%
9.	SSAMarine/Carrix	8.6	1.6%
10.	Modern Terminals	8.3	1.5%

An additional 168 million TEU of port traffic will bring the global total to nearly 850 million TEU in 2019; this assumes that Asia accounts for more than 60% of the forecast global demand growth and that the deployment of ultra large container ships with new mega alliances is adding to capacity pressures on international terminal operators. The predicted average global container port demands a growth of 4.5% per annum through to 2019 (Drewry, 2015).

The growing vessels and increase in demands for global maritime container ports are forcing terminal operators to make significant investments in additional capacity. According to DSC (2015), APM Terminals and DP World are most actively developing new projects in the pipeline, but PSN International is adding the most capacity in the port of Singapore. Hutchison, CMA CGM, TIL, and ICTSI also have significant plans, with the latter's expansion representing a 40% increase over the current capacity of its portfolio, as shown in Figure 2.1. The primary expansion focus of international terminal operators is greenfield developments in emerging market locations, with acquisition and divestment activity decreasing from last year.

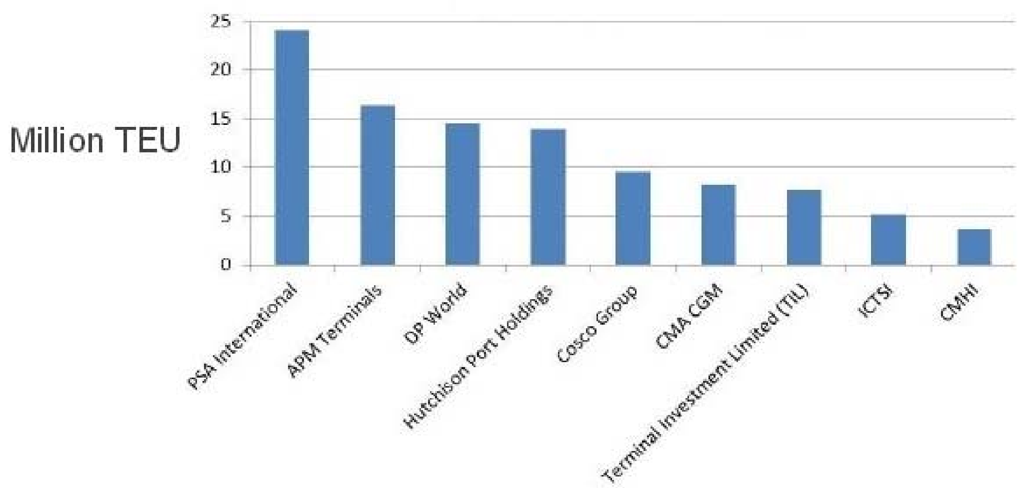

Figure 2.1: Project capacity expansion for major global terminals operators by 2019 (DSC, 2015)

2.2.2. Global containerisation growth

World container traffic comprised 38,9 million TEU container movements in 1980. That figure increased to 88,1 million TEU in 1990, to 236,7 million in 2000, and to 419,8 million in 2010. The Compound Average Growth Rate (CAGR) of world container traffic from 2000 to 2010 is estimated at 8.6% compared with a global real gross domestic product (GDP) CAGR of 2.6% for the same period. After a decline of approximately 9% in 2009 caused by the global economic crisis, global container shipping throughput increased by 13.8% in 2010, exceeding pre-downturn volumes. The 2011 world container movements are estimated to reach approximately 439,2 million thousand TEU (Global Ports, 2011).

In the recent years, the use of containers for intercontinental maritime transport has dramatically increased. Between 1990 and 2008, container traffic has grown from 28.7

million to 152.0 million TEU, an increase of about 430% (Drewry, 2007). Figure 2.2 displays world container traffic and throughput from 1980 to 2010.

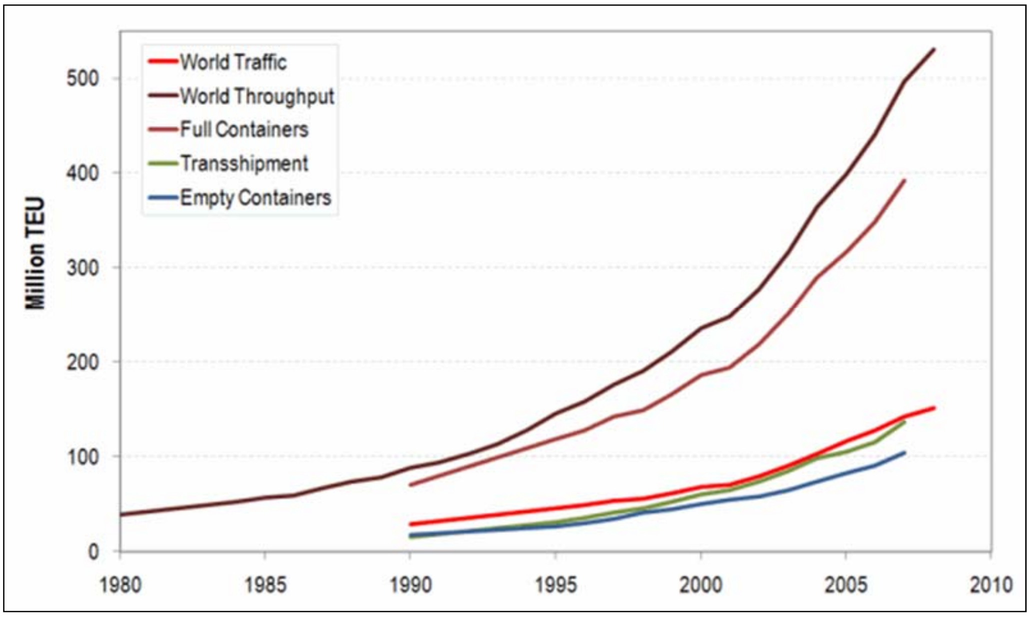

Figure 2.2: The world container traffic and throughput (DSC, 2007)

In 1998, Rayan observed that "the growth in containerized trade continues as more and more cargo are transferred from break-bulk to containers." Today, more than 60% of the world's deep-sea general cargo is transported in containers, and some routes, especially those between economically strong and stable countries, are containerised up to 100% (Drewry, 2015).

The growth rate of container flows from 2002 to 2020 is still expected to be 7.5% per year. Every major port is expected to double and possibly triple its cargo by 2020 (Liu et al., 2002). At the same time, existing and newly planned terminals are trying to attract as much volume as they can handle, making the container-handling sector very competitive. Furthermore, since globally acting industrial companies have considerably increased their production capacities in Asian countries, the container traffic between Asia and the rest of the world has steadily increased (Wang, 2005).

Ports are crucial in interfacing sea and land transportation systems, and by extension the economy, leading to a high share of imports in GDP and worldwide economic growth. Asian ports continue to dominate the league table for port throughput and terminal efficiency, as shown in Table 2.3.

Table 2.3: Top 10 world container ports

Source: (WSC, 2015b; Alphaliner, 2015)

Rank	Port	Volume 2011 (Million TEU)	Volume 2012 (Million TEU)	Volume 2013 (Million TEU)	Volume 2014 (Million TEU)
1	Shanghai, China	31.74	32.53	33.62	35.29
2	Singapore	29.94	31.65	32.6	33.87
3	Shenzhen, China	22.57	22.94	23.28	24.04
4	Hong Kong, S.A.R., China	24.38	23.12	22.35	22.23
5	Ningbo-Zhoushan, China	14.72	16.83	17.33	19.45
6	Busan, South Korea	16.18	17.04	17.69	18.68
7	Guangzhou Harbor, China	14.42	14.74	15.31	16.63
8	Qingdao, China	13.02	14.50	15.52	16.62
9	Jebel Ali, Dubai, United Arab Emirates	13.00	13.30	13.64	15.25
10	Tianjin, China	11.59	12.30	13.01	14.05

The leading global container ports are mostly from China which ranks among the top five along with 7th and 8th place from 2011 to 2014. Singapore placed in the second place of the leading global container ports ranking, while Busan in 6th and Jebel Ali in the 9th (WSC, 2015b; Alphaliner, 2015). The leading global container port is Shanghai, with an equity-adjusted throughput of 35.29 million TEU, approximately 5% higher than in 2013. Table 2.4 shows the throughput percentage rate for each port.

Table 2.4: Leading global container ports throughput percentage rate

Rank	Port	Throughput percentage rate
1	Shanghai, China	5%
2	Singapore	4%
3	Shenzhen, China	3.3%
4	Hong Kong, S.A.R., China	-0.6%
5	Ningbo-Zhoushan, China	12.1%
6	Busan, South Korea	5.6%
7	Guangzhou Harbor, China	7.2%
8	Qingdao, China	7.1%
9	Jebel Ali, Dubai, United Arab Emirates	11.8%
10	Tianjin, China	3.8%

Over the last four decades, the container has been an essential part of unit loads; the concept is now an integral part of international sea freight transportation. With ever-increasing containerisation, the amount of seaport container terminals and competition among them has become quite remarkable. As seen in previous industrial statistical analyses, investments in containerisation continue to grow steadily. Moreover, there is evidence of increased privatisation, and the container shipping industry proved in 2009 that it is economically resilient in the face of adversity. Ports, operators, customers, and investors clearly recognise this advantage.

2.3. Container Terminal Port Operations Overview

Containers entered the market for international conveyance of sea freights almost five decades ago. Containers are large boxes used to transport goods from one destination to another. The use of containers has several advantages, namely less product packaging, fewer damages, and higher productivity (Agerschou et al., 1983). The standardisation of metal boxes also offers customers many advantages, as it protects against weather and pilferage and improves and simplifies scheduling and controlling, resulting in a profitable physical flow of cargo (Steenken et al., 2004).

Container dimensions have been standardised using the term TEU, which refers to one container with a length of 20 feet. Containers are measured in TEU (i.e., 40 and 45 feet containers represent two TEUs). Different types of containers are available; the most common is the standard dry cargo container. Some other types are referred to as special equipment and include open end, open side, open top, half height, flat rack, refrigerated (i.e., reefer), liquid bulk (i.e., tank), and modular containers. All are built to the lengths and widths of standard dry cargo containers.

Every container has a unique unit number, often called a box number, that can be used by ship captains, crews, coastguards, dock supervisors, customs officers, and warehouse managers to identify a container’s owner or shipping user; they are even able to track the container anywhere in the world.

Several modes can be used to transport containers from one destination to another: ships that carry transport over the sea; trucks or trains over land; and some other special modes, which will be in Section 2.3.3, used for handling processes within terminal operations.

2.3.1. Container ship-related port operations

Large container ships are being built with the justification that they will produce economies of scale, as evidenced by the maritime container industry movement towards capacity expansion and growing container ship sizes. Encounter Bay was one of the first to be launched in 1968, with 1530 TEU, and 337 ships of 338,627 TEU were delivered between 1968 and 1973 (Levinson, 2010). In six years, the fleet grew 9.02 times the ship amount and 17.97 times carrying capacity. Vessel production increased beyond 1,000 TEU, becoming the largest group with about 95 new ships, totalling 132,172 TEU. The expansion continued in the 1970s by over 16% per year, delivering 176 ships and totalling 219,072 TEU. The sub-panamax generation also emerged, with 2,000–2,999 TEU, and grew quickly to deploy 61 ships, totalling 152,167 TEU (Tran & Haasis, 2015).

CSCL Globe was the world's largest container ship at the end of 2014, carrying over 19,000 TEU. The vessel did not keep this title for long, however, as MSC Oscar Mediterranean Shipping announced in early January 2015 that its latest vessel had a nominal capacity of 19,224 TEU (Martín et al., 2015). The container ship revolution is an on-going process, and ships as large as 22,000 TEU are expected to be in service as early as 2018. Capacity expansion and container ship growth since 1968 are described in Figure 2.3.

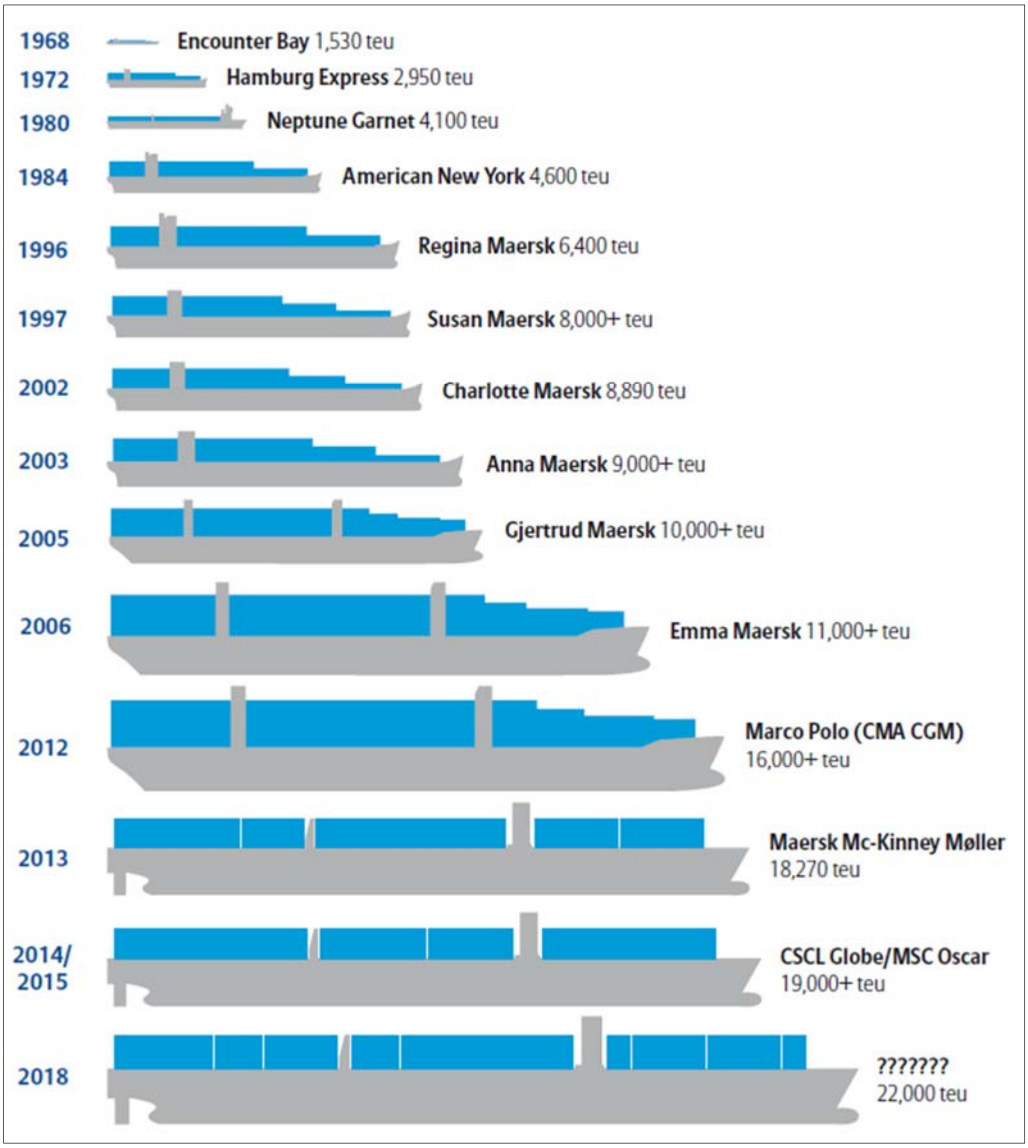

Figure 2.3: Container ship size growth and capacity expansion

In the quest for economies of scale, capacity expansion is being achieved through growth of ship size rather than the number of ships, because the unit costs of transport service decrease with vessel size; consequently, the earnings per unit of transport service increase with vessel size if freight rates hold steady (LIM, 1998). However, the employment of increasingly large container ships increases the risk of serious overcapacity, especially when several operators are introducing new vessels to the same trade routes. The operator with the largest capacity has an early cost advantage, putting pressure on other operators on mainstream trade routes to move quickly and aggressively for large and economical containerships to stay competitive. There is a strong tendency toward overbuilding, reaching far beyond foreseeable needs (Wu & Lin, 2015).

In regards to container ship safety from an engineering perspective, it is always much easier to increase vessel breadth or width than length in order to maintain ship stability. On the other hand, emerging torsion problems of ship hulls should be considered.

In addition, and more relevant to this research, ports and terminals have responded to the expansion of container ship capacity by making large and rapid investments in infrastructure and handling equipment. These investments could provide adequate service capacity, but the next ship generation, namely echelon, has elicited great concern from terminal operators' points of view (AGCS, 2014).

Operational managers are confronted with issues besides infrastructure: environmental concerns related to terminal size growth; containership loading problems with an increased quantity of TEU handling; restrictions on cranes; limited outreach; lack of qualified workforce; 24/5 or 24/7 customs check availability; hinterland transportation operations, in which truck route competition is likely to increase; and the most critical aspects of berth depth and time.

The movement towards larger ships presents port authorities with a number of pressing issues regarding investing in stronger tugs: deepening and/or widening approach channels, as larger ships have access to fewer ports due to the limited draught of the ports and turning basins; environmental and regulatory constraints; expansion projects; traffic organisation; and environmental, social, and business interruption costs (Sys et al., 2008).

Capacity expansion and container ship size growths have significant impacts, not only on shipping companies' businesses, but also on ports and container terminal operators. Ports and terminals continue responding to size growth by making large capital expenditure and investment plans, as the main limiting factors of the water depth in ports, navigable waterways and the length of the vessel are not breached. In addition, operation of bigger vessels raises terminal, intermodal, and commercial issues. According to previous analysis, container ship size growth and optimum terminal operations are interrelated; both concepts develop similarly regarding transport modes, terminal types, trade lanes, and technology.

2.3.2. Container terminal port overview

A container terminal is a facility in which containers are transhipped between different destinations for onward transportation. Transhipment within a terminal is namely between container ships (seaside), yard (stack), and land transportation vehicles (landside). Figure 2.4 presents an example of terminal layout at Altenwerder (CTA) in Hamburg.

Maritime container terminals tend to be part of a larger port, and the biggest maritime container terminals are situated around major harbours. Inland container terminals tend to be located in or near major cities, with transportation mode connections to maritime container terminals.

Both maritime and inland container terminals usually provide storage facilities for both loaded and unloaded (empty) containers. Loaded containers are stored for relatively short periods while waiting for onward transportation. Unloaded containers may be stored for longer periods awaiting their next use. Containers are normally stacked for storage, and the resulting stores are known as container stacks.

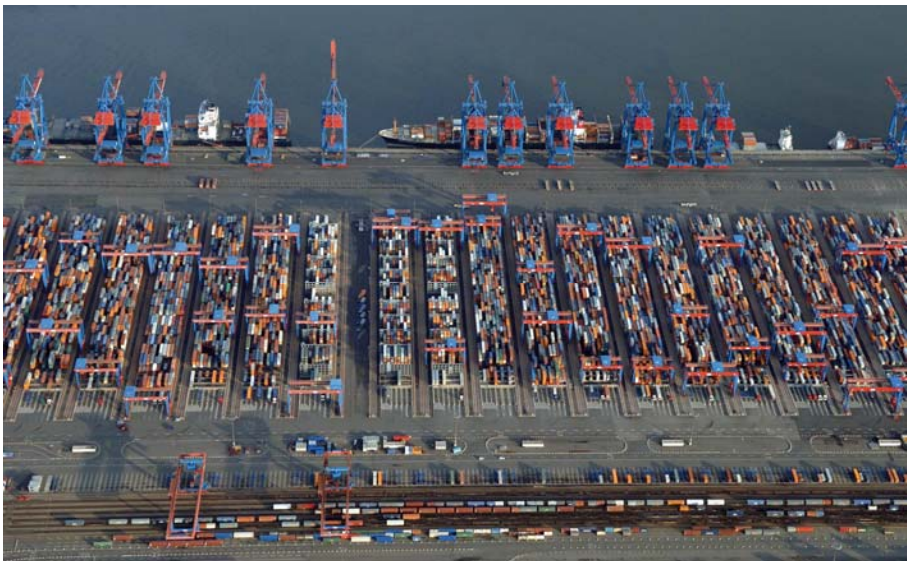

Figure 2.4: Container terminal layout, Altenwerder (CTA) in Hamburg

In general, container terminals are considered material-handling systems that have two interfaces for input and output flows. The interfaces are waterside when loading and unloading containers from ships, and landside for trucks and trains. In the heart of the container terminal is a stacking area, where containers are temporarily stored. The marine apron is a space designed for travelling vehicles, located between the stacking area and berth quay.

2.3.3. Container terminal port operation process

In recent years, methodological advances regarding container terminal operations have considerably improved. Although container terminals considerably differ in size, function, and geometric layout, they consist of the same sub-systems (Murty et al., 2005). The ship operation, or berthing area, is equipped with quay cranes for loading and unloading vessels. Import and export containers are stocked in a yard, which is divided into a number of blocks. Special stack areas are reserved for reefer containers that need an electrical supply for cooling or to store hazardous goods. Separate areas are used for empty containers. Some terminals employ sheds for stuffing and stripping containers or for additional logistics services.

The operation process commences when a ship arrives at a port, and the import and tranship containers have to be unloaded from the ship by the Quay Crane (QC). Next, the prime mover transfers the containers from the QC to connection units that travel between the ship and container yard. The containers are stored until the Rubber Tired Gantry (RTG) crane transports them to their next destination. After another period of time, the prime mover retrieves and transports the containers to ships or feeder vessels. This process can be executed in reverse order to load export or tranship containers onto a vessel. The containers stacked on the yard and vessel can be piled, meaning that not every container is directly accessible, which limits storage space (Vis & Koster, 2003). The process is illustrated in Figure 2.5.

The truck and train operation area links the terminal to outside transportation systems. The unloading and loading process at a typical modern container terminal is illustrated in Figure 2.6. After the container arrivals at the terminal by truck or train, it is identified and registered using its major data (*e.g.,* content, destination, outbound vessel, and shipping line), picked up by internal transportation equipment, and distributed to one of the storage blocks in the yard (Günther et al., 2006).

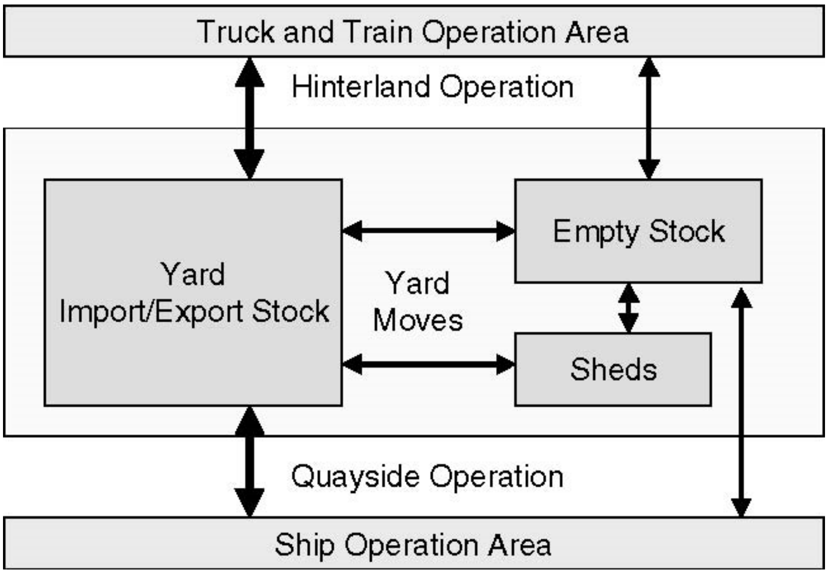

Figure 2.5: Operation areas of container terminal and flow of transports

The respective storage location is given by row, bay, and tier within the block and is assigned in real time upon arrival in the terminal. Specific cranes or lifting vehicles are used to store containers at the yard block. Finally, after the arrival of the designated vessel, the container is unloaded from the yard block and transported to the berth, where QCs load the container onto the vessel in a predefined stacking position (Stahlbock & Voß, 2008).

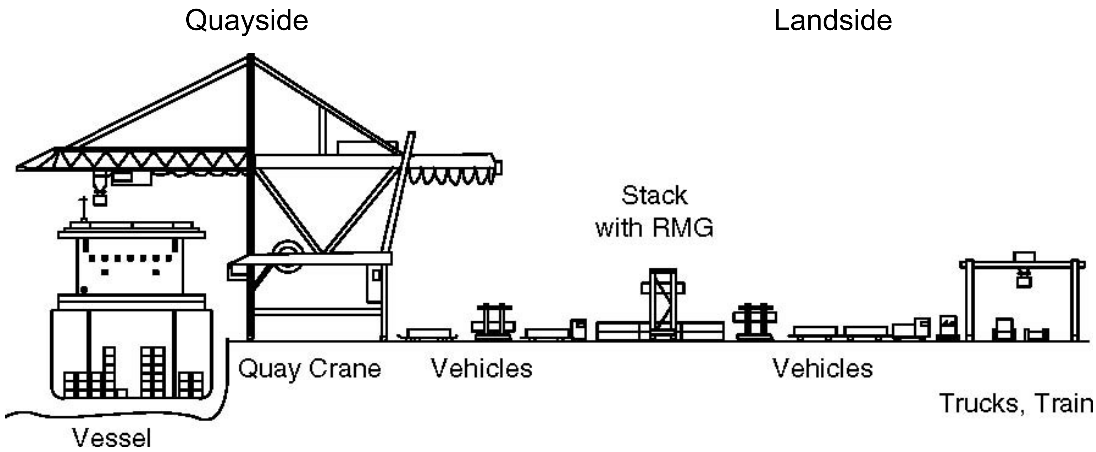

Figure 2.6: Transportation and handling chain of a container

The operations necessary to handle an import container are performed in reverse order. Figure 2.7 illustrates sub processes that correspond with the systems of Figure 2.6. Scheduling the huge number of concurrent operations, as well as the different types of transportation and handling equipment, is an extremely complex task.

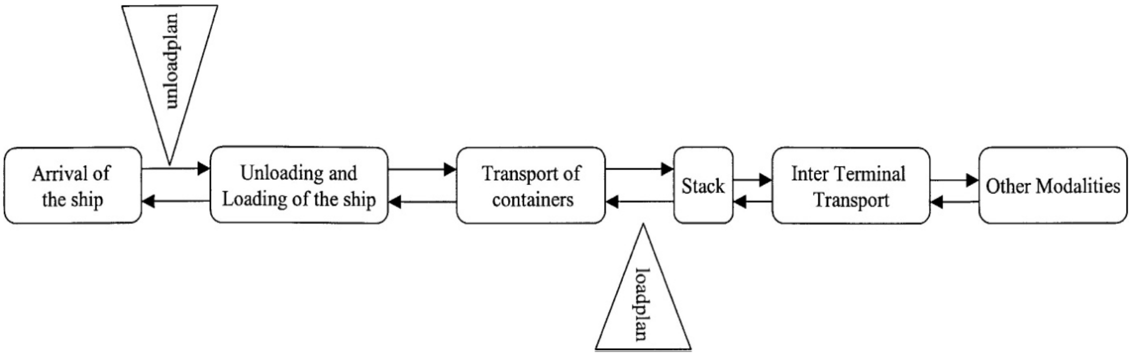

Figure 2.7: Processes at a container terminal

2.3.4. Container handling operations

Seaport container terminals greatly differ by transportation type and handling equipment (Günther et al., 2006). When a ship arrives at port, QCs take the import containers off the ship's hold or deck. In fact, QCs serve as single or dual-trolley cranes that can move along the crane arm to transport the container from the ship to the transport vehicle and vice versa. An example of a QC is given in Figure 2.8. QCs are manned because automating this process presents practical problems, such as exact positioning of containers (Vis & Koster, 2003), and QCs are used at both automated and manned terminals. The containers are picked up with a spreader, a pick-up device attached to the trolley.

Figure 2.8: Quay cranes

The QCs move on rails to the different holds, where they take/put containers off/on the deck and holds. One QC can unload a container while another simultaneously loads. Decisions at the operational level, such as which cranes should go where, which containers should be on the ship, and which containers should be taken out of the hold first, are in practice made by the crane driver or determined by the loading and unloading plan. Very little literature studies these types of problems (Stahlbock & Voß, 2008).

2.3.5. Yard handling equipment

As aforementioned, containers have to be transported from the ship to the stack and vice versa. Vehicles like forklift trucks, yard trucks, or straddle carriers can be used when designing a terminal. Straddle carriers and forklift trucks can pick up containers from the ground. A crane is needed to put the container on the yard truck (Vis & Koster, 2003). The most common types of yard cranes are Rail-Mounted Gantry (RMG) cranes, RTG cranes, Straddle Carriers (SC), Reach Stackers (RS), and chassis-based transporters, as illustrated in Figure 2.9 (Günther et al., 2006). It is worth mentioning that only RMG cranes are suited for fully automated container handling operations, while SCs can both transport and stack containers in a yard.

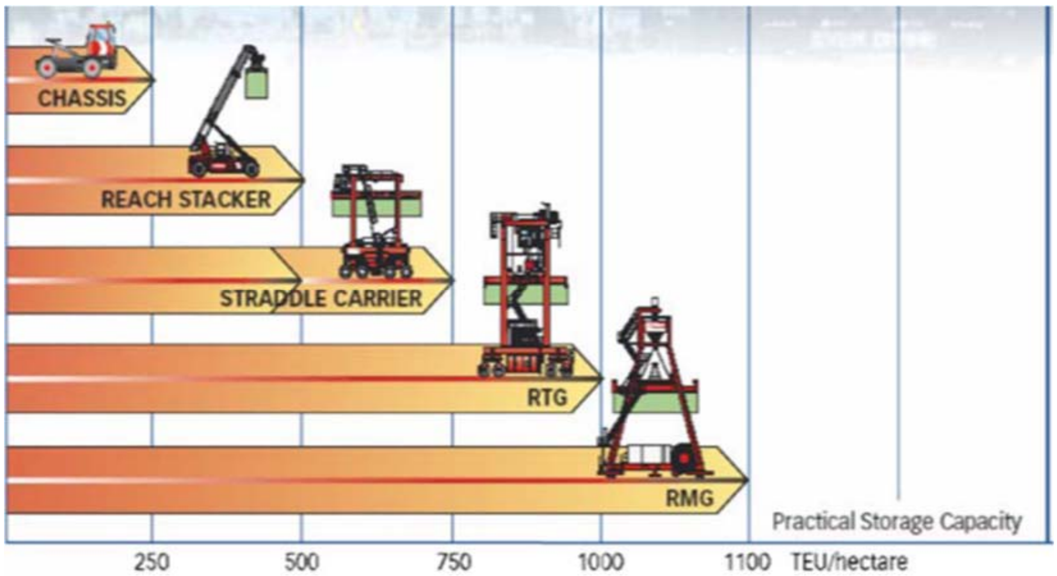

Figure 2.9: Different types of handling equipment
(Günther et al., 2006) (Vis & Koster, 2003)

Different types of vehicles can be used for both ship-to-yard transportation and interface between the yard and hinterland. The most common types are multi-trailer systems with manned trucks, Automated Guided Vehicles (AGVs), and Automated Lifting Vehicles (ALVs). The latter two types can load one 40’/45’ container or two 20’ containers, as seen in Figure 2.10.

AGVs are robotic vehicles that travel along predefined paths and can perform multiple load operations. ALVs are capable of independently lifting containers (Yang et al., 2004).

Figure 2.10: Automated guided vehicle (AGV)

In terms of operations, a route must be chosen by operation managers, as well as which vehicle transports which container.

2.3.6. Yard transhipment

A stack stores import and export containers for certain periods of time, as illustrated in Figure 2.11. A stack is divided into multiple blocks or lanes, each with a number of rows. Stacking height varies per terminal, ranging between two and eight containers high. A transfer point is situated at the end of each lane, and the crane takes/places the container off/on the vehicle transporting the container. Empty containers are usually stored separately (Steenken et al., 2004).

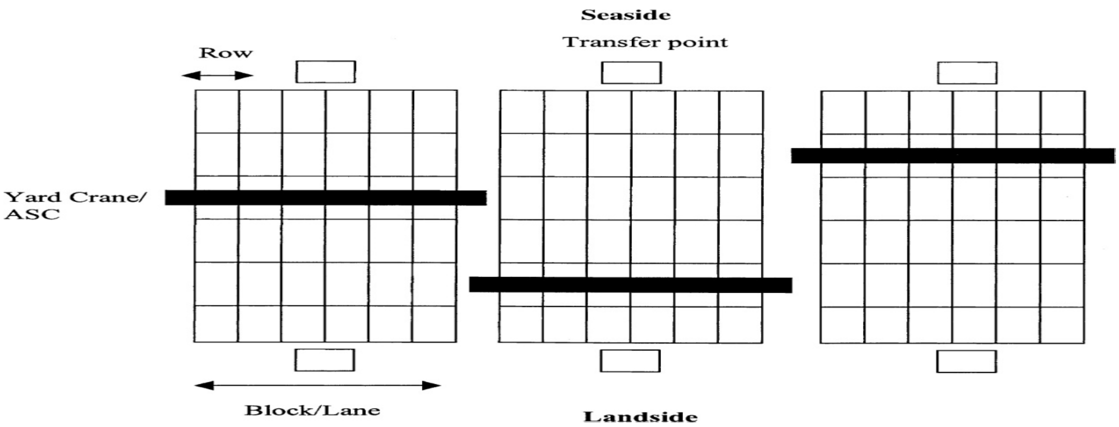

Figure 2.11: Schematic top view of the stack area

There are two methods for storing containers: storing on a chassis system in which each container is individually accessible; and piling containers on the ground, meaning that not every container is directly accessible. Due to limited storage space, stacking on the ground is currently more common (Stahlbock & Voß, 2008).

2.4. Maritime Port Safety

Seaport safety is playing an increasingly important role in ensuring supply chain resilience and sustainability, and is inspiring risk-related research from operational, organisational, and economic perspectives (Trbojevic & Carr, 2000; Soares & Teixeira, 2001; Marlo & Casaca, 2003; Legato & Monaco, 2004; Garrick *et al*., 2004; Madni & Jackson, 2009; Fabiano et al., 2010; Mokhtari et al., 2011;). However, compared to shipping risk analysis (Hänninen, 2014; Wu *et al.*, 2015; Banda *et al.*, 2015), studies on seaport risk and safety management are scarce in the literature. A review by Pallis et al., (2010) on 395 port-related journal papers published between 1997 and 2008 discloses that, despite the criticality of safety and security in efficient supply chains and international trade, risk analysis persistently occupies a backseat role within port research; it is overwhelmed by other aspects, such as efficiency analysis, port competition, geographical analysis, spatial evolution, and policy and governance.

A review of 984 papers published in the *Journal of Maritime Policy and Management* by Notteboom et al., (2013) reveals that core themes in seaport studies over the past 40 years include frameworks and techniques around many fields, including geography, econometrics, welfare economics, operations research, logistics/supply chain management, and strategic management. In the last five years, port research has been dominated by transport and supply chains, port governance, and port competition. During the first two decades of the Journal of Maritime Policy and Management, research attention focused on regulatory issues referring to competition, pricing, financing, environmental, safety, and security-related policy practices. Since then, port terminals, including container terminals, have developed rapidly and aggressively, creating a growing interest in examining the prospects and limits of port operation safety.

Over the last decade, the limitations on maritime port safety analysis has been acknowledged in the existing risk management approaches for port complex systems and resilience engineering. Therefore, significant effort is ongoing to enhance the port safety systems by developing a robust, flexible and effective methods to optimise critical systems operations safety (Wang, 2006; Mokhtari et al., 2011 and John et al., 2014).

Risk management of a maritime port systems is a highly complex task due to the dynamic interactions among its interrelated components of technical, organisational, operational, safety and security aspects of their daily operations. US Department of Homeland

Security described the level of interdependences and complexity of the system's operations as: ''*all areas and things of, on, under, relating to, adjacent to, or bordering on a sea, ocean, or other navigable waterway, including all maritime related activities, infrastructure, people, cargo, vessels and other conveyances.*'' (Moteff and Parfomak, 2004). One logical way to conduct an effective risk management framework of a seaport is by breaking down the system into functional structure comprising subsystems and components. The risk-based decision support methodology of the functional structure can be carried out to examine the interrelationships and then the system safety management model can be formulated for risk based modelling in all phases of the system's life, from its conception and design to its operation, maintenance and decommissioning (John et al., 2014).

Risk management as a subset of any management system, aims to develop, plan, comprehend and follow operations processes to implement an effective risk management framework that provides preventive actions to eliminate and/or mitigate risks related to the safety of people, environment and property (Hänninen, 2014). Maritime risk management framework covers several subareas of organizational management that describing the elements of maritime port operations on how these elements interact to provide useful information on the functioning of the risk-based decision support methodology in order to serve as an assessment and monitoring tool that help stakeholders for continuous improvement and decision making when managing maritime port operations safety.

The scholarly community has proposed several frameworks to assess the organizational aspects effects on risk within different domains, to name but a few (Embrey, 1992; Paté-Cornell & Murphy, 1996; Øien, 2001; Roelen et al., 2003; Mohaghegh, Kazemi, & Mosleh, 2009), in the maritime transportation field (Trucco et al., 2008; Oltedal & McArthur, 2011; Ek et al., 2014) and maritime port disruptions and resilience (John et al., 2014; Zhang et al., 2015; Lam & Su, 2015; John et al., 2016) However, safety management have not been adequately addressed and there is not safety management model based on the established safety management norms or standards have been published (Hänninen, 2014). in the light of the above facts and arguments, the existing models are rather limited and don't have a comprehensive reasoning of the maritime risk management mechanisms based decision-support. The maritime risk management subarea interactions seem to be lacking an appropriate risk management framework and research upon that approximates the risk management realities for maritime terminals' and ports' complex activities, especially on the operational aspects.

In addition, large numbers of regulations and legislations on maritime port safety have been proposed by various international and professional bodies to enhance the operational safety and efficiency of maritime ports systems including maritime port terminals which will discussed in details in Section 2.5.3.

Safety and reliability of maritime ports is important for the protection of human life and health, the environment, and the economy. Safe port terminal operation has a profound impact on service quality, productivity cost, and lifestyle. Therefore, system safety evaluations that include the early detection of hazards are critical in avoiding performance degradation and damage to human life or machinery. Furthermore, the development and enforcement of a robust forecasting mechanism can eliminate or reduce the effect of accidents and/or disasters that jeopardise terminal operations. Many engineering systems are repairable, and their safety measures are evolving; implementing these changes going forward can evaluate and improve the growth or deterioration of systems (Hu et al., 2010). The necessity and importance of evaluating a system safety is dependent on the fact that decision makers are generally interested in predicting future system failures for resource planning, inventory management, development of realistic policies for age replacement, and logistics support.

2.5. Container Terminal Port Safety

Maritime infrastructure, such as container terminals, is critical, as well as costly engineering systems that enable economic activities through the transfer of goods and services between national and international destinations. Given the significance of their operations to the world economy, container terminals face a variety of operational and environmental uncertainties that make them vulnerable to hazards (Mansouri et al., 2009). Container terminal operations are conducted by a large number of workers at different facilities, sites, and workplaces, and safety issues are of significant importance to the operation of these sites and workplaces. Quantitative research on safety and security analysis of container terminal operations has not yet been well conducted, but Yang, Ng, and Wang (2014) have raised the issue. If risks cannot be quantified, industrial stakeholders may not be motivated to confidently take control measures. A container terminal safety study by Fabiano et al., (2009) examines the factors that affect occupational accident frequency in ports and terminals; it discloses that scientific research has not properly explored the container revolution's impact on port safety.

Sea ports and marine terminals (i.e., infrastructures) are essential economic elements of any coastal state; therefore, recent years have seen research and subsequent improvements in areas that affect seaports and marine terminals, including operational, organisational, economic, business, and natural conditions. Researchers have carried out significant work over recent years. International bodies such as the IMO, UNCTAD, World Bank, European Commission, Asian Development Bank, and Academic Bodies have been leaders in marine port and terminal research. Professional and academic bodies aim to enhance the efficiency and effectiveness of marine ports and terminals.

In regards to container terminal operational safety from a practical point of view, constantly changing elements can determine the performance of different container terminals, taking into account a range of internal and external factors influencing the system's productivity (Legato & Monaco, 2004).

Growing public concern over supply chain safety and security in the past decade has stimulated risk analysis of container terminals (often deemed safety-critical nodes/components in container supply chains); this risk analysis is considered an effective solution for reducing/mitigating the negative impacts caused by possible hazardous events (Mokhtari et al., 2011). The risk analysis of large maritime engineering systems, such as container terminal infrastructure, is affected by many factors related to transport safety, including shipping efficiency, supply chain distribution reliability, and loss prevention.

In regards to operational improvement, performance indicators are important factors in determining the efficiency of the seaports and marine terminals (UNCTAD, 1996; World Bank, 2001; Marlo & Casaca, 2003). The performance of marine ports and terminals can be determined by different, constantly changing elements and a range of internal and external risk factors that influence the system's productivity (Legato & Monaco, 2004).

Regarding marine port organisational improvement, Shannon et al., (1997) note that the relationship between different organisational culture including the role of management style, information technology and the workforce has a great impact on health and safety. Liu et al., (2002) and Steenken et al., (2004) investigate container terminal optimisation improvements, including automated equipment, terminal operation-related computer technology, and management of various types of activities within ports. In reviewing technological opportunities for container terminals, Frankel (2001) explains that advanced technology enables seaports to integrate cargo transfer into individual customer logistical requirements. Günther et al., (2006) research recent developments and examine research issues concerning quantitative analysis and decision support for container terminal logistics.

In terms of economic improvement perspectives for ports and terminals, UNCTAD (1996) and World Bank (2001) examine how competitiveness among ports and terminals can influence different countries' economies and trade values. Palmer (1999) emphasises the need for efficient port facilities and operations to improve their competitive positioning. Goss (1990) expresses that efficient seaports can positively influence a nation's economies of scale. Many researchers have studied businesses with respect to individual ports and terminals and included case studies and reviews of seaport development to enhance efficiency, as discussed in Section 2.2.

In terms of natural conditions' impacts on marine ports and terminals, seaports have demonstrated a high vulnerability to seismic motion, and associated ground failures severely impact health and the economy (Pachakis & Kiremidjian, 2004). The 1995 Japanese Hyogoken Nanbu earthquake showed that low resilience of port activity in the wake of natural disasters results in severe economic losses. Past experience shows that earthquakes can significantly impact port components, including quay walls, piers, cranes, and warehouses. Natural disasters can severely disrupt terminal operations and negatively affect a region's economy (Na & Shinozuka, 2009).

The increasing number of publications in the last decade indicates the importance of the aforementioned areas of research. However, dynamic and enforced changes occurring in marine ports and offshore terminals including operational, organisational, economic, business, and natural factors related to environments have made it imperative to study safety aspects, including recent risk-management related issues regarding externally and internally driven elements. Therefore, this study mainly focuses on operational aspects, including technical and personnel factors, leaving other risk aspects to be addressed in future work. Other risk concerns influencing port safety—such as management, policy implications, and natural and political issues—also need investigation in order to provide a panoramic view on terminal risk analysis.

2.5.1. Some Noteworthy Accidents

The shipping industry is regulated by a complicated international legal framework. Basically, it is based on the recommendations and guidelines of more than 50 conventions with numerous protocols and amendments (Knapp and Velden, 2010). These conventions are developed mainly by the International Maritime Organization (IMO) and the International Labour Organization (ILO) with the support of various national and international bodies. However, there are still some loopholes in their enforcement system, which can lead to incidents. Shipping incidents tend to carry very high economic costs, due to the large asset values and the high operational risks involved in shipping.

Despite the efforts being made by IMO"s member states to change this process, preventive actions are still uncommon, resulting in the creation or amendment of legislation being reactive and typically following the outcome of a major disaster. Ultimately in terms of legislation in practice, the maritime ports industry has suffered a lot in the past and produced some disjointed, conflicting regulations, mainly in response to disasters involving considerable loss of life, property, and environmental damage.

The American Bureau of Shipping (ABS) analysis showed that 50% of maritime accidents were initiated by observable erroneous human action, while another 30% of maritime accidents occurred due to failures of verifiable human actions to avoid an accident (ABS, 2003). However, the magnitude of damage inflicted by a major shipping accident increases virtually with the public attention paid to those accidents and their negative influence on the perceived safety of shipping. Unfortunately, it is a fact of life that design for safety and safety operational practices are only appreciated after serious accidents have occurred.

2.5.1.1. Chicago Port disaster

On the evening of July 17, 1944, the SS Quinault Victory and SS E.A. Bryan, two merchant ships, were being loaded and packed with 4,600 tons of explosives. Another 400 tons of explosives were nearby on rail cars. At 22:18, a series of massive explosions over several seconds destroyed everything and everyone in the vicinity. Every building in Port Chicago was damaged, 320 people were killed, 390 others were injured and fire with smoke extended nearly two miles into the air. The pilot of a plane flying at 9,000 feet in the area claimed that metal chunks from the explosion flew past him (Jones et al., 2006).

The exact cause of the explosion was never revealed. However, the inquiry covered possible explosion scenarios involving problems with steam winches and rigging, organizational problems within the management system and lack of handling training, but it was mainly poor safety procedures and misconducting handling practices that led to the catastrophe.

2.5.1.2. Tianjin Port disaster

Late in the evening of 12 August 2015, a series of explosions at a container storage station at the Port of Tianjin, China was occurred. The first two explosions occurred within 30 seconds of each other at the facility, which is located in the Binhai new Area of Tianjin. The second explosion was far larger and involved the detonation of about 800 tonnes of ammonium nitrate. Fires caused by the initial explosions continued to burn uncontrolled for the next three days, repeatedly causing secondary explosions, with eight additional explosions occurring on 15 August (Independent, 2015).

One month after the explosion, the casualty report was 173 deaths, 8 missing, and 797 non-fatal injuries. The accident has cost nearly 1bilion GBP. The official report into the disaster found 123 people, including senior officials, responsible for the illegal storage of 11,300 tonnes of hazardous chemicals. The cause of the explosions was not immediately known, but an investigation concluded in February 2016 that an overheated container of dry nitrocellulose was the cause of the initial explosion.

Over the past nine years more than 1,200 accidents occurred in maritime container ports have been brought to the attention of the Health and Safety Executive, 120 major incidents which have caused fatal or serious injuries to staff while at work (HSE, 2008). Lack of compliance with safety practice and misconducting proper inspections has been found as main root causes for many cases. Still no one has argued strictly for lack of complying with a generic or any specific risk management based methodology for OSP in container terminals and maritime ports. The accidents described above together with other disasters may justify the need for the maritime industry to improve its safety culture and so move towards a risk-based regime in both design and operations.

2.5.2. Existing container terminal port safety-related methodologies

The increasing number of container shipments causes higher demands on seaport container terminal management and logistics, as well as on technical equipment (Steenken et al., 2004); this heightened demand has led to significant research on logistics issues that arise from decision-making problems. Academic work has been devoted to the analysis of security and environmental issues (Yip et al., 2002; Yang et al., 2010; Riahi, 2010) or container terminal optimisation, including management and automated technology (Liu et al., 2002; Vis & Koster, 2003; Steenken et al., 2004; Günther et al., 2006).

Very little research, however, has focused on container terminal safety and transportation. In a broader scope, few scholars have paid attention to the performance reliability of ports' transportation systems. Container transportation began five decades ago, and containerisation has developed rapidly since then; its impact on safety, from ships and ports to global trade patterns, has not been properly explored in scientific research.

Trade globalisation has led to a rapid increase in container vessel movements in many seaports. As trade continues growing, most busy seaports face risks related to economic wealth, operational efficiency, personnel safety, and terminal security. The increasing number of container shipments put high demand on container terminal management. While significant academic effort is devoted to port-centred logistics and operational optimisation (Liu et al., 2002; Vis & Koster, 2003; Steenken et al., 2004; Güntheret et al., 2006), relatively few studies examine port safety and risk (Yip et al., 2002; Yang et al., 2010), revealing a major research gap. Safety analysis is broadly defined as the study of system failure consequences in relation to possible harm to people and/or damage to environment or property, including financial assets (HSE, 1997).

Safety has been an issue for centuries, from the beginning of the shipping industry, and will likely remain an issue as industry growth continues. When tracking the industry's history, the need for measured risk-control implementation is often recognised after catastrophic accidents. For instance, the Titanic disaster in 1912 led to the first International Conference on Safety of Life at Sea (SOLAS). In 1960, following the capsize of liner Andrea Doria, the United States hosted the International Safety Conference advocating for ship safety measurement. The International Convention for the Prevention of Pollution (MARPOL) from Ships was initiated during the 1970s due to several oil tanker accidents. The 1990 Exxon Valdez disaster resulted in the mandated use of double hull tankers. All aforementioned incidents and the subsequent acts from member states or international bodies indicate the constant necessity for introducing modern risk management methods to the maritime industry.

A systematic focus on risk-based methodology began in the aerospace sector following the fire of the Apollo test AS-204 in 1967 as the basic method of probabilistic risk assessment. The nuclear industry developed probabilistic safety assessments in the 1970s, introducing the first full-scale application of this method, including the reactor safety study WASH-1400 which analysed the accident's consequences (Jensen, 2002). The chemical industry used Quantitative Risk Assessment (QRA) in the 1970s, which the Norwegian offshore industry developed and applied in the 1980s after the Alexander accident (Bai & Jin, 2016). The development of Safety case as a mandatory requirement in the UK after the Piper Alpha accident in 1988 (HSE, 1992). After Lord Carver's 1992 investigation of the capsizing of the Herald of Free Enterprise, the UK proposed the FSA, a safety regime risk management framework, to the IMO in 1993.

Various industries perform risk-based methodologies. Most, if not all, of these methodologies function in one of three main categories (i.e., quantitative, qualitative, and a combination of both) to identify, evaluate, and mitigate the impact of risk factors on the industry. The following subsections briefly describe the most widely applied risk-based methodologies.

2.5.2.1. Quantitative Risk Analysis (QRA)

QRA, also called Probabilistic Risk Analysis (PRA) or Probabilistic Safety Analysis (PSA), is being applied to many domains, including transportation, construction, energy, chemical processing, aerospace, the military, and financial planning and management (Bedford & Cooke, 2001). Relevant authorities have adopted QRA approaches as part of the schematic framework for many industries. QRA methodology provides numerical evidence to other sectors to ensure safety claims or determine the need for further improvement (Haigh, 2003).

QRA is not a standard practice, as proven by the trend in many domains to support management decision-making and risk management strategizing. However, QRA varies in goals, size, complexity, and techniques depending on each sector's characteristics.

Essentially, QRA answers the following three questions (Farquharson & McDuffee, 2003):

- What can happen? Or, what are the initiators or initiating events (i.e., undesirable starting events) that lead to adverse consequences?
- How likely is it to happen? Or, what are their frequencies?
- Given that it occurs, what are the consequences? Or, what and how severe are the potential determinants?

Risk is defined by identifying possible hazards, quantifying frequencies, and determining the severity of consequences (Bedford & Cooke, 2001). The analytical process of QRA is illustrated in Figure 2.12.

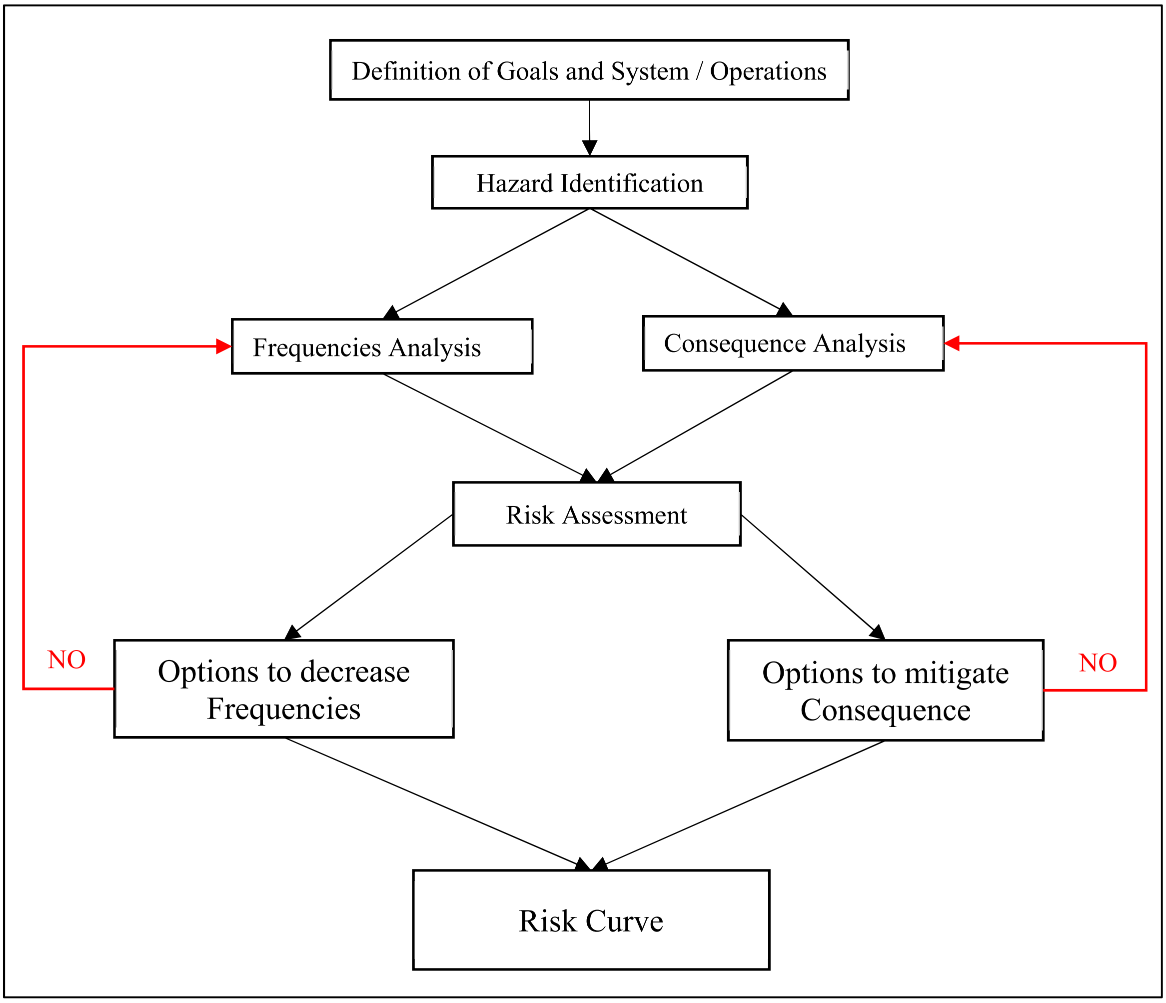

Figure 2.12: Analytical process of QRA

Detailed answers to these three questions are obtained by performing an analytical process phase for each question. The first phase requires technical knowledge and specialised information on the possible causes of harmful outcomes from a given action or activity. Rationale techniques and logic tools such as Master Logic Diagrams (MLD) and Failure Modes and Effects Analysis (FMEA) are useful for focusing on the most important initiating events. The second phase calculates frequency of initiating events using Boolean Logic methods for model development, as well as probabilistic or statistical methods for the quantification portion of model analysis. Boolean logic tools include inductive logic methods like Event Tree Analysis (ETA) and Event Sequence Diagrams (ESD), and deductive methods like Fault Tree Analysis (FTA).

When an event's frequency is fully defined by historical statistical data, it can be used if the uncertainty in the data is very low. For some system failures events in which there is no historical failure data or the data are very sparse, quantitative failure models are developed with deductive logic tools, such as FTA, or inductive logic tools such as Reliability Block Diagrams (RBD) and FMEA. In the second and third phases, developing and quantifying accident scenarios tracks the chains of events linking initiating events to the detrimental consequences (Stamatelatos, 2000).

The third phase requires a deterministic analysis to describe the severity of consequences that could occur from the accident. Beginning with the initiating events, the chain forms a risk curve by plotting the frequency of consequence value excess and a function of the consequence values. The risk curve illustrates the frequency of a certain number of casualties in a given period of time, as shown in Figure 2.13.

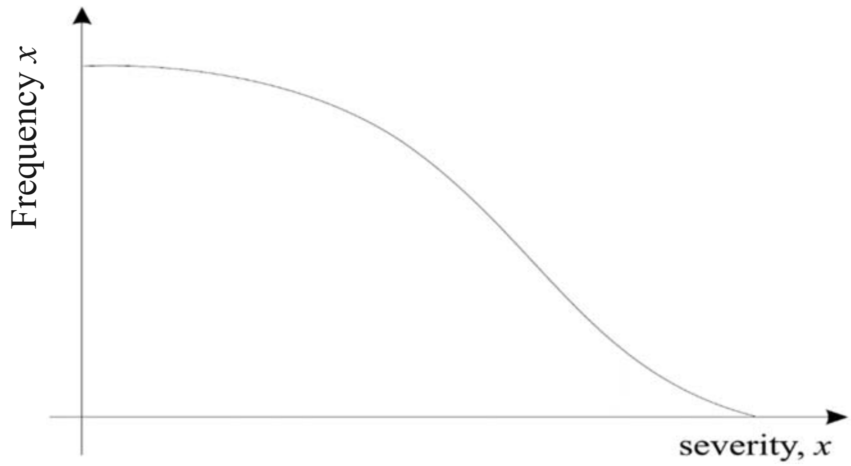

Figure 2.13: Risk curve

As a risk-based method, this may look quite similar to offshore safety case procedures. However, the process for conducting each step, as well as the use of techniques and tools, may differ from safety case applications.

2.5.2.2. Safety case

A safety case aims to ensure an adequate level of safety for a particular facility, based on management and control of the facility's associated risks. A central feature of a safety case is a facility's designers and operators (i.e., duty holders) assessing the risks associated with their facility, as well as documenting how the safety management system appropriately limits those risks (Sutton, 2014b). The document that contains risk assessment details and the safety management system is called a safety case. The safety case demonstrates, to duty holders, customers, and society at large, that ship operation risks are adequately understood and controlled.

A safety case includes a comprehensive description of the facility, its operation, and the environment within which it operates. Risk assessment is conducted using a number of established techniques, such as FMEA, Hazard and Operability Study (HAZOP) studies for hazard identification, FTA, and ETA. Risks are then quantified to the appropriate extent. Risk criteria are set, relevant to the facility and its operational context, and usually in accordance with the "As Low As is Reasonably Practicable" (ALARP) principle. The safety management system includes key elements of safety case concepts for setting policy, including organising, planning, and implementation, as well as monitoring, review, and feedback of performance against the policy to ensure that safety objectives are achieved efficiently and without damaging the environment (HSE, 1992). The key elements of the case concepts are illustrated in Figure 2.14 and described below (Wang, 2002; Sutton, 2014b).

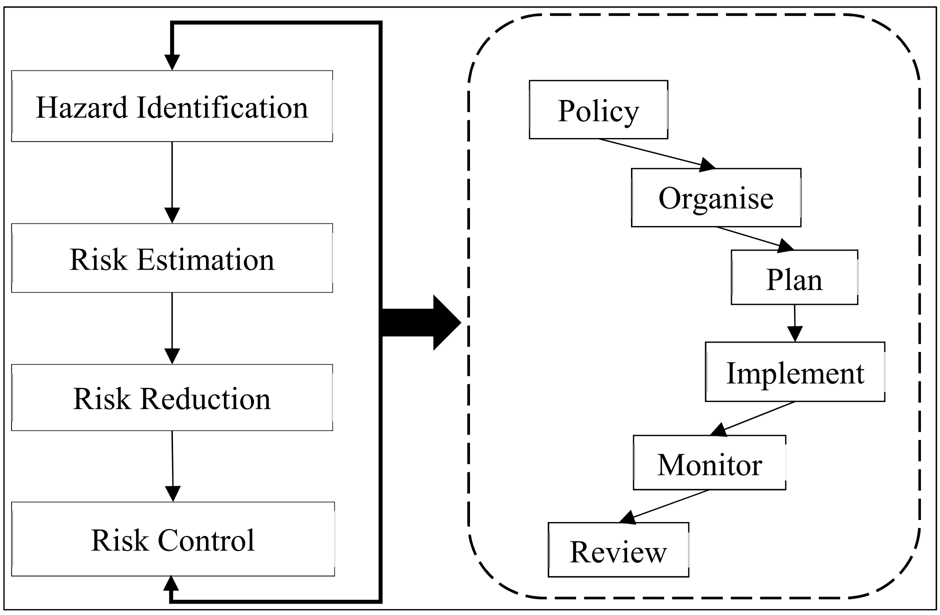

Figure 2.14: The key elements of the safety case concepts

1. Identify hazards.

2. Estimate risks for all identified hazards. All hazards can generally be classified in accordance with the ALARP principle as the intolerable, tolerable, and negligible risk regions (HSE, 1992), as shown in Figure 2.15.

3. Reduce risks associated with significant hazards, and institute mitigation measures should a major incident occur.

4. Utilise risk control to take the most appropriate action in the event that a hazard becomes a reality to minimise its effects on operators, facility, and the environment.

5. Develop and implement a Safety Management System (SMS) and ensure that it meets pertinent health and safety rules and regulations. SMS effectiveness is usually monitored and verified by means of regular audits and inspections to ensure compliance with safety case requirements.

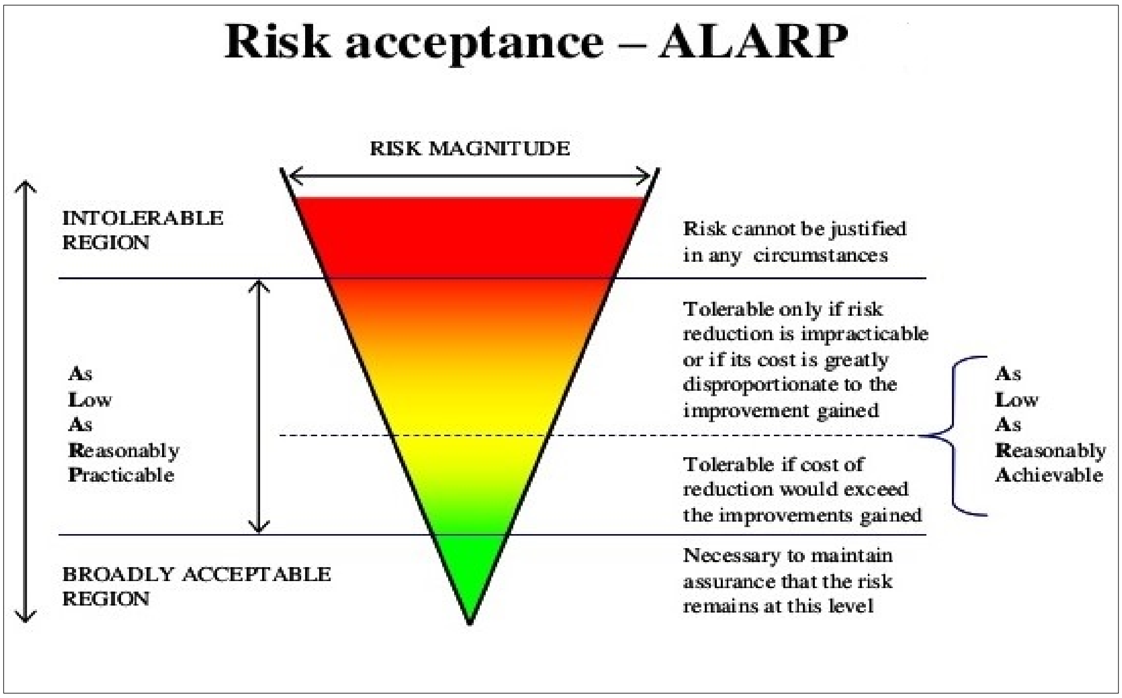

Figure 2.15: The tolerability of risk (HSE, 1992)

2.5.2.3. Formal Safety Assessment (FSA)

FSA as a risk-based methodology is, in some aspects, similar to the safety case regime used for the UK Continental Shelf. The philosophy of both methods is generally the same, but while a safety case is applied to specific maritime shipping sectors, FSA is generally applied to any maritime shipping sector for common safety issues; the actual content of each step, however, as well as the techniques and tools used, may differ from offshore applications. This framework is due to the unique maritime industry structure, which has no universal regulator, culture, education, or qualification system. FSA is a tool for decision makers to rationalise their process and achieve a balance between maritime safety and protection of environment and costs (IMO, 2002). The functional components in the FSA process are listed below and then illustrated in Figure 2.16.

1. Hazards identification
2. Risk analysis
3. Risk control options
4. Cost benefit assessment
5. Recommendations for decision-making

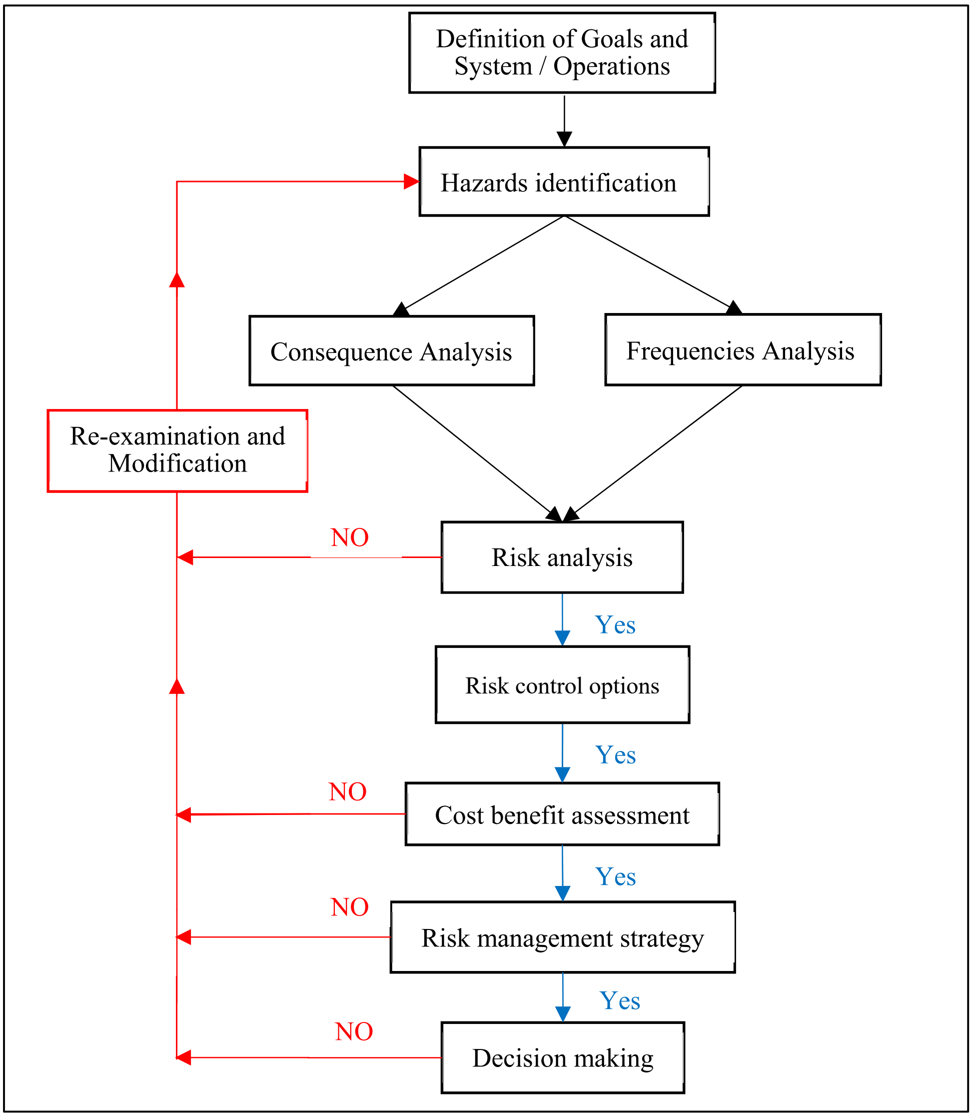

Figure 2.16: FSA process and functional components

FSA's use in shipping represents a fundamental cultural change, from a largely reactive approach to a structured and systematic methodology that uses risk evaluation and is integrated, proactive, and effective (Pillay & Wang, 2003). FSA's main characteristics are below.

- FSA is a systematic approach for sociotechnical systems that may consist of hardware, environment, human organisations, operations, and procedures.
- Hazards are proactively identified through the hazard identification process, and may apply different hazard identification approaches.
- Risks associated with various hazards are described and analysed. Usually, risk is a composite of the likelihood and consequences of a potential undesirable event arising from a hazard; other risk attributes can be assigned to the conventional risk composition to improve the system's safety. Risk analysis covers the time span of operational life, and may involve various quantitative or qualitative tools to perform risk composition calculations.
- Risk quantification determines risk level and whether it is acceptable or significant based on predefined acceptance criteria. When risk is significant, it is necessary to devise regulatory measures to control and reduce that risk.
- The above step may be followed by cost-benefit analysis to compare preventive/protective measure costs with benefits.
- Basic elements are integrated into a risk model with information about the hazards, their associated risks, and the cost effectiveness of alternative risk control options. The objective is to recommend the most cost-effective, preventive, and mitigating measures for a risk management strategy.

FSA was designed as a tool to assist maritime stakeholders and, generally, the entire shipping industry; it was not intended for application to individual ships. The main features of FSA are formalised procedure, audible process, communicated safety objectives, and priorities based on cost effectiveness (Bai & Jin, 2016). These elements have made FSA a more rational risk management method within the maritime industry in regards to improving safety aspects by addressing the impact of risk factors.

2.5.2. Risk management process

Various industries have carried out risk management for many years. However, the QRA approach is increasingly being applied and developed, particularly for its probabilistic approach to risk assessments (EMSA, 2012). The nuclear, aviation, and process industries have been performing QRA for many years, for instance. These industries are dealing with equipment whose failures can have catastrophic consequences; therefore, it is necessary that they operate at very high reliability levels (Haigh, 2003). In such complex systems and operational situations, qualitative and global assessments alone are unable to cope with the technical and operational specifics; this has created a need not only for quantified risk assessments, but also for systematic and transparent risk management approaches.

Pressure from the public and the scientific community has raised the maritime industry's awareness of needing risk-based methodology. FSA is the term most often used to distinguish new methods from earlier risk management approaches. Although other industries use different terms, such as QRA, Safety Case, and FSA, the main features of any risk-based methodology are the same. Beyond their names, risk assessment procedures consist of similar phases that identify, evaluate, and mitigate the impact of risk factors affecting an industry and addressing those three phases in different risk-based processes.

Risk management has an important role in many risk-based decisions, as seen through on-going developments in modern risk-management approaches, particularly for decisions involving uncertainty and deviation from standard practice, for which regulations including the maritime sector are less appropriate (HSE, 2002). In fact, institutional diversity can offer considerable advantages when addressing complex, uncertain, and ambiguous risk problems, because risk problems with different scopes can be managed at different levels. Furthermore, an inherent degree of overlap and redundancy makes non-hierarchical adaptive and integrative risk governance systems more resilient and therefore less vulnerable; in addition, the larger number of actors facilitates experimentation and learning (Renn et al., 2011).

2.5.2.1. HAZard IDentification (HAZID)

The first and most important phase in any risk assessment process is HAZID (Sutton, 2015; UNCTAD, 2006; IMO, 2002; HSE, 2000; Jensen, 2002). HAZID should be carried out to ensure that all situations with the potential to cause harm to people and/or damage to a system's environment or property have been identified, and the risk factors as a result of these causes are defined (Bai & Jin, 2016). In engineering and industrial sectors, HAZID is a general term used to describe a practice whose goal is to identify all significant activities that have the potential to result in significant consequences (Pillay & Wang, 2003; Wang & Trbojevic, 2007). The HAZID process can differ depending on evaluated facility/system characteristics (such as an operation's complexity, activity magnitude, work force, and equipment) and accessible resources.

A variety of techniques are used to perform HAZID, including qualitative and quantitative approaches, which in turn include literature review and research, physical inspection, flow charts, check lists, specialist brainstorming, What-If Analysis/Structured What-If Technique (SWIFT), safety audits, organisational charts, HAZOP, Task Analysis (TA) and FMEA (HSE, 2000; ABS 2003; Dickson, 2003). These are popular techniques for identifying conceivable and relevant hazards, although some are complex to perform to the appropriate standard, and have been used for a long time; these include HAZOP, FTA, safety audits, FMEA, and TA (HSE, 2000). Many reviews contain information on more than one technique, and where possible, have not been used as a basis to describe the technique.

The literature reviews as one of the HAZID can provide a high quality analysis where the hazard based data has been searched and justified for related topic which can be used in conjunction with the other qualitative and quantitative methods (ABS, 2003; Saunders et al., 2007). In addition, HAZID is more efficient and less costly than other techniques. HAZID brainstorming sessions are generally used to analyse technical systems and thereby generate main qualitative results. These sessions are conducted by a team of specialists to determine potential consequences of a deviation. Teams should represent a cross section of disciplines and functions—including operations, engineering, maintenance, management, and process design—to ensure that all hazard scenarios are detected and discussed (Sutton, 2015; Bai & Jin, 2016). Hazards usually have multiple causes, and the collaboration among team members helps uncover the hazards that may be caused by miscommunication or misunderstandings between departments (Sutton, 2015). For instance, QC breakdowns may be caused by management miscommunication, operating errors, or equipment malfunction. Redundancy can also be important; as common failure modes, can affect several parts of a system at once. These sessions should therefore list and acknowledge as many hazard causes as possible.

2.5.2.2. Risk evaluation

Risk evaluation develops a total risk estimation by consolidating all information for specific hazards, including events/scenarios, frequencies/likelihoods, and consequences. Risk estimation uses gathered information to identify affected parts of a high-risk system and the main risk contributors (Bai & Jin, 2016). The key element related to risk evaluation is predefined acceptable risk levels. After obtaining total estimation, risk can be evaluated according to risk levels. The results of any risk evaluation are conditional based on evaluation background knowledge, including phenomenological understanding, models, data, and expert statements (Berner & Flage, 2016).

Many techniques can be used in the risk evaluation process, including qualitative, semi-quantitative, and quantitative methods (HSE, 2000; Krishna et al., 2003). In general, qualitative techniques are easiest to apply because they require the least resource demands and additional required skill sets, but they also provide the least amount of insight. Conversely, quantitative techniques are the most demanding techniques in terms of resources and skill sets, but they often deliver the most detailed understanding and provide the best basis if significant expenditure is involved. Semi-quantitative approaches lie between these extremes (HSE, 2000). However, due the potential sources' highly subjective nature, lack of information, or simplistic assumptions, it is usually difficult to accurately determine risk attributes (i.e., frequencies/likelihoods and impact). The most practical and common way to express these attributes is through qualitative verbal expressions (i.e., linguistic terms), especially using expert judgments; this makes it easier for experts to provide input (Borek et al., 2014). Often, this method is a combination of empirical data, technical/engineering knowledge of the system, comparison with similar phenomena, and other expert sources (Luko, 2014). For instance, to evaluate frequency/likelihood, the method may use such linguistic terms as low, medium, and high. The same linguistic terms and variables may be used with consequence evaluation, including slight, minor, moderate, critical, and catastrophic.

A variety of risk evaluation techniques have been introduced by the Academic Bodies and used by the industries, including ALARP, FMEA, Failure Mode Effects and Criticality Analysis (FMECA), BN, ER, FTA, ETA, Preliminary Hazard Analysis (PHA), Cause-Consequence Analysis (CCA), and Human Reliability Analysis (HRA), all of which use either qualitative or quantitative techniques (HSE, 2000; Dickson, 2003; Luko, 2014; Borek et al., 2014; Alyami et al., 2014, 2016; Sutton, 2015; Bai & Jin, 2016). These techniques have been developed in different industrial settings, usually in response to practical system problems. The project manager or safety officer needs to choose the right approach for the system, which can be difficult given the different risk evaluation techniques and many different specific methods involved. While there is no single correct approach for a specific activity or system features, some approaches are more suitable than others, and a decision framework is helpful in the selection process.

2.5.2.3. Risk mitigation

Once the risks have been evaluated, the next phase is to identify the options available for controlling them. These can range from doing nothing to introducing risk control options in order to eliminate the cause of the risk altogether or reduce the cause to secure certain benefits to a system's people, environment, and property, with the confidence that the risk is under control and worth taking. There are two methods for controlling risk:

- Reactive approach to reduce the severity of failure
- Proactive approach to reduce the frequency of an initiating event

A reactive approach, or a mitigating option approach, refers to risk mitigation actions initiated after risk events occur, and can be seen as a contingency plan initiation. A pro-active approach, or preventive approach, refers to actions initiated based on the probabil-ity of a risk event occurring, such as marine insurance domains that use risk mitigation option strategies (Kartam & Kartam, 2001; Bai & Jin, 2016). Risk management can apply a combination of these two approaches to reduce the likelihood and consequences of risk; this can be extended further to risk avoidance, transfer, or retention (RMS, 2005). The basic goal is risk reduction, and the key test is one of reasonable practicability; that is, the cost of further risk reduction is grossly disproportionate to benefits gained which involves cost benefit analysis.

Risk events jeopardise and disrupt system objectives/operations when harmful effects are realised due to unexpected circumstances. Systematic and detailed risk management at-tempts to cover all aspects of system activities so that all controllable events have a risk control plan (Ahmed et al., 2007). Strategies for risk control include applying engineering practice and implementing regulatory procedures. Reanalysing the risk and comparing these results to the can be determined the effectiveness of risk control actions; if they were ineffective, utilised strategies must be changed (Bai & Jin, 2016). Available courses of action are varied, and they are chosen depending on the need for a reactive or proactive approach during the risk mitigation phase. For instance, Functional Safety and the IEC 61508 series, Safety Integrity Level, Protection layers include Basic Process Control System, Critical Alarms and Human Intervention, and Safety Instrumented Functions. Physical protection and emergency response were used for risk control measure in the process industry and all mitigate the frequency of occurrence or mitigate the severity consequence (Lassen, 2008). In addition, all statutory regulations introduced by international bodies including classification society rules and IMO Conventions and Codes are typical examples of strategies used for risk control.

In this phase, the risk management objective is to avoid accidents, and can be measured by evaluating the avoidance of harm to people and damages to property, environment, and other costs. To achieve a balance, risk control action benefits must be compared to implementation cost using a cost benefit analysis (Bai & Jin, 2016). Risk control measure's costs are estimated by taking into account both enforcement cost, such as personnel work force which includes inspection, auditing and installation and regulatory capital and compliance costs (EUC, 2013). Similar to how cost estimation process estimates benefits, each option's net worth value can be calculated by deducting cost benefits. Sensitivity analysis estimates the level of confidence attached to calculated net worth value of each option; then, risk control options are ranked based on cost effectiveness (HSE, 2001; Ahmed et al., 2007). Risk control options are selected based on cost effectiveness and by using ALARP to judge the level of acceptable risk; regardless of costs, intolerable risk must be controlled. Several methods analyse benefit analysis, usually referred to as MCDM techniques. Among these techniques, and widely used in academic research, are TOPSIS (Kahraman et al., 2007), AHP (Golec & Taskin, 2007), Analytic Network Process (ANP) (Yuksel & Dagdeviren, 2007), ELECTRE (Wang & Triantaphyllou, 2005), PROMETHEE (Dagdeviren, 2008), and Axiomatic Design (AD) (Kulak & Kahraman, 2005). There is no single correct technique, but some are more suitable than others (Mergias et al., 2007).

2.5.3. Container terminal port safety-related legislation

Seaports and maritime terminal infrastructures face risk challenges from various perspectives, including economic, operational, technical, and environmental perspectives. As discussed in Section 2.5.1, the scholarly community has intensively researched logistics and operational optimisation in order to improve terminal productivity; along with this, some leading International Bodies are involved in the maritime shipping sector. However, the paradigm has been steadily shifted. The latter (i.e. leading International Bodies) took initiative to direct this shift. For instance, between 1971 and 2007, the perspective at UNCTAD changed from focusing on the development of ports and terminals, management efficiency improvements, commercial challenges, and organisational issues to initiating descriptions and developing a systemic strategy for safety and security risk assessment and management framework.

Another example is the United States Government Accountability Office (USGAO), which recently focused on ports' risk management strategy, identifying hazards, prioritising protective measures at marine ports, and other critical infrastructures that need to be refined and assessed (USGAO, 2005; 2007). In addition, in 2009, the UK's Department of Transport (DFT) required all marine ports to perform risk assessment of marine operations to implement a safety management system.

The IMO, a specialised agency of the United Nations, has set a global standard for safety, security, and environmental performance of international shipping, aiming to create a fair and effective regulatory framework for the shipping industry. Other International Bodies that have close relationships to the shipping industry represent different maritime interests concerning regulatory, operational, and legal issues. These bodies work to ensure safety either through their own firm or through a joint effort with other International Bodies whose main purposes are also to avoid and prevent potentials for different hazards or risk factors and/or to take preventive and corrective actions.

Recently, the International Chamber of Shipping (ICS) and the World Shipping Council (WSC) have developed guidelines on Industry Best Practices, including Safe Transport of Containers by Sea. In 2010, they issued a joint statement calling on the IMO Maritime Safety Committee (MSC) to establish an international legal requirement that all loaded containers should be weighed at the terminal port facility before being stowed aboard a vessel for export (ICS, 2011). Miss-declared container weights have contributed to severe consequences related to container loss at sea and other terminal operational safety problems. On November 21, 2014, the MSC 94 officially adopted the new SOLAS requirement for vessel loading that container weights be verified before the shipper boards them on ships. The SOLAS container weight verification requirement became legally binding on July 1, 2016 (IMO, 2014).

In 2008, the ICS and the WSC published Transport of Containers by Sea, an industry guide for shippers and container stuffers when loading containers, as proper handling is very important to the safety and stability of the containers, ships, trucks, and trains (ICS, 2008).

The Marine Safety Agency (MSA) emphasised the necessity of safe operational practice and qualified duty holders by proposing FSA to the IMO for the purposes of improving safety of and pollution prevention within ports to reduce and mitigate the negative impacts caused by possible risk factors and to ensure strategic safety oversight (Trbojevic & Carr, 2000). However, there is no evidence of international safety standards addressing safety performance in container terminals operation.

The IMO and the United Nations Economic Commission for Europe (UNECE) have updated the Code of Practice for Packing of Cargo Transport Units (CTU), which outlines specific procedures and techniques for safety improvement, including equal weight distribution within containers and proper positioning, blocking, and bracing according to cargo type. The code was published in 1997 and needed revisions. Following recommendations from an IMO-organised 2011 Global Dialogue Forum, IMO, ILO, UNECE, and ILO developed a joint code for packing intermodal CTU, which received final approval in November 2014 (IMO, 1997).

In May 2012, the Port Equipment Manufacturers Association (PEMA) published new industry recommendations on equipment protection and human safety in container yards, addressing minimum safety specifications for quay container cranes. PEMA's compilation of its initial publications regarding safety standards for QCs was published in June 2011 as a joint initiative with the Through Transport Mutual Insurance Association Limited (TT Club) and the International Cargo Handling Co-ordination Association (ICHCA). It was prompted by results of a TT Club global analysis showing that 34% of asset-related insurance claims were directly related to QCs (Stiehler, 2012).

Several individual contributions worked toward safety practice in container terminals in respect of offshore terminals' operations. For instance, the Health and Safety Executive (HSE) focused on health, safety, and environmental issues for offshore terminal operations, particularly after the 1988 Piper Alpha disaster (Mokhtari et al., 2011).

In October 2010, the HSE cooperated with the UK ports industry to publish the Guidance on Container Handling (GCH) to help container terminal industry workers under the health and safety legislation to identify relevant risk sources in various terminal operations. However, the impact of containerisation appears to have advantages regarding the expense of safe terminal operations. The application of safe operational practice and qualified duty holders is essential, but these requirements are not widely recognised by many in the container terminal industry, and it is a matter of individual choice (Soares & Teixeira, 2001). In addition, the UK Department of Transport required all marine ports to perform risk assessment of their marine operations in order to implement the Port Marine Safety Code (DFT, 2009).

In terminal sectors, risk-based process activities and operation safety are discussed mainly under integrity management, safety, reliability management, or engineering (Sutton, 2014). Most aforementioned international and/or local bodies are trying to manage existing hazards by using guidelines and/or codes of conduct-related terms and applying risk mitigation methods to justify that they were involved in a risk management-related processes. None are using a generic risk management framework or methodology to address container terminal operation safety.

2.6. Conclusion

This chapter reviewed the maritime container terminals market to exhibit the expansive impact of containerisation on container terminal operation. Container terminal operational processes, including container ships, terminal facilities, and equipment interfacing handling were described, followed by a careful analysis of the widely applied risk management-based methodologies. The impetus for this study lies in the comprehensive literature review related to container terminal safety and the critical analysis of risk management processes in maritime ports. Furthermore, the literature review concerning the methods and modelling techniques for FL, BN, ER and ANN are carried out in related technical chapters.

Publications focusing on the maritime container terminal sector are very comprehensive and consistent in how they employ managerial strategic efficiency and logistics optimisation concepts, but they fail to address tactical safety aspects related to operational issues—a research gap that must be addressed. The increasing number of publications in the last decade indicates the importance of operation research methods in the field of optimising container terminal operations. However, most publications deal with logistical issues that arise from decision-making problems at manned container terminals and automated container terminals. The lack of research on safety compared to optimisation makes it imperative to examine safety issues in order to protect lives and resources, as well as increase efficiency on the operational and managerial levels, which will reflect negatively or positively on revenue.

Chapter 3 — Modelling Container Terminal Risk Evaluation (CTRE)

Summary

Risk analysis plays an increasingly important role in ensuring port operation reliability, maritime transportation safety, and supply chain distribution resilience. However, the task is not straightforward given that port safety is affected by multiple factors related to its design, installation, operation, and maintenance and that traditional risk assessment methods such as quantitative risk analysis cannot sufficiently address uncertainty in failure data. Further, a careful literature search has also disclosed that safety is not often primary within port research, being overwhelmed by other aspects involving efficiency evaluation, port competition, geographical analysis, policy, and governance. Furthermore, among the studies addressing port safety, many have focused on policy issues based on descriptive or qualitative approaches which, together with the above challenges, critically point out the need for developing a robust and efficient quantitative risk analysis approach to prioritise hazards. This chapter adapts a novel FMEA approach incorporating Fuzzy Rule Base Bayesian Network (FRBN) to evaluate risk criticality of the HEs in a container terminal. Compared to conventional FMEA, the new approach integrates FRB and BN in a complementary way, in which the former provides a realistic and flexible way to describe input failure information while the latter allows easy update of Risk Estimation (RE) results and facilitates real time safety evaluation and dynamic risk-based decision support in container terminals. The proposed approach can also be tailored for wider applications in other engineering and management systems, especially when instant risk ranking is required by the stakeholders to measure, predict, and improve their system safety and reliability performance.

3.1. Introduction

Traditional QRA methods such as FMEA can be used to identify high-risk hazards in situations in which objective failure data is available. However, a careful literature search reveals that a high level of data uncertainty and incapability of FMEA to address such uncertainty exists in port risk analysis. Novel risk approaches are needed. To overcome such intrinsic drawbacks, many new methods based on uncertainty treatment theories such as FL, Dempster-Shafer (D-S) theory, grey theory, Monte Carlo simulation, BN, Markov models, and AANs have been proposed in the literature to enhance the performance of FMEA, especially when criticality analysis is concerned (Yang et al., 2008). However, such new methods contribute to the development of more precise failure criticality analysis and also render themselves vulnerable by losing visibility and easiness, which are advances of the conventional FMEA method.

Yang et al., (2008) proposed a new hybrid methodology to explain in a complementary way the role of Bayesian marginalisation (BN) in FRB risk inference, in which the BN rule is used to aggregate all relevant IF-THEN rules with belief structures and produce failure priority values expressed by posterior probabilities of linguistic risk expressions, while FRB is used as an effective tool to elicit expert judgments for rationalising the configuration of subjective probabilities. Although attractive, such a method still reveals a significant application problem, which is the associated with determining how to incorporate the importance of risk parameters into the establishment of FRB with belief degrees.

This chapter aims to develop a novel FMEA approach FRBN by incorporating FRB and BN to rationalise the Degrees of Belief (DoB) distribution in order to evaluate risk criticality of the HEs in a container terminal. To achieve the aim, this chapter is organised as follows. An analytical overview of ports and container terminals risk analysis and FuRBaR proposed by Yang et al., (2008) in FMEA particular concerning its application in port risk analysis is carried out in Section 3.2. Section 3.3 describes the novel FMEA framework capable of incorporating different weights of risk parameters into FRB. A particular test case regarding container terminal safety evaluation is investigated to demonstrate the feasibility of the new methodology in Section 3.4. Section 3.5 develops a discussion based on the results obtained. Section 3.6 concludes the chapter. Consequently, this study will make a contribution to facilitating the FMEA applications in risk theoretical research and to enhancing practical safety management for container terminals.

3.2. Research Background

3.2.1. Fundamental aspects of the notion of risk

Risk as a concept has been researched at all levels from various national and international industries and governments as discussed in Sections 2.4 and 2.5. Correspondingly, literature on the subject has expanded, and the words “risk,” “hazard,” and “uncertainty” are used to refer to many different risks, including safety, business, economic, investment, social, political, and military. It is important to draw distinctions between these words to establish a uniform and consistent usage.

3.2.1.1. The distinction between risk and hazard

Scientific literature includes few empirical studies that distinguish between hazard and risk (Wiedemann et al., 2010). Moreover, language dealing with risk assessment is mainly grounded in English, where there is a clear linguistic distinction between "risk" and "hazard." However, this crucial linguistic distinction is not the same in Arabic, Swedish, German, or Dutch (Lofstedt, 2011) leading to greater confusion. Arabic and Swedish, for instance, do not have specific expressions for risk or hazard; instead, the closest word is "خطر (i.e., khatar) in Arabic or fara in Swedish", meaning danger.

The Oxford English Dictionary defines a hazard as "a potential source of danger" and risk as "the possibility that something unpleasant or unwelcome will happen." In terms of work activities for regulatory control of risk from occupational hazards, HSE (2001) defines hazard as "something (i.e., an object, a property of a substance, a phenomenon, or an activity) that can cause adverse effects." Risk is "the likelihood that a hazard will actually cause its adverse effects, together with a measure of the effect." This is a two-part concept, and both parts should be considered to make sense of the term. Likelihoods can be expressed as probabilities (one in one hundred), frequencies (10 cases per year), or qualitative terms (negligible, significant). In terms of maritime safety, IMO (2002) defines hazard as "a potential to threaten human life, health, property or the environment," and risk as "The combination of the frequency and the severity of the consequence."

In the light of these definitions, information about a hazard is different from that of a risk, even if this difference is not always made clear. Hazard as the potential for harm arising from an intrinsic property or disposition of something to cause detriment, and risk as the chance that someone or something that is valued will be adversely affected by the hazard. Hazard, therefore, exists as a source. Risk includes the likelihood of conversion of that source into delivery of loss, injury, or some form of damage. This is the sense in which these words should be used.

3.2.1.2. The distinction between risk and uncertainty

The understanding and definitions of uncertainty vary substantially between different academic disciplines involved in risk assessment. The term "uncertainty" is used to describe a wide variety of attributes in an investigation, ranging from quantitative to qualitative, and even unquantifiable ignorance (Walker et al., 2003). Discussions about uncertainty and risk are complicated by the varying ways in which these concepts are defined and applied, both within and between disciplines (Brown & Damery, 2009). Numerous classifications of uncertainty have been proposed in recent years, especially in economics (Alessandri et al., 2004; Alvarez & Barney, 2005; Liesch et al., 2011). These include many types of classifications for uncertainty, such as imperfect knowledge, error, indeterminacy, and ignorance (Suter et al., 1987; Smithson, 2012; Regan et al., 2002). As the major sources of uncertainty vary between cases, it is common for detailed studies to employ different terminologies (Brown & Damery, 2009). However, there is a similar pattern in strategic management that treats risk and uncertainty synonymously (Alvarez & Barney, 2005). Furthermore, a trend in this research is that many container terminal stakeholders, including managers, safety officers, and workers, struggle to identify and define whether they are dealing with risk or uncertainty, as seen in questionnaires and narrative expositions. This section therefore distinguishes risk and uncertainty involved in risk assessment.

Frank Knight and John Keynes originally distinguished between risk and uncertainty in the 1920s, and their definition remains fundamental today. Economist Knight drew the first conceptual distinction between decisions under risk and uncertainty. Risk refers to situations in which the decision-maker knows with certainty the mathematical probabilities of possible outcomes of choice alternatives; uncertainty refers to situations in which the likelihood of different outcomes cannot be expressed with any mathematical precision (Weber & Johnson 2008). However, the notion of risk involves both uncertainty and some kind of potential loss or damage (Kaplan & Garrick, 1981). Risk and uncertainty have different implications on decision-making, although the concept of uncertainty is not always consistently applied. For instance, uncertainty may refer to situations with either unknowable futures or futures that are knowable but not measurable. Risk refers to decisions in which the consequences of a given outcome are subject to known probability distributions (Knight, 2012).

Based on the above analysis, the first distinction between risk and uncertainty depends on the probability of occurrence. Risk involves a situation with known possible outcomes for which a numerical probability distribution can be defined, whether objective or subjective. An uncertain situation occurs when either the set of outcomes is unknown or the probability distribution cannot be calculated. Uncertainty exists due to the limitedness or even absence of adequate knowledge (data and information from qualitative or quantitative approaches), which makes it difficult to precisely assess the probability and possible outcomes of harmful effects (Renn et al., 2011; Aven & Renn, 2009; Filar &

Haurie, 2010). In the context of risk assessment, it is essential to acknowledge that human knowledge is always incomplete and selective, and thus contingent upon uncertain assumptions, assertions, and predictions (Functowicz & Ravetz, 1992; Renn, 2009).

The other distinction between risk and uncertainty lies in the definition of uncertainty, which is a lack of precise knowledge or confidence of the truth, whether qualitative or quantitative (NRC, 1994; Brown, 2004). Risk refers to a lack of confidence, in which the precise outcome is unknown but one or more possible outcomes of action may cause harm. Uncertainty here is a lack of confidence about human knowledge. Human confidence may vary from being certain that something is correct, incorrect (i.e., in error), or irrelevant; this extends the concept of uncertainty to decision making where the potential for loss is known (e.g., in terms of time, money, property, handling machinery, or human life), but the precise nature of the loss, including the probability of occurrence, is unclear (Brown & Damery, 2009).

Risk and uncertainty both affect the nature and content of decisions or actions, based on the fact that the future can never be accurately predicted; therefore, using expectations and assumptions about the future has varying degrees of confidence and uncertainty when planning safety measures and assessing hazard events, exposure, and consequent risks to human health (Liesch et al., 2011); (Ramsey, 2009). Classifying risk in relation to complexity, uncertainty, and ambiguity is not a trivial task. Some risks might look simple early in an analysis, then turn out to be more sophisticated, uncertain, or ambiguous than originally assumed; therefore, a group of interdisciplinary experts, stakeholders, and risk managers should make judgments at the beginning of the assessment process and reassess them later, particularly during the evaluation phase (Dreyer et al., 2009; Renn et al., 2011). Other scholars, including Hertz & Thomas (1983), expand this distinction to include strategic and tactical risk. Strategic decision-making situations involve strategic uncertainty or uncertainty about the structure and outcome of the problem, and strategic risk is therefore particularly pertinent to the public decision-making process. Another dimension to distinguishing between risk and uncertainty is that the uncertainty does not imply risk if there are no direct consequences to the individual or decision-maker. Uncertainty is therefore a necessary condition for risk, but it is not sufficient, and reducing uncertainty in a system does not necessarily reduce risk (Gough, 1988).

3.2.2. A brief review of fuzzy FMEA

FMEA is one of the most widely applied hazard identification and risk analysis methods due to its visibility and simplicity (Braglia et al., 2003). The traditional FMEA method has three fundamental attributes, namely failure occurrence likelihood (L), consequence severity (C), and probability of failures being undetected (P). These three attributes are used to assess the safety level of failure modes and to calculate their Risk Priority Numbers (RPN) (Wang et al., 1996).

The classical RPN approach suffered from some critical drawbacks (Yang et al., 2008). The method has therefore incorporated advanced uncertainty modelling techniques such as fuzzy sets, grey theory, ER, and BNs to facilitate its practical applications in maritime and offshore engineering safety (Sii et al., 2001), system reliability and failure mode analysis (Braglia et al., 2003) and engineering system safety (Liu et al., 2005), and maritime and port security (Yang et al., 2009).

Among the quantitative development of FMEA (through incorporating advanced uncertainty modelling techniques), a hybrid Fuzzy Rule-based Bayesian Reasoning (FuRBaR) methodology was proposed by Yang et al., (2008) to delineate the role of Bayesian Reasoning in FRB risk inference in a complementary way and to achieve sensitive failure priority values without compromising the simplification of the traditional RPN approach. All steps required for developing criticality analysis using the FuRBaR approach are outlined in Yang et al., (2008):

1. Establishment of FRB with belief structures in FMEA;
2. Failure estimation and transformation;
3. Rule aggregation using a Bayesian reasoning mechanism;
4. Development of utility functions for failure ranking; and
5. Validation using benchmarking and sensitivity analysis.

Compared to the RPN approach, FuRBaR used domain expert knowledge to develop FRB with a structure of DoB and to establish the connections between the three risk parameters L, C and P. For example,

IF L is very low, C is negligible and P is <u>highly unlikely</u>

THEN the safety level is good with a 100% DoB.

IF L is very low, C is negligible and P is <u>unlikely</u>

THEN the safety level is good with 91% DoB and average with a 9% DoB.

The approach uses the Bayesian marginalisation rule to accommodate all relevant IF-THEN rules with belief structures and calculates failure priority values in posterior probabilities. An FRB is employed as an effective way to elicit expert judgments for rationalising the configuration of subjective probabilities. Although showing much potential, the approach still has a significant applicable problem. This problem is associated with the establishment of an FRB with a rational structure of DoB; the problem needs to be appropriately addressed in order to stimulate the implementation of FuRBaR in real safety critical systems.

This work aims to develop an advanced safety analysis FRBN approach to evaluate the criticality of the HEs in a container terminal. The new method rationalises the DoB distribution and develops a new risk-based decision support tool for effective seaport risk evaluation.

An FRB with belief structures is more informative and realistic than the traditional *IF-THEN* rule because of its high effectiveness in functional mapping between antecedents and the conclusion, particularly in view of vague knowledge representation (Yang et al., 2008).

The BN mechanism is a simple mathematical formula for calculating conditional and marginal probabilities of a random event. Conditional probability is the probability of an event given the occurrence of an influencing event whereas marginal probability is the unconditional probability of an event. BN is used as a tool to perform FRB risk inference to model uncertainty in a domain or system. It also deals with subjective probability that may represent the degree of belief from an expert and applies it in a precise and relevant manner (Jones et al., 2010).

3.3. Methodology for modelling CTSE

Due to the lack of objective failure data, a subjective knowledge-based fuzzy IF-THEN rule-based approach is proposed to model CTRE in this section. A rule-based method consists of IF-THEN rules and an interpreter controlling the application of the rules, which in FMEA risk analysis is described as the relationship between risk parameters in the IF portion and risk levels in the THEN portion. These IF-THEN rule statements are used to formulate the conditional statements that comprise the complete knowledge base.

The steps for developing novel FMEA analysis for modelling CTRE based on the proposed FRBN approach are outlined as follows:

1. Establish a FRB with belief structure in FMEA for CTRE.
2. Identify HEs (i.e., failure modes) in container terminals.
3. Prioritise the HEs using the new approach with rational distribution of DoBs in FRB.
4. Validation by using sensitivity analysis techniques.

3.3.1. Establishment of an FRB with belief structure in FMEA of CTRE

In traditional FMEA, three risk parameters, L, C, and D, are used to evaluate the safety level of each failure mode. However, when conducting CTRE, the impact (I) of a failure to the resilience of port operational systems is crucial and is being taken into account in this study. Consequently, the four risk parameters (L, C, D, and I) are constructed to form the IF portion while the Risk Evaluation (RE) of failures is presented in the THEN portion in an FRB. To facilitate subjective data collection, a set of linguistic grades of High, Medium, and Low is employed to describe L, C, D, I, and RE (Tah & Carr, 2000; Wang et al., 2008). The degrees of the parameters estimated for each HE is based on knowledge accumulated from past events, and their definitions are presented in Table 3.1, taking into account domain experts' judgements.

Table 3.1: The linguistic grades for each HE

Parameter	Linguistic Grades	Definition
HE occurrence probability **(L)**	High (H)	Occurs more than once per month
	Medium (M)	Occurs once per quarter
	Low (L)	Occurs less than once per year
HE consequences/ severity **(C)**	High (H)	Death or permanent total disability; loss/damage of major facilities; severe environmental damage
	Medium (M)	Minor injury; minor incapability of systems, equipment or facilities that disrupts operations over 3 hours; minor damage to the environment.
	Low (L)	Minor medical treatment; slight equipment or system damage but fully functional and serviceable; little or no environment damage.
Probability of HE being undetected	High (H)	Impossible or difficult to be detected through intensive or regular checks or maintenance

(P)	Medium (M)	Possible to be detected through intensive checks or maintenance
	Low (L)	Possible to be detected through regular checks or maintenance
HE impacts on the resilience of port operational systems **(I)**	High (H)	Loss of ability to accomplish the operations or operation failure in the port
	Medium (M)	Degraded operations capability or readiness of the port
	Low (L)	Little or no adverse impact on operations capability of the port

A belief structure is introduced to model the incompleteness in the THEN portion. It has been formed as follows (Yang et al., 2008).

$$R_k: IF\ A_1^k\ and\ A_2^k\ and\ A_3^k\ and\ \cdots and\ A_m^k, THEN\ R^k \qquad 3.1$$

where, the k^{th} rule is defined as a multiple-inputs and single-output rule and

m^{th} represents the number of the antecedent parameters.

It is noted that the subjective judgements from multiple experts identify all the parameters and the DoB of the rules at the knowledge acquisition phrase. For example,

Rule 1: If L is Low, C is Low, P is Low and I is Low,
Then R is Low with a 100% DoB, Medium with a 0% DoB and High with a 0% DoB.
Rule 2: If L is Low, C is Low, P is Low and I is Medium,
Then R is Low with a 75% DoB, Medium with a 25% DoB and High with a 0% DoB.
Rule 3: If L is Low, C is Low, P is Low and I is High,
Then R is Low with a 75% DoB, Medium with a 0% DoB and High with a 25% DoB.

Such rules suggest that a proportion method is used to rationalise the DoB distribution. Specifically, the DoB belonging to a particular grade in the THEN portion is calculated by dividing the number of the risk parameters, which receive the same grade in the IF portion, by four.

For example, in *Rule 1*, the number of the risk parameters receiving the Low grade in the IF portion is four. The DoB belonging to Low in the THEN portion is therefore computed as 100% (4/4 = 100%). In *Rule 2*, the numbers of the risk parameters receiving the Low and Medium grades in the IF portion are three and one, respectively. The DoBs belonging to Low and Medium in the THEN portion are therefore 75% (3/4 = 75%) and 25% (1/4 = 25%). It can be formed as follows.

$$DoB_h = \frac{\sum_{j=1}^{r} DoB_{hx}}{r} \qquad 3.2$$

where, h^{th} represents the linguistic terms number ($h = 1, \ldots, 3$),

r represents the total number of the inputs attributes, and

x represents individual inputs attribute.

It can be further expressed for the benefit of this model application as follows.

$$DoB_h = \frac{\sum_1^4 DoB_{h1} + DoB_{h2} + DoB_{h3} + DoB_{h4}}{4} \qquad 3.3$$

Similarly, the FRB used in CTRE containing 81 rules (3×3×3×3) with a rational DoB distribution can be obtained and partially shown in Table 3.2, and fully presented in Appendix I-1.

Table 3.2: The established FRB with a belief structure for CTRE

Rules	Four risk parameters in the IF part				DoB in the THEN part		
No	(L)	(C)	(P)	(I)	Low (R1)	Medium (R2)	High (R3)
1.	Low (L1)	Low (C1)	Low (P1)	Low (I1)	1	0	0
2.	Low (L1)	Low (C1)	Low (P1)	Medium (I2)	0.75	0.25	0
3.	Low (L1)	Low (C1)	Low (P1)	High (I3)	0.75	0	0.25
4.	Low (L1)	Medium (C2)	Low (P1)	Low (I1)	0.75	0.25	0
5.	Low (L1)	Medium (C2)	Low (P1)	Medium (I2)	0.50	0.50	0
	…	…	…	…	…	…	…
77.	High (L3)	Medium (C2)	High (P3)	Medium (I2)	0	0.50	0.50
78.	High (L3)	Medium (C2)	High (P3)	High (I3)	0	0.25	0.75
79.	High (L3)	High (C3)	High (P3)	Low (I1)	0.25	0	0.75
80.	High (L3)	High (C3)	High (P3)	Medium (I2)	0	0.25	0.75
81.	High (L3)	High (C3)	High (P3)	High (I3)	0	0	1

3.3.2. Identification of the HEs in container terminals

Container terminals are often described as open systems of container flows within a quayside for cargo loading and/or unloading and a landside where containers are moved from or to trucks and/or trains. A stacking area for storing containers normally between the quayside and landside is equipped with various facilities for the decoupling of the quayside and landside operations. The hazardous events investigated in this study are those that occurred in the terminal areas defined above. The risks associated with the external interfaces of the terminals such as berth and port waters are not taken into account as depicted in Figure 3.1.

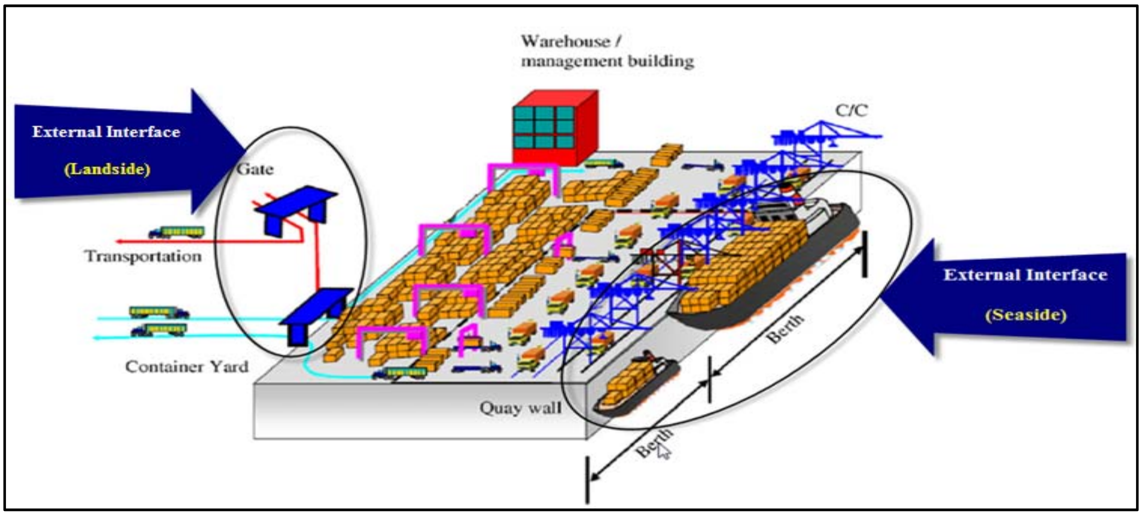

Figure 3.1: Scope of container terminal operations

In terms of container terminal operations conducted by a large number of workers and equipment in a variety of activities at different sites, safety issues are of significant importance. Regarding container terminal operational safety, the performance of different container terminals can be determined by different elements that are continuously taking into account a range of internal and external factors influencing the productivity of the system (Legato & Monaco, 2004).

The HEs associated with container terminal operations including cargo handling equipment and transport facilities were identified through a careful literature review which allowed for identification of the sources of significant hazards in container terminals and provides a good view on possible solutions to some hazards.

Therefore, the investigated HEs were taken into account from a literature review of the major HEs associated with container terminal operations in terms of consequences or severity, while others HEs were taken into account from several domain experts involved.

For example, one of the most significant HEs in terms of severity is moving the crane without raising the boom of the gantry crane, which can result in damage to the accommodation superstructure (Shang & Tseng, 2010).

Christou (1999) analysed many accidents related to fire, explosions and release of toxic materials, indicating that risk factors connected with the handling and storage of dangerous goods in port areas mainly originates from the complicated nature of the activities taking place. Darbra and Casal (2004) observed an increasing trend in the occurrence of fires, explosions, and gas cloud accident frequency during the period 1941–2002, which included 471 accidents in seaports. They concluded that the trend could be attributed to the increase in port activity and the growth of hazardous substances moving through seaports.

The HSE in 2010 identified more than fifty risk factors to help workers of the container terminal industry in various duties in GCH. According to the Pacific Maritime Association, from 2008 to 2009 the total of coast wide container terminal tonnage declined 16%, yet the injury rate increased 19%. The top eight categories of the accidents were placed in the container yard area (PMA, 2010).

The next step is the process of determining the investigated HEs is conducted by using a "What-If Analysis" technique in a brainstorming meeting with several domain experts involved. There are seven steps in performing a "What-If Analysis" technique (Golfarelli & Rizzi, 2009) as follows:

I. Define the activity or system of interest.
II. Define the problems of interest for the analysis.
III. Subdivide the activity or system for analysis.
IV. Generate what-if questions for each element of the activity or system.
V. Respond to the what-if questions.
VI. Further, subdivide the elements of the activity or system (if necessary).
VII. Use the results in the decision-making process.

The preliminary study of determining the investigated HEs took place in July 2012 in the UK with seven safety and security officers, port managers and scholars. Further, in September 2012, another meeting took place in the Kingdom of Saudi Arabia (KSA) with five safety and security officers and port managers to further study the investigated HEs.

The experts selected, based on their experience in Table 3.3, have been actively working in container terminals and/or researching on container terminals for over 20 years.

During the meetings, they identified the major threats and impacts posed by 76 risk sources and hazard events in container port operations. Consequently, a hierarchy of 24 significant hazards and the origin of their types in terms of container terminal operations is constructed and presented in the following list. The graphical presentation of the hierarchal structure is depicted in Figure 3.2.

Table 3.3: Experts' knowledge and experience

Experts	Position	Company	Working Experience
1	Senior operational managers	A leading port in the UK	Involved in port safety and operational services
2			
3	A professor, Head of port management studies and Director of maritime research institute	A university in the UK	Involved in maritime safety, port operational management and container supply chain management
4	A senior lecturer in maritime transportation, marine engineering and qualified chief engineer	A university in the UK	Involved in maritime port/ship operations and port safety and security management
5	A senior safety and security officer	A leading port in the UK	Involved import safety and operational services
6	Senior security officers	A leading port in the UK	Involved in container customs and border protection
7			
8	Head of safety department	A leading port in the KSA	Head of safety department in several container terminals worldwide
9	Deputy safety manager	A leading port in the KSA	Fleet safety and security officer
10	An assistant terminal manager	A leading port in the UAE	Operations manager in UAE and employed as vessel planner, and vessel operations manager

11	A harbourmaster and qualified master mariner	A leading port in the UAE	Safety officer in a number of container terminals worldwide and some shipping companies
12	A safety officer	A leading port in the KSA	Involved in container terminal safety operations and assigned in many leading ports in KSA as a safety officer

1) Collision between Rail-Mounted Gantry (RMG) crane and Trailer (CRMGT).
2) Collision between Rubber-Tired Gantry (RTG) crane and Trailer (CRTGT).
3) Collision between Straddles Carriers (SC) and Rubber-Tired Gantry crane CRTGSC).
4) Collision between the Quay Crane and the Ship (CQCS).
5) Collision between two Quay Cranes (CQC's).
6) Crane Breakdown due to human error (CBD).
7) Moving the Crane Without Raising the Boom (Lifting Arm) of the Gantry Crane (MCWRLAGC).
8) Leakage/ Emission of Dangerous Goods from a Container (LEDGC)
9) Ignition Sources from Equipment near Dangerous Goods premises (ISEDG).
10) Person Falls from height due to being too Near to Unprotected Edges (PFNUE).
11) Person falls from height due to Non-Provision or Maintenance of safe access between adjacent Cargo Bays (PFNMCB).
12) Person Slips, trips, and falls whilst working on Surfaces that are Not Even (PSNE).
13) Person Slips, trips, and falls whilst working on surfaces with Presence of Leaking Cargo (PSPLC).
14) Person Slips, trips, and falls whilst Working on surfaces with presence of water or Ice (PSWI).
15) Person Slips, trips, and falls whilst working on Surfaces with presence of Oils (PSO).
16) Person Struck by Falling Object(s) (PSFO).
17) Person handling Dangerous Goods in containers that have Not been Declared (PDGCND).
18) Person Struck by Quay Crane (PSTQC).
19) Person Struck by Straddle Carrier (PSTSC).
20) Person Struck by Chassis-Based transporters (PSTCB).
21) Person Struck by Truck (PSTT).
22) Person Crushed against a Fixed object and Ship or terminal structure (PCFS).

23) Person Crushed against a Fixed object and stacked containers and Suspended containers (PCFC).

24) Person crushed against a fixed object and closing the twin lift container spreaders (PCB).

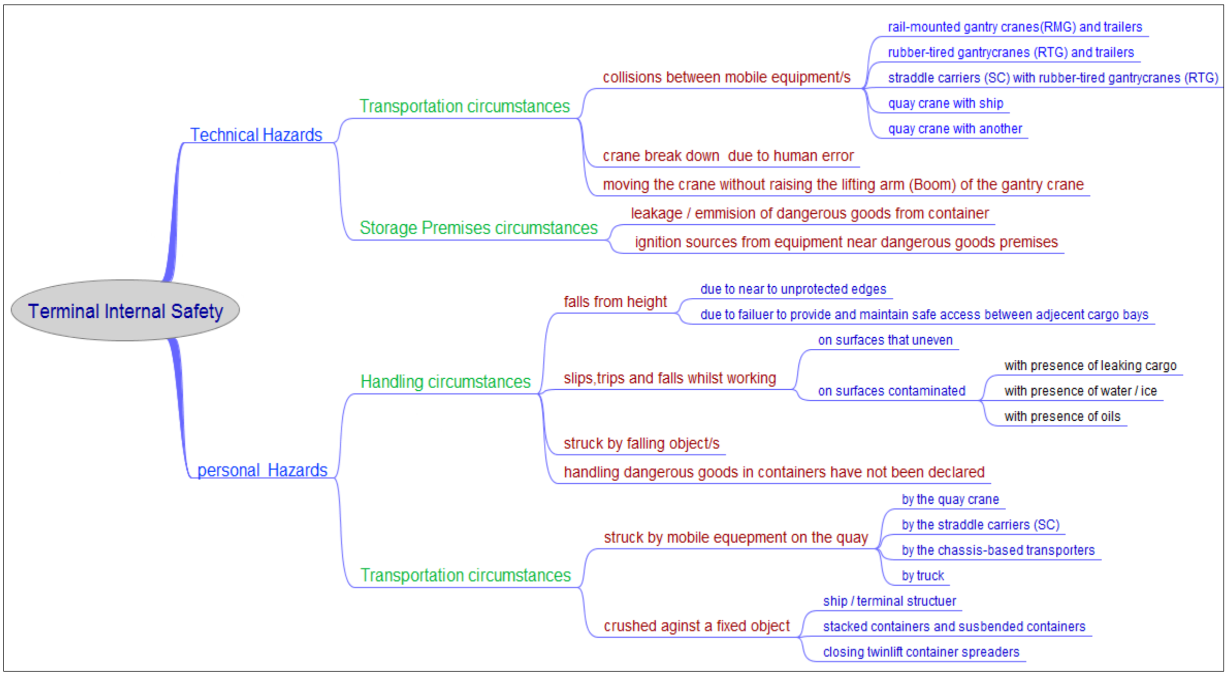

Figure 3.2: Hierarchy of 24 significant hazards of container terminal operations

3.3.3. Development of FRBN model

3.3.3.1. Rule aggregation for prior probability of HEs

Due to the possible uncertainty involved, some HEs inputs may be fed to the FMEA modelling using the defined linguistic grades with DoBs, such as *High with a 50% DoB* and *Medium with a 50% DoB*. That means that multiple rules will be employed in risk evaluation of a particular HE, requiring a powerful tool capable of synthesising the associated DoBs in the THEN portions of the different rules involved. The ability of BN to capture non-linear causal relationships, and modelling DoBs in the THEN portion of FRB, has been widely known (Yang et al., 2008). To use BN, the FRB developed in Section 3.3.1 needs firstly to be represented in the form of conditional probabilities. For example, Rule 2 in Table 3.2 can be displayed as follows:

$Rule_2$: IF *Low* (L_1), *Low* (C_1), *Low* (P_1) and *Medium* (I_2),

THEN {(0.75, *Low* (R_1)), (0.25, *Medium* (R_2)), (0, *High* (R_3))}.

It can be further expressed in the form of conditional probability as follows:

Given L_1, and C_1, P_1 and I_2, the probability of the risk evaluation for each linguistic term (Rh) where Rh ($R_1 = Low$, $R_2 = Medium$, $R_3 =$ High) is (0.75, 0.25, 0) or

$p\ (Rh|L_1, C_1, P_1, I_2) = (0.75, 0.25, 0)$ 3.4

where "|" symbolises conditional probability.

Port risk analysts can evaluate a HE using their subjective judgments based on real observations with respect to the four risk parameters and their associated linguistic grades. Averaging the DoBs assigned by multiple experts to the linguistic grades of each parameter enables the calculation of the prior probabilities $p(L_i)$, $p(C_j)$, $p(P_k)$ and $p(I_l)$ of the four parent nodes, *NL, NC, NP* and *NI*.

3.3.3.2. Bayesian reasoning mechanism

Using a BN technique, the FRB constructed in FMEA of CTRE can be modelled and converted into a five-node converging connection that includes the four parent nodes N_L, N_C, N_D, and N_I (Nodes *L*, *C, D,* and *I*) and the child node N_R (Node *R*). Having transferred the rule base into a BN framework, the rule-based risk inference for the failure criticality analysis will be simplified as the calculation of the marginal probability of the child node N_R from the four parent nodes, N_L, N_C, N_P, and N_I.

To marginalise *R*, the required conditional probability table of N_R, $p\ (R|L, C, D, I)$, can be obtained using Table 3.2. It denotes a 3×3×3×3 table containing values $p\ (Rh|Li, Cj, Dk, Il)$ ($h, i, j, k, l = 1, \ldots, 3$). The marginal probability of N_R can be calculated as

$$p(Rh) = \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{l=1}^{3} p(Rh \mid Li, Cj, Dk, Il)\, p(Li)\, p(Cj)\, p(Dk)\, p(Il)$$

$Rh\ (R_1 = Low, R_2 = Medium, R_3 = High)$ 3.5

3.3.3.3. Utility functions for HEs ranking

The overall belief structure provides a panoramic view that shows the ratings and intervals for each HE assessment with the DoBs assessed. However, in practical reality, the risk priority of HEs cannot be easily determined by analysing their overall belief structures. Thus, the overall belief structures need to be converted into expected risk scores.The main aim of using a utility function is to prioritise the HEs and Rh (h = 1, …, 3) requires the assignment of appropriate utility values U_{Rh}. The utility values can be defined as U_{R1} = 1, U_{R2} = 10 and U_{R3} = 100. A new HE priority/Ranking Index *(RI)* can be developed as

$$RI = \sum_{h=1}^{3} p(Rh)U_{Rh} \tag{3.6}$$

where the larger the value of *RI* is, the higher the RE of potential HE.

3.3.3.4. Prioritisation of the HEs using the new FRBN

Based on the results of the HE priority/Ranking Index (*RI)* it can be easily nominating the most significant HE that have great impact on the safety of the container terminal operations. The higher the value of RI for HE the higher the risk on container terminal safety performance. Therefore, an effective measure should be applied to reduce or mitigate the risk.

3.3.3.5. Model validation process

A new proposed engineering model requires testing to ensure its reliability and sound applicability for applications. Testing is important, especially in the involvement of subjective elements in the generated methodology (Yang et al., 2008). One of the most popular mechanistic validation methods available for a methodology that has not been broadly used in practice is sensitivity analysis, which is conducted to test the accuracy of the belief structures based on subjective judgments.

Testing the sensitivity in the FRBN method provides an analytical value judgment for the conclusions risk estimate *RI* or the safety index. Parameter sensitivity is usually performed as a series of tests in which the modeller sets different parameter values to measure the changes caused by a change in the risk parameter (Lucia & Mark, 2001). There are two possible axioms that can be used as a mechanism for validating the proposed BN model (Yang et al., 2008; Jones et al., 2010), which are listed below. Denote that the axiom can vary depending on the study of interest and universally accepted as a principle or rule of statements that are taken to be true within the system of logic defined and self-evident truth that requires no proof.

Axiom 1. A slight increase or decrease in the prior subjective probabilities of each input node should certainly result in the effect of a relative increase or decrease of the posterior probability values of the output node.

Axiom 2. The total influence magnitudes of the combination of the probability variations from x attributes (evidence) on the values should be always greater than the one from the set of $x - y$ ($y \in x$) attributes (sub evidence).

3.4. Red Sea Gateway Terminal Company (RSGT) case study

This section will demonstrate the applicability and the visibility of the FRBN method, along with the selected RSGT to conduct the CTRE. In order to evaluate the internal container safety as related to transportation issues, the five-step methodology presented in Section 3.3 is used.

3.4.1. Establishment of fuzzy rule base with belief structure

The FRB established in Section 3.3.2 is used in this study. The FRB provides a rational distribution of the DoB as well as transparency and low complexity in the risk parameters. It has the advantage of increasing flexibility in the definition of the DoB distributions in individual rules to enable an easy validation by experts and the possibility of inserting additional rules based on the experts' experience, especially in areas that have not been covered by measurements.

3.4.2. Identification of the HEs in RSGT

Five sufficiently experienced safety officers and managers of the RSGT contributed their ideas and opinions on developing a scientific model and determining the HEs in their terminal. The experts selected are actively working at RSGT. Their knowledge is described in the following summaries:

Expert A has been working in container terminal industry for over twenty years. He is primarily involved in container terminal risk analysis. He became the head of the safety department in several container terminals worldwide including in the United Kingdom, Ghana, India, and Saudi Arabia.

Expert B has been working in the container terminal industry for over twenty years. He started his career as a management trainee at the Islamic Port of Jeddah in 1985. He worked in a number of shipping companies as a fleet safety and security officer from 1986 to 2000. Since 2000 he has been working as the deputy safety manager in container terminal companies.

Expert C has been working in the container terminal industry for over forty years. He was an Operations Manager at the Dubai World Container Terminal until 1994. Since 1995, he has been employed by the Gulf Shipping as an assistant terminal manager, a vessel planner, and a vessel operations manager and in the past three years as the head of the security department of RSGT.

Expert D has been working in the container terminal industry for over fifteen years. He worked in a number of container terminals worldwide and some shipping companies from 1990 to 2005. He is a qualified master mariner.

Expert E has been working in the container terminal industry for over fifteen years. He is primarily involved in container terminal safety operations and has been assigned in many Saudi Arabian ports as a safety officer.

A questionnaire is designed to identify the HEs. Noted that some of the existing HEs identified in this study were audited specifically for RSGT characteristics, listed as follows:

1. Collision between Terminal Tractor (TT) and trailer.
2. Collision between Rubber-Tired Gantry (RTG) crane and trailer.
3. Collision between TT and RTG.
4. Collision between quay crane and ship.
5. Collision between two quay cranes.
6. Crane break down due to human error.
7. Moving the crane without raising the Boom of the gantry crane.
8. Leakage or emission of dangerous goods from a container.
9. Ignition sources from equipment near dangerous goods premises.
10. Person falls from height due to being too near to unprotected edges.
11. Person falls from height due to non-provision or maintenance of safe access between adjacent cargo bays.
12. Working on surfaces that are not even.
13. Person slips, trips, and falls whilst working on surfaces with presence of leaking cargo.

14. Person slips, trips, and falls whilst working on surfaces with presence of water or ice.
15. Person slips, trips, and falls whilst working on surfaces with presence of oils.
16. Person struck by falling object/s.
17. Person handling dangerous goods in container that has not been declared.
18. Person struck by quay crane.
19. Person struck by Terminal Tractor (TT).
20. Person struck by rubber-tired gantry (RTG) crane.
21. Person struck by truck.
22. Person crushed against a fixed object and ship or terminal structure.
23. Person crushed against a fixed object and stacked containers.
24. Person crushed by closing the twin lift container spreaders.

In the questionnaire, the experts are requested to evaluate each of the 24 significant HEs identified with respect to the four risk parameters using their associated linguistic grades and DoBs.

3.4.3. Development of FRBN model

3.4.3.1. Rule aggregation for HEs prior probability

The feedback received from the five experts is first combined (by conducting an average calculation) to produce HEs input values in terms of the four risk parameters. The averaged HEs input is then used in the new FRBN in Section 3.3 based on the new FRB with rational DoBs in Section 3.3.1 to rank the 24 HEs.

Given the Equation 3.4, the prior probabilities of the four nodes in BN based FMEA can be obtained. For example, to evaluate HE1, *Collision between Terminal Tractor (TT) and* Trailer (CTTT), the HE input values in terms of the four risk parameters are obtained from the experts then the prior probabilities of the four nodes can be calculated, as shown in Table 3.4.

Table 3.4: Prior Probabilities of NL, NC, NP, and NI when evaluating CTTT

Attributes / HE	Experts	Probability of failure/ Likelihood			Probability of failures being undetected			Consequences/ Severity			Impact of the HE on the resilience of port operational systems		
		H	**M**	**L**	**H**	**M**	**L**	**H**	**M**	**L**	**H**	**M**	**L**
Collision between Terminal Tractor (TT) and trailer	**A**	**100**	**0**	**0**	**40**	**40**	**20**	**80**	**20**	**0**	**30**	**30**	**40**
	B	**90**	**5**	**5**	**50**	**50**	**0**	**70**	**20**	**10**	**40**	**40**	**20**
	C	**100**	**0**	**0**	**40**	**40**	**20**	**85**	**10**	**5**	**40**	**40**	**20**
	D	**95**	**5**	**0**	**50**	**40**	**10**	**90**	**10**	**0**	**50**	**50**	**0**
	E	**80**	**20**	**0**	**55**	**25**	**20**	**95**	**5**	**0**	**50**	**50**	**0**
	Prior Probability	**93**	**6**	**1**	**47**	**39**	**14**	**84**	**13**	**3**	**42**	**42**	**16**

3.4.3.2. Bayesian reasoning mechanism

Once the previously identified probabilities of the four nodes in BN based FMEA are obtained in Table 3.4, it can be converted to obtain *p* (*Rh|Li, Cj, Pk, Il*) and the RE of CTTT can be calculated by the Equation 3.5 as *p* (*Rh*) = {(8.5% Low, 25% Medium, 66.5% High)}. The calculation can be computerised using the *Hugin* software (Anderson et al., 1990), as shown in Figure 3.3.

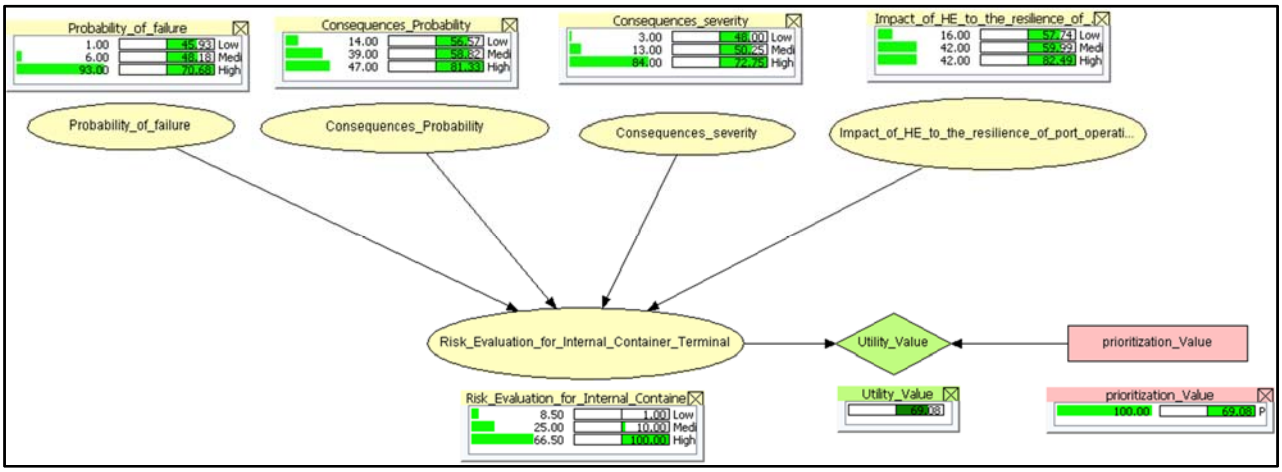

Figure 3.3: Risk evaluation of CTTT using Hugin software

3.4.3.3. Utility functions for HEs ranking

The result can be explained as the RE of CTTT being low with an 8.5% DoB, medium with a 25% DoB and high with a 66.5% DoB. Next, the Equation 3.6 is used to calculate the risk ranking index value of CTTT as 69.1 (= 8.5% × 1 + 25% × 10 + 66.5% × 100).

Similarly, the ranking index values of all the 24 HEs can be obtained and presented in Table 3.5.

Table 3.5: Risk ranking index values of HEs

HE#	HEs	Risk evaluation			Ranking index
		Low	Medium	High	
1.	Collision between Terminal Tractor (TT) and trailer.	8.5	25	66.5	69.1
2.	Collision between Rubber-Tired Gantry (RTG) crane and trailer.	17.75	25.25	57	59.7
3.	Collision between TT and RTG.	19.56	18.12	62.32	64.3
4.	Collision between quay crane and ship.	13.25	13.25	73.5	75
5.	Collision between two quay cranes.	18.75	8.5	72.75	73.8
6.	Crane breakdown due to human error.	23.5	5.5	71	71.8
7.	Moving the crane without raising the Boom of the gantry crane.	24.75	9.75	65.5	66.7
8.	Leakage/ emission of dangerous goods from a container.	41	11.25	47.75	49.3
9.	Ignition sources from equipment near dangerous goods premises.	35	27.5	37.5	40.6
10.	Person falls from height due to being too near to unprotected edges.	25.5	22.75	51.75	54.3
11.	Person falls from height due to non-provision / maintenance of safe access between adjacent cargo bays.	19	21	60	62.3
12.	Working on surfaces that are not even.	23	18.5	58.5	60.6
13.	Person slips, trips, and falls whilst working on surfaces with presence of leaking cargo.	22	11.25	66.75	68.1
14.	Person slips, trips, and falls whilst working on surfaces with presence of water / ice.	25	15.25	59.75	61.5

15.	Person slips, trips and falls whilst working on surfaces with presence of oils.	23.25	8.5	68.25	69.3
16.	Person struck by falling object/s.	28.5	22.5	49	51.5
17.	Person handling dangerous goods in container that has not been declared.	43.5	12.5	44	45.7
18.	Person struck by quay crane.	44.5	7.75	47.75	49
19.	Person struck by Terminal Tractor (TT).	45.24	16	38.75	40.8
20.	Person struck by rubber-tired gantry crane (RTG).	43.5	15.75	40.75	49
21.	Person struck by trucks.	38.5	22	39.5	42
22.	Person crushed against a fixed object and ship / terminal structure.	41	16.25	42.75	44.8
23.	Person crushed against a fixed object and stacked containers.	37.75	23.25	39	41.7
24.	Person crushed by closing the twin lift container spreaders.	53	16.25	30.75	32.9

3.4.3.4. Prioritisation of the HEs using the new FRBN

Based on the results shown in Table 3.5, the most significant HEs can be prioritised as follows:

- Collision between the quay crane and the ship (HE4).
- Collision between two quay cranes (HE5).
- Crane break down due to human error (HE6).
- Person slips, trips and falls whilst working on surfaces with presence of oils (HE15).
- Collision between Terminal Tractor (TT) and trailer (HE1).
- Person slips, trips and falls whilst working on surfaces with presence of leaking cargo (HE13).
- Moving the crane without raising the Boom (lifting arm) of the gantry crane (7).

3.4.3.5. Model validation process

The model of an engineering problem needs to be verified. The accuracy of the previous analysis result and the reliability of the model can be tested using validation techniques. A sensitivity analysis has been carried out to validate the reliability of the developed approach. In this chapter, the model with its simulation as illustrated in Figure 3.4 would be verified with the aim of satisfying the two axioms involved in the process described in Section 3.3.3.5. The examination of the model is conducted for CTTT as follows:

By setting the prior probability value of the node " consequences severity " to 100% "$High$", the posterior probability value of the output "$Risk\ Evaluation = High$" increases from 66.5% to be 70.5% respectively as shown in Figure 3.4.

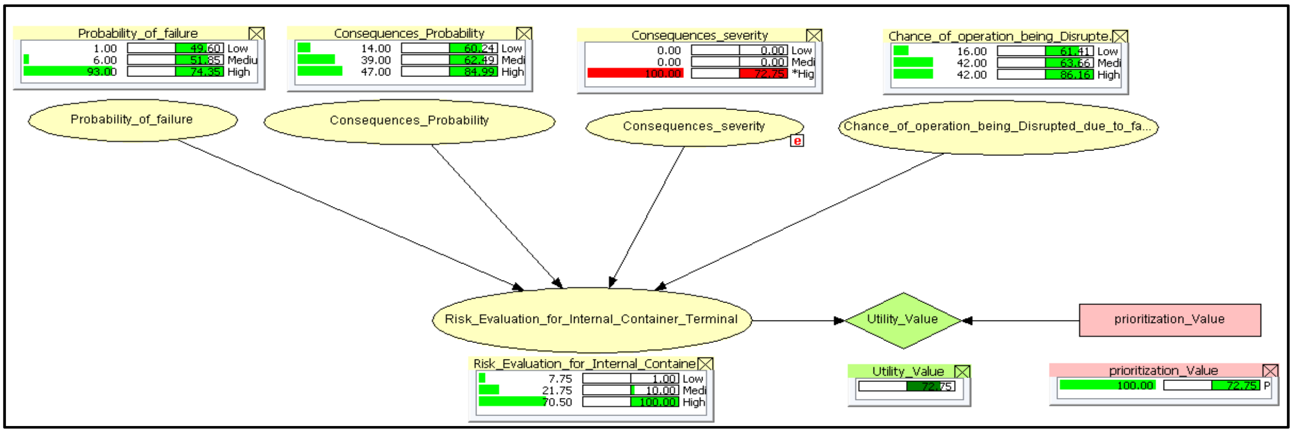

Figure 3.4: The evaluation of RE given a piece of evidence to "C=100% High" to HE1

The change that took place in Figure 3.4 and further change to the node "The impact of the HE on the resilience of port operational systems" when set to 100% "$High$" resulted in a further increase of the posterior probability value of the output "$Risk\ Evaluation = High$" from 66.5% to be 81% respectively as shown in Figure 3.5.

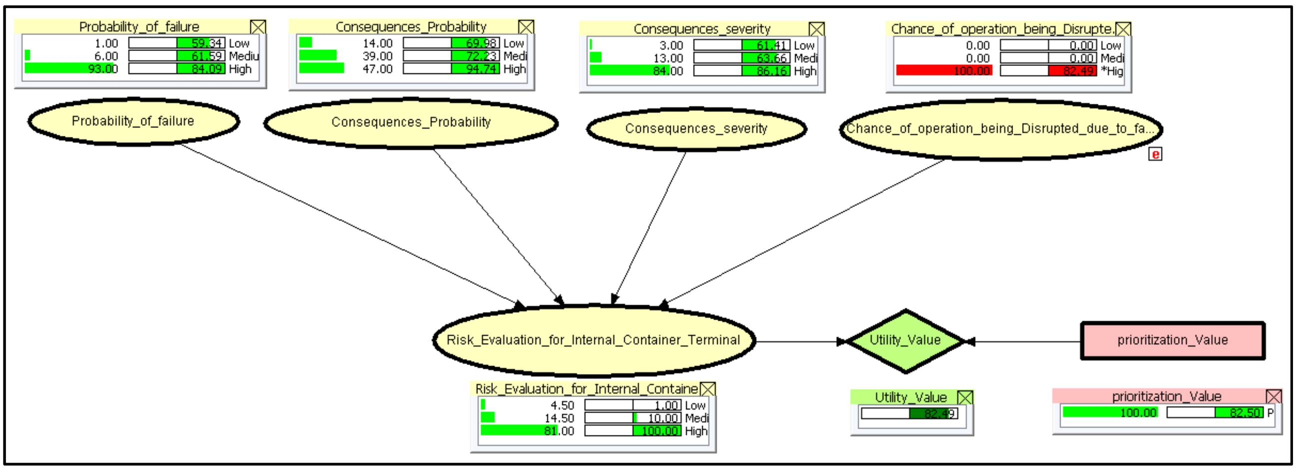

Figure 3.5: The evaluation of RE given evidence to "C=100% High and R=100% High" to HE1

Incorporating the changing of the previous probability values described in Figure 3.5 with the additional change of the node “$Probability\ of\ failure$” to 100%“$High$” also resulted in yet a further increase of the posterior probability value of the output “$Risk\ Evaluation = High$” from 66.5% to 86.75% respectively as shown in Figure 3.6.

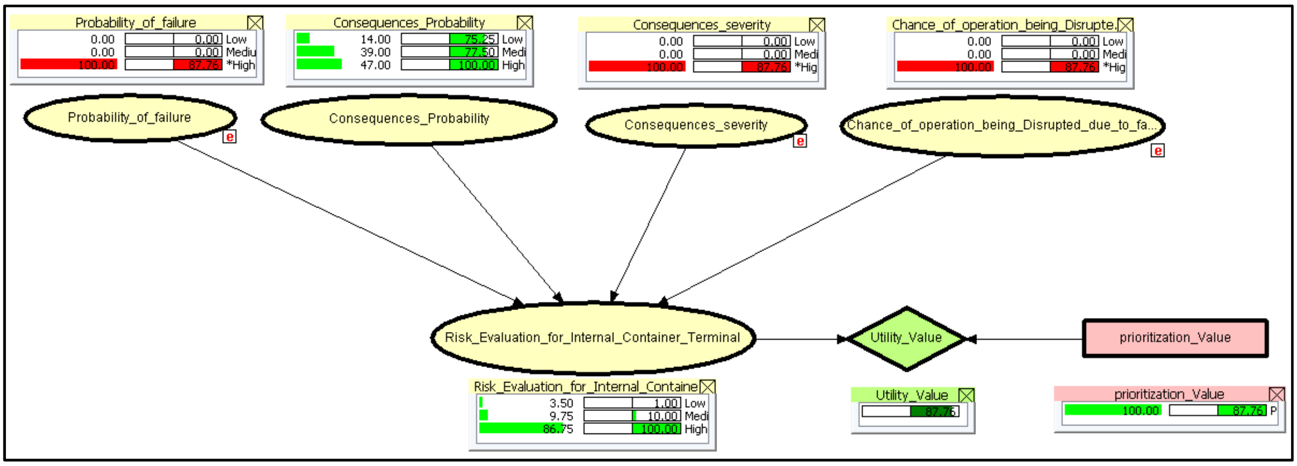

Figure 3.6: The evaluation of RE given evidence to “C =100% High, R =100% High and D =100% High” to HE1

The three figures described in this step suggest that the output node is sensitive to the change of the previous probability values of the input nodes. Furthermore, explanations of the model validation process are described as follows:

Axiom 1: The output value of “$Risk\ Evaluation$=High” in Figure 3.4 is greater than the posterior probability value in Figure 3.3, which suggests that a slight change in the prior probability value of each input node resulted in the effect of the relative increase or decrease of the posterior probability values of the output node.

Axiom 2: The output value of “$Risk\ Evaluation$=High” in Figure 3.5 is higher than the output values in Figures 3.3 and 3.5, suggesting that the total influence magnitude of the combination of the probability variations from two attributes on the values is always greater than one attribute.

Axiom 3: The output value of “$Risk\ Evaluation$=High” in Figure 3.6 is higher than the output values in Figures 3.4 and 3.5, indicating that the total influence magnitude of the combination of the probability variations from three attributes on the values is always greater than two attributes and one attribute.

3.5. Results and Discussion

The HEs associated with container terminal operations may vary, depending on the unique safety characteristics of an individual container terminal. For the investigated container terminal, the new FRBN method delivers the result as shown in Table 3.6, through which the HE4 of a collision between a quay crane and a ship is the most significant, followed by HE5 (*collision between two quay cranes*), HE6 (*crane break down due to human error*), HE15 (*person slips, trips, and falls whilst working on surfaces with presence of oils*), HE1 (*collision between Terminal Tractor (TT) and trailer*), HE13 (*person slips, trips, and falls whilst working on surfaces with presence of leaking cargo*) and HE7 (*moving the crane without raising the Boom (lifting arm) of the gantry crane*).

Table 3.6: Most significant HEs in Red Sea Gateway Terminal

HE #	HEs	Risk Evaluation			Ranking Index
		Low	Medium	High	
4.	Collision between quay crane and ship.	13.25	13.25	73.5	75
5.	Collision between two quay cranes.	18.75	8.5	72.75	73.8
6.	Crane breakdown due to human error.	23.5	5.5	71	71.8
15.	Person slips, trips, and falls whilst working on surfaces with presence of oils.	23.25	8.5	68.25	69.3
1.	Collision between Terminal Tractor (TT) and trailer.	8.5	25	66.5	69
13.	Person slips, trips, and falls whilst working on surfaces with presence of leaking cargo.	22	11.25	66.75	68.1
7.	Moving the crane without raising the Boom (lifting arm) of the gantry crane.	24.75	9.75	65.5	66.7

3.6. Conclusion

System safety analysis often requires the use of domain experts' knowledge when risk records are incomplete. The combination of fuzzy set modelling and BNs, notably FRBN, provides an effective tool to incorporate subjective judgments for characterising a criticality analysis on prioritising failures in FMEA under uncertainty. The new mechanism proposed to rationalise the DoB distribution of FRB by employing the same set of input and output data and facilitate its implementation in CTRE in practice. Compared to the conventional FMEA, this chapter also shows that the new method is capable of presenting sensitive and flexible risk results in real situations by simplifying the description of fuzzy failure information, improving both the accuracy and visibility of FMEA.

More importantly, it provides a powerful risk evaluation tool for port safety management. The proposed method highlights its potential in facilitating risk analysis of system design and operations in a wide context when being appropriately tailored to use in other container ports. Managerial, policy implications, and natural and political factors can also be investigated in a similar way in order to provide a panoramic view on terminal risk analysis.

Chapter 4 — Modelling Container Terminal Operation System (CTOS)

Summary

Globalisation has led to a rapid increase of container movements in seaports. Risks in seaports need to be appropriately addressed to ensure economic wealth, operational efficiency, personnel safety, and terminal security. As a result, the safety performance of the CTOS plays a growing role in improving the efficiency of international trade, maritime safety, and environmental protection. This chapter proposes a novel method to facilitate the application of FMEA in assessing the safety performance of CTOS. The new approach is developed through incorporating an FRBN developed in chapter 3 with ER in a complementary manner. The former provides a realistic and flexible method to describe input failure information for risk estimates of individual HEs at the bottom level of a risk analysis hierarchy. The latter is used to aggregate HEs safety estimates collectively, allowing dynamic risk-based decision support in CTOS from a systematic perspective. The novel feature of the proposed method, compared to those in traditional port risk analysis, lies in a dynamic model capable of dealing with continually changing operational conditions in ports. More importantly, a new sensitivity analysis method is developed and carried out to rank the HEs by taking into account their specific risk estimations (locally) and their RI to a port's safety system (globally). Due to its generality, the new approach can be tailored for a wide range of applications in different safety and reliability engineering and management systems, particularly when instant risk ranking is required to measure, predict, and improve the associated system safety performance. In addition, the stakeholders should realise that a CTOS value depends on many variables. Therefore, in order to correct any deviation on time, it has to be evaluated appropriately and regularly.

4.1. Introduction

Maintaining safe and reliable operations in container terminals is of great significance for the protection of human life and health, the environment, and the economy. The adequate and correct functioning of container terminal operations has a profound impact on productivity, cost, and quality. Therefore, a system evaluation that includes the early detection of hazards is critical in avoiding performance degradation and damage to human life or machinery. Furthermore, accidents or disasters that would jeopardise the terminal operations will be avoided if a robust evaluation system forecasting mechanism is developed and effectively enforced.

In practical situations, most engineering systems are repairable and their safety measures change with time; by considering these changes as a time-series process, the “growth” or “deterioration” of the system can be evaluated and improved (Hu et al., 2010). The necessity and importance of evaluating the system safety lies in that decision makers are generally interested in estimating future occurrences of system failures for resource planning, inventory management, development of realistic policies for age replacement, and logistics support.

The IMO aims to enhance maritime operation safety, including protection of life, health, marine environment, and property. As a result, the FSA was approved in 2002 and used as a rational and systematic process for assessing the risks associated with shipping activities and for evaluating the costs and benefits. Furthermore, the World Economic Forum (2014) also emphasised the need towards a structured evaluation of risks on critical maritime systems in order to ensure the safety, security, and resilience of their operations. An accurate risk management system can not only monitor safe operation performance and reliability but also offer valuable information for decision makers to use to take the correct actions in order to improve the quality and reduce the cost of their systems (Hu et al., 2010).

The incapability of traditional quantitative risk analysis methods such as FMEA in addressing uncertainty in data in many contexts has stimulated the development of new methods based on uncertainty treatment theories such as fuzzy logic, D-S theory, grey theory, Monte Carlo simulation, BN, Markov model, and artificial neural network (Yang et al., 2008). Most of the current modelling schemes in FMEA were developed using linear or nonlinear multiple regression which is comparatively reliable. However, in many circumstances they may not perform well in terms of accuracy or speed, and suffer from a number of drawbacks such as lack of suitable models, exceptional assumption used in analysis due to the lack of applicable safety related data/records and a high level of uncertainty involved in the available failure data (Sii *et al.,* 2001). The incapability of traditional FMEA in addressing uncertainty in data in particular contexts has stimulated the development of new methods based on uncertainty treatment theories such as fuzzy logic, ER, grey theory, Monte Carlo simulation, BN, Markov model, and artificial neural network (Yang *et al.*, 2008). Safety evaluation and risk analysis involving MADM have also been developed by a large community of researchers.

Many decision problems in engineering and management systems involve multiple attributes of both a quantitative and qualitative nature with uncertain or missing information that causes complexity in multiple attribute assessment (Yang & Xu, 2002). Researchers have paid increasing attention to MADM models in a wide variety of practical applications that have evolved the assessments process. Examples of practical applications include urban and community planning; resource allocation; supplier evaluation; employee/organisation evaluation; marketing strategies; credit analysis; and engineering design evaluations including safety management (Eom, 1989; Eom & Lee, 1990; Eom et al., 1998). Specific applications of MADM can found in the functional assessment for disability index and the ergonomics consultation (Jen & Min, 1994), the restoration planning for power distribution systems (Chen, 2005), the evaluation of the suitability of manufacturing technology (Chuu, 2009), expert systems (Beynon et al., 2001), and motorcycle evaluation (Yang & Xu, 2002b). In recent years, different risk analysis models involving MADM have been proposed to evaluate and predict system safety and reliability. Examples of such models include a marine system safety assessments approach (Wang et al., 1995, 1996), a belief function model (Srivastava & Liu, 2003), a model for strategic research and development project assessments (Liu et al., 2008), a nonlinear programming model (Zhou et al., 2010) and failure mode and effects analysis using fuzzy evidential reasoning approach and grey theory (Liu *et al*., 2008b). Thus, MADM has been increasingly used in safety management and risk analysis.

In engineering risk analysis practice, safe operation is a fundamental attribute of system reliability for any modern technological system. Focusing on container operation safety, evaluation process and risk analysis aims at the quantification of the probability of the failure of the system. However, the task is not straightforward given the challenges, including that container operations are affected by multiple factors related to their capacity, workforce, machinery, management, and geographical location that deal with both numerical data and qualitative information with uncertainty. Therefore, rational decision analysis is essential to properly represent and use uncertain information in the aforementioned factors to enhance container terminal safe operation.

In container terminals as such and for a similar complex engineering system, safety evaluation and risk analysis problems involve quantitative data and qualitative information, as well as various types of uncertainties such as incompleteness and fuzziness. As a result, under these circumstances, there is an urgent need to develop a new safety management method for container terminals that can efficiently deal with various types of uncertainties and overcome the aforementioned drawbacks.

This chapter aims to develop a novel method to facilitate the application of the FMEA approach in port safety analysis through incorporating MADM approaches (*i.e.* ER with FRBN) to prioritise each HE's safety level individually in a container terminal and then to aggregate them collectively to evaluate the safety performance of CTOS as an entity and quantify the HE's safety impact to the system accordingly. The True Risk Influence (TRI) for each HE is assessed taking into account their specific local risk estimations and their RI to a port's safety system is then prioritised accordingly to facilitate the subjective safety based decision-making modelling for container terminal safety. The novelty of this method, compared to the relevant studies in the literature, primarily lies in that a) it for the very first time incorporates risk impact of components to the whole system into risk quantification of ports; b) it combines various uncertainty models, such as fuzzy Bayesian for HEs' risk estimate and ER for risk synthesis from components to system levels, in a systemic way and c) it newly uses a "max and min" DoB (degree of belief) allocation approach to measure the risk reduction of a port system due to the best and worst safety performance of the investigated HE so as to test the sensitivity of the model and to prioritise hazards from both their own risk as well as their impacts on the system safety. From a theoretical perspective, the proposed hybrid method can be tailored for risk prioritisation of any large engineering system of similar features (*i.e.* a hierarchical risk structure).

This chapter develops a novel method to facilitate the application of the FMEA approach in port safety analysis through incorporating MADM approach (i.e., ER) with FRBN (Alyami et al., 2014) developed in chapter 3 to prioritise each HE's safety level individually in a container terminal and then to aggregate them collectively to evaluate the performance of CTOS as an entity and quantify the HE's safety impact to the system accordingly. To achieve this aim, this chapter is organised as follows. An analytical overview of MCDM methods including ports and container terminals risk analysis is carried out in Section 4.2. A brief review of ER in MADM in particular concerning its wide application in academia including risk analysis and safety management and an ER algorithm explanation is conducted in Section 4.3. A novel modified FMEA framework capable of integrating different weights of risk parameters into ER and the aggregation process is described in Section 4.4. A particular test case regarding CTOS of RSGT is investigated to demonstrate the feasibility and applicability of the proposed methodology in Section 4.5. Section 4.6 develops a discussion based on the results obtained. Section 4.7 concludes the chapter. Consequently, this study contributes to facilitating FMEA applications for enhancing container terminals risk management in a situation where uncertainty in historical failure data is high and traditional probabilistic risk analysis methods relying on complete data are not applicable.

4.2. Research Background

4.2.1. A brief review of research on Evidential Reasoning

The theory of evidence first presented by Dempster (1967) went through many modifications and improvements by Shafer (1972, 1976); often it is referred to as Dempster - Shafer theory of evidence or D-S theory. Originally, it was used for information aggregation in expert systems as an approximate reasoning tool (Buchanan & Shortliffe, 1984; Lopez de Mantaras, 1990). Thereafter it has been used in decision-making under uncertainty (Yager, 1992; 1995).

ER was developed in the 90s to deal with MCDM problems under uncertainty based on the D-S theory. The use of ER (Evidential Reasoning) as a decision making tool has been widely reported in the literature and has been developed by a large community of researchers.

The major advantage, and perhaps the most important for applying ER to decision analysis, is to incorporate ER into traditional MCDM methods (Beynon et al., 2001). One realistic way to analyse unavailable data is to employ subjective assessment using the combination of fuzzy logic and an ER. The ER approach developed particularly for MCDM problems with both qualitative and quantitative criteria under uncertainty utilises individual's knowledge, expertise, and experience in the forms of belief functions (Riahi, 2010). In the ER approach, evidence is represented by DoB and then all pieces of evidence are aggregated to obtain the results. Unlike the traditional MADA methods, ER approach as a combination of the D-S theory (Dempster, 1967; Shafer, G., 1976) with a distributed modelling framework can provide engineering precision and logic on modelling complex MADA problems.

In respect to traditional weighting MCDM methods, compared to ER, the criteria aggregation process is generally a non-linear process that is decided by the weights of criteria and the way each criterion is assessed. In other words, ER employs a belief structure to represent an assessment as a distribution instead of as a single numerical score and it aggregate degrees of belief rather than scores (Yang et al., 2001).

Furthermore, the ER frameworks not only provide flexibility in describing a MCDM problem, but also prevent any loss of information due to the conversion from a distribution to a single value in the modelling process (Guo et al., 2009).

In addition, ER can handle the incomplete information by establishing the utility intervals to describe the impact of missing information on decision analysis, which provides a basis for improving the quality of original data and for conducting sensitivity analysis (Riahi, 2010).

4.2.2. The applications of Evidential Reasoning

A careful literature review has disclosed that there are many ER applications in risk areas (Wang et al., 1995, 1996; Yang & Sen, 1996; Yang, 2001; Yang et al., 2005; Yang et al., 2009). Some other typical studies have made a useful contribution towards the applications of ER for representing and managing uncertainty (Yen, 1990; De Korvin & Shipley, 1993; Sönmez et al., 2001; Yang et al., 2004; Zhang *et al.*, 2005; XU et al., 2006a; XU et al., 2006b; and Riahi et al., 2012). ER developed particularly for MADM problems with both qualitative and quantitative criteria under uncertainty utilises an individual's knowledge, expertise, and experience in the forms of belief functions (Riahi, 2010). Therefore, it, together with other uncertainty modelling methods such as BNs and/or fuzzy logic, has shown superiority in tackling the diversity and uncertainty of the subjective information in general and effectively handling linguistic evaluations for risk analysis in particular. The ER algorithm, which was generated by Yang and Singh (1994) and later updated by Yang (2001) and further modified by Yang and Xu (2002b), has been applied in various domains.

Sönmez et al., (2001) presented the process of building a multiple-criteria decision model of a hierarchical structure with both quantitative and qualitative criteria to show the process of converting lower-level criterion assessments to upper-level criterion.

Tang et al., (2004) assessed the condition of a transformer by the use of ER and combined ER with a diagnosis technique to provide a meaningful and accurate diagnosis. The result showed that ER is capable of determining the condition of a transformer.

Chin et al., (2009) used the group-based ER approach to develop a risk priority model that included the assessment of the risk factors using belief structures. Thereafter, they converted the overall belief structures into expected risk scores and then ranked them using the mini-max regret approach. ER was used to model the diversity and uncertainty of the assessment information.

Hu et al., (2010) proposed a reliability prediction model based on ER to forecast reliability in turbocharger engine systems. The proposed method allows the identification of the appropriate internal representation between basic attributes associated with system prediction output to define the relationships between past historical data and the corresponding targets, which allows future output values to be predicted if the new inputs become available.

Deng et al., (2011) introduced a fuzzy evidential reasoning-based approach for risk analysis. It is assumed that the proposed method can efficiently deal with the linguistic evaluations of experts and uncertain data or information. Similarity measures between linguistic evaluation and a predefined fuzzy scale are used to derive basic probability assignments. The system risk score has been obtained using the Dumpster rule of combination based on the risk values calculated for each component of the system.

With respect to the above literature review, the major benefits of using the ER approach are listed as follows (Yang & Xu, 2002a; Riahi, 2010):

- It is capable of handling incompleteness, uncertainty, and vagueness data, as well as complete and precise data in MADA problems.
- It is able to provide the users with unlimited flexibility by allowing them to express their judgements both subjectively and quantitatively.
- It is capable of accommodating or representing the uncertainty and risk inherent in decision analysis for multiple-factor analysis.
- It is able to offer a rational and reformulated methodology to aggregate the data assessed based on its hierarchical evaluation process.
- It transforms mature computing software, and uses the Intelligent Decision System (IDS) to obtain the assessment output, which relieves the users from the lengthy and tedious model building and result analysis process using window-based click and design activity.

4.3. Methodology for Modelling CTOS

The FMEA as a hazard identification and risk analysis methods is widely applied due to its visibility and ease (Braglia et al., 2003). The method has incorporated advanced uncertainty modelling techniques such as fuzzy Sets, grey theory, BN and ER to facilitate its practical applications in maritime and offshore engineering safety (Sii et al., 2001), system reliability and failure mode analysis (Braglia et al., 2003), engineering system safety (Liu et al., 2005), and maritime port security (Yang et al., 2009).

The traditional FMEA method has three fundamental attributes, namely failure occurrence likelihood (L), consequence severity (C), and probability of failures being undetected (P) that are employed to assess the safety level of a failure (Wang et al., 1996). Among the quantitative development of FMEA, FRBN approaches using a Bayesian Network mechanism to conduct FRB risk inference in order to achieve sensitive failure priority values based on domain expert knowledge has been proposed in chapter 3 (Alyami et al., 2014).

In Alyami et al., (2014), a new risk-based decision tool for effective seaport HEs risk evaluation was developed. The development was on the rational distribution structure on DoB with the connections established between the four risk parameters and risk evaluation of the identified HEs in a container port operational system (i.e., failure occurrence likelihood (L), consequence severity (C), probability of failures being undetected (D), and the impact of a failure to the resilience of port operational systems (I)) as described in chapter 3.

The steps that are required for developing FRBN (Alyami et al., 2014) are described in Section 3.3. In this study, the risk analysis was only constrained for HEs that are located at the bottom level of a hierarchy of a port safety system. It has not really addressed the risk and safety analysis from a systematic perspective, revealing a significant research gap to fill.

The ER approach in this chapter is used for aggregating risk estimations of all the HEs based on a DoB decision matrix and the evidence combination rule of D-S theory. It uses a distributed modelling framework, in which the RE of each HE is accessed using a set of collectively exhaustive and mutually exclusive assessment grades obtained from a FRBN method.

The proposed methodology for modelling CTOS using the integrated FRBN and ER approaches can not only model the diversity and uncertainty of the assessment information in complex FMEA, but also incorporate the relative safety importance of HEs into the determination of risk priority values in a precise and logical way by conducting a sensitivity analysis. More importantly, by incorporating ER with the FRBN analysis, the RE of each HE can be investigated from both local (i.e., its own risk level) and global (i.e., its RI to the system safety) perspectives.

In order to write this chapter, a combination of different decision-making techniques, such as FRB and an ER approach (FRBER) was used. FRB technique and its mathematical background are presented in chapter 3 Section 3.3.1 while the ER technique and its mathematical backgrounds are presented later in this chapter.

The first part of evaluating the safety performance of CTOS is to prioritise HEs individually in a container terminal using the FRBN approach from chapter 3. It provides a realistic and flexible way of describing input failure information with easy update of RE and facilitates risk evaluation of HEs individually. The second part is to aggregate the HEs' REs collectively by using the ER approach, and then quantifying the HEs for risk-based decision support of CTOS as an entity (i.e., as a system). More importantly, a new sensitivity analysis method is carried out to analyse the safety importance of each HE in a whole port operational safety system. Having carefully analysed the RE of each HE locally in a port safety system using the FRBN in chapter 3, this work focuses more on the application of ER for risk aggregation and sensitivity analysis for evaluating the risk contribution of each HE globally.

4.3.1. Risk assessment for collective HEs using the ER approach

The steps for incorporating ER in FMEA in this study are described in a stepwise manner as follows.

I. *Develop a hierarchical structure to describe the CTOS safety performance.*
II. *Use the ER algorithm to synthesise the risk result of each HE for the safety estimate of the whole system.*
III. *Evaluate the risk impact of each HE on the system by using sensitivity analysis.*

I. Develop the hierarchical structure

The HEs investigated in this study are those identified through the combination of surveys, field investigation, and literature search. In Alyami et al., (2014) the 24 HEs at the bottom level were identified, while in this chapter, the hierarchy presenting their positions and relations is the focus. It is presented in Figure 4.2. The HEs identified in the hierarchical structure are those associated with container terminal operations including cargo handling equipment and transport facilities while other risk aspects such as managerial, policy implications, environmental and political issues are to be addressed in future work. During the investigation, it was found that the risk attributes used to evaluate environmental HEs such as sea level rise, flooding, and storm surge are different with those relating to operations. For instance, a key risk attribute used to estimate environmental HEs is timeframe, which is less relevant in this study. It is noteworthy that the main contribution of this research is to continue the FRBN model for the safety estimate of a whole container operational system and the risk impact analysis of each HE on the whole system.

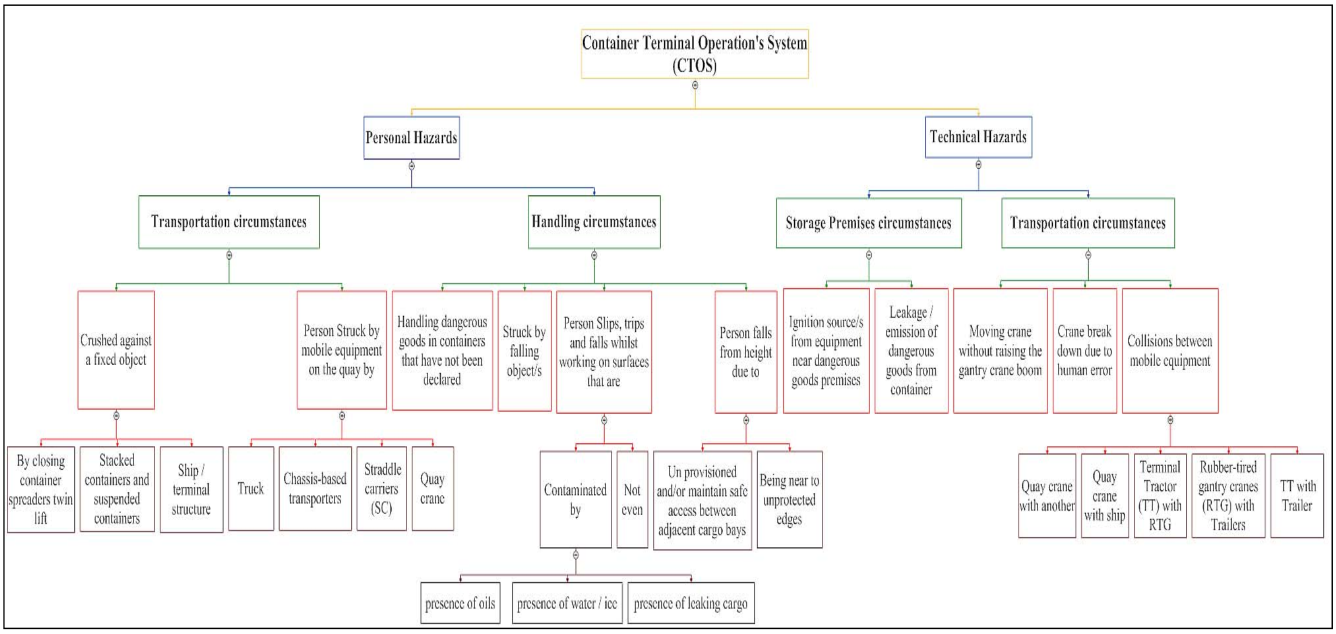

Figure 4.1: Hierarchy for the risk factors during terminal operations

II. System safety estimate by synthesising the risk result of all HEs using ER method

The REs of all the HEs can be presented in both linguistic variables with DoB and numerical values based on utility values, as the output of applying the FRBN model in Alyami et al., (2014). The result expressed by linguistics variables will be used as the input value in the ER for calculating the RE of CTOS.

The ER scheme adapted and applied in this study was first generated from Dempster (1967) and subsequently developed by Shafer (1976) to form D–S theory. The combination of D-S theory and fuzzy rule bases is an appropriate way to solve MADM problems that include fuzzy information from multiple sources. One direction is to extend D-S theory to include the feature of fuzzy set theory so that its capability can be enhanced to process both crisp and fuzzy information.

In D-S's rule of combination, suppose subsets B and C defined on θ are associated with confidence estimates m_1 and m_2 , respectively, that were obtained from two independent sources. The orthogonal sum of m_1 and m_2 is defined as follows:

$$(m_1 \oplus m_2)(A) = \frac{\sum_{B \cap C = A} m_1(B) \times m_2(C)}{1 - \sum_{B \cap C = \emptyset} m_1(B) \times (m_2)(C)} \quad (4.1)$$

ER algorithm based on the D-S theory has been developed, improved, and modified towards a more rational way by a large community of researchers by continuously researching and practicing the processes (Yang & Xu, 2002b).

The algorithm can be analysed and explained as follows. The 24 HEs identified are going to be synthesised in order to obtain the safety estimation of CTOS. Taking two HEs as an example, let S represent the set of the three safety expressions (i.e., "High", "Medium", and "Low") and be synthesised by two subsets S_1 and S_2 from different assessors. Then$S$, "S_1 and S_2 can separately be expressed by:

$$S = [(DoB_s\ , Low), (DoB_s\ , Medium), (DoB_s\ , High)] \quad (4.2)$$

$$S_1 = \left[\left(DoB_{s_1}\ , Low\right), \left(DoB_{s_1}\ , Medium\right), \left(DoB_{s_1}\ , High\right)\right] \quad (4.3)$$

$$S_2 = \left[\left(DoB_{s_2}\ , Low\right), \left(DoB_{s_2}\ , Medium\right), \left(DoB_{s_2}\ , High\right)\right] \quad (4.4)$$

where " Low ", " $Medium$ ", " $High$ " are assessed with their corresponding DoB.

Suppose the normalised relative weights of safety assessors in the safety evaluation process are given as $w_1$and $w_2$where $(w_1\ + w_2\ = 1)$ and w_1 and w_2 can be estimated by using established methods such as simple rating methods or more elaborate methods based on pair-wise comparisons (Yang et al., 2001). However, Alyami et al., (2014) in the FRBN approach (chapter 3) considered the equally important weight of the safety assessors, and the weights of all HEs identified at the same level in the hierarchy were evenly distributed to minimise the subjective influence on their risk impact on the whole system.

Suppose $M_1^m$and $M_2^m (m = 1,2 \dots 3)$ are individual degrees to which the subsets "S_1" and "S_2"support the hypothesis that the safety evaluation is confirmed to the four safety expressions. Then, M_1^m and M_2^m can be obtained as follows (Riahi et al., 2012):

$$M_1^m = w_1 \beta_1^m \tag{4.5}$$

$$M_2^m = w_2 \beta_2^m \tag{4.6}$$

where $(m = 1,2, \dots 3)$. Therefore,

$$M_1^1 = w_1 \beta_1^1 \qquad M_2^1 = w_2 \beta_2^1 \tag{4.7}$$

$$M_1^2 = w_1 \beta_1^2 \qquad M_2^2 = w_2 \beta_2^2 \tag{4.8}$$

$$M_1^3 = w_1 \beta_1^3 \qquad M_2^3 = w_2 \beta_2^3 \tag{4.9}$$

Suppose H_1 and H_2 are the individual remaining belief values unassigned for M_1^m and $M_2^m (m = 1,2, \dots 3)$. Then, H_1 and H_2can be expressed as follows (Yang & Xu, 2002; Riahi et al., 2012):

$$H_1 = \overline{H}_1 + \widetilde{H}_1 \tag{4.10}$$

$$H_2 = \overline{H}_2 + \widetilde{H}_2 \tag{4.11}$$

where $\overline{H}_n (n = 1 \; or \; 2)$ represents the degree to which the other assessor can play a role in the assessment and $\widetilde{H}_n (n = 1 \; or \; 2)$ caused by the possible incompleteness in the subsets "S_1"and "S_2", can be described, respectively, as follows (Riahi et al., 2012):

$$\overline{H}_1 = 1 - w_1 = w_2 \tag{4.12}$$

$$\overline{H}_2 = 1 - w_2 = w_1 \tag{4.13}$$

$$\widetilde{H}_1 = w_1 (1 - \textstyle\sum_{m=1}^{3} \beta_1^m) = w_1 [1 - (\beta_1^1 + \beta_1^2 + \beta_1^3)] \tag{4.14}$$

$$\widetilde{H}_2 = w_2 (1 - \textstyle\sum_{m=1}^{3} \beta_2^m) = w_2 [1 - (\beta_2^1 + \beta_2^2 + \beta_2^3)] \tag{4.15}$$

Suppose $\beta^{m'} (m = 1,2 \dots 3)$ represents the non-normalised degree to which the safety evaluation is confirmed to the four safety expressions as a result of the synthesis of the judgments produced by assessors 1 and 2. Suppose $H_{U'}$ represents the non-normalised remaining belief unassigned after the commitment of belief to the four safety expressions because of the synthesis of the judgments produced by assessors 1 and 2.

The ER algorithm can be stated as follows (Yang & Xu, 2002; Riahi et al., 2012):

$$\beta^{m'} = K(M_1^m M_2^m + M_1^m H_2 + H_1 M_2^m) \tag{4.16}$$

$$\bar{H}_{U'} = K(\bar{H}_1 \bar{H}_2) \tag{4.17}$$

$$\tilde{H}_{U'} = K\left(\tilde{H}_1 \tilde{H}_2 + \tilde{H}_1 \bar{H}_2 + \bar{H}_1 \tilde{H}_2\right) \tag{4.18}$$

$$K = \left[1 - \sum_{T=1}^{3} \sum_{\substack{R=1 \\ R \neq T}}^{3} M_1^T M_2^R\right]^{-1} \tag{4.19}$$

After the above aggregation, the combined degrees of belief are generated by assigning $\bar{H}_{U'}$ back to the three safety expressions using the following normalisation process (Riahi et al., 2012):

$$\beta^m = \beta^{m'}/1 - \bar{H}_{U'} \; (m = 1,2,3) \tag{4.20}$$

$$H_U = \tilde{H}_{U'}/1 - \bar{H}_{U'} \tag{4.21}$$

where H_U refers to the unassigned DoB representing the extent of incompleteness in the overall assessment.

The above is the process of combining two fuzzy sets. If three fuzzy sets are required to be combined, the result obtained from the combination of any two sets can be further synthesised with the third one using the above algorithm. In a similar way, multiple fuzzy sets from the judgements of multiple assessors or the safety evaluations of lower level risks in a hierarchy (i.e., components or subsystems) can also be combined (Riahi et al., 2012).

The synthesised result will be presented in the form of linguistic terms with their associated DoBs for all HEs levels in the CTOS from the bottom level to the highest-level criterion. Therefore, in order to evaluate the CTOS safety improvement, the synthesised result is converted into a single crisp value for CTOS final risk score (i.e., highest-level criterion) and can be further used with the sensitivity analysis to verify the safety importance of each HE from a systematic perspective. The utility value can be calculated by a utility-based technique as follows:

$$RI = \sum_{h=1}^{3} p(Rh)U_{Rh} \quad (4.22)$$

where *p(Rh)* is the marginal probability of each grade of “High”, “Medium”, and “Low” in RE. *Rh*= *(1,2,3)* and U_{R1} = 1, U_{R2} = 10 and U_{R3} = 100

III. Sensitivity analysis to quantify the impact of HEs on the system

Sensitivity analysis is required to evaluate the HE’s risk impact by obtaining the risk magnitude of each HE on the entire system through sensitivity tests. The sensitivity tests carried out in this study have been developed on the analysis process of the proposed methodology validation in order to quantify the risk impact of each HE on the system.

The proposed new sensitivity analysis approach allows us to evaluate the risk impact of each HE on the system safety and rank them accordingly by taking into account their specific risk estimate (locally) and their RI to a port’s safety system (globally) through three steps applied on each HE. First, increase the DoBs associated with linguistic term “High” to 100% and obtains the High Risk Inference (HRI). Secondly, increase the DoBs associated with linguistic term “Low” to 100% to obtain the Low Risk Inference (LRI). Lastly, the average between HRI and HLI (i.e., risk inference values) will show the True Risk Influence (TRI) of each HE on the entire system and can be described as follows:

$$TRI = \frac{\text{HRI} + \text{LRI}}{2} \quad (4.23)$$

In addition, the proposed methodology is validated by another sensitivity test. The sensitivity analysis refers to analysing how sensitive the result would be (i.e., outputs) to a minor change in the inputs. The change may be a variation of the parameters of the model or may be changes of the DoB assigned to the linguistic variables used to describe the parameters (Yang et al., 2009). All HEs’ REs assigned to the CTOS in this study were obtained by applying FRBN in chapter 3. The rest of this section will analyse the variation effect on DoB of the HEs’ risk parameters introduced in FRBN. The variation is given to the DoB assigned to the linguistic variables of the HEs’ risk parameters, namely Probability of HE/ Likelihood (L), probability of failures being undetected (P), Consequences/ Severity (C) and Impact of an HE to the resilience of port operational systems (I). If the methodology is sound and its inference reasoning is logical, then the sensitivity analysis must at least pursue the following two axioms.

Axiom 1: Given variation to DoB associated with the linguistic variable "High" for a particular HE risk parameter, or combined simultaneously with the same variation given to the same linguistic variable (i.e., "High") for other HE risk parameters will certainly result in the effect of relative increment/decrement on the RI of the model output (i.e., the goal).

Axiom 2: The total influence magnitudes of x factors (evidence) will always be greater than the one from the set of x-y (y ∈ x) factors (sub-evidence) given a variation in the HEs' risk parameters on the RI of CTOS.

The reason behind the selection of the above-mentioned axioms is to use the sensitivity tests to validate the reliability of the developed approach by measuring the effect of one criterion over another based on the risk parameters prior probabilities variations. It is noteworthy that it is possible to define other axioms for further research.

The ER model presented can be described as a hierarchical evaluation process in which all the decision criteria are aggregated to the highest sole criterion (the goal). Synthesis may be achieved through manual calculation (Dempster, 1967; Shafer, 1976; Yang et al., 2001; Yang & Xu, 2002b; Riahi et al., 2012) or through IDS software that is used in this study. The IDS selection is attributable to its accessibility to other industries and academia. In addition, it not only has user-friendly interfaces for applying the ER method but also knowledge management, report generation, and data presentation functions. Therefore, the CTOS model synthesis and aggregation is supported with IDS in this study.

4.4. Case study of Red sea gateway terminal co. (RSGT)

The RSGT container terminal in Jeddah, Kingdom of Saudi Arabia was selected to conduct a case study in order to demonstrate the feasibility of the proposed ER method. The first part is to *locally* evaluate the RE for each HE to rank them accordingly by applying the FRBN introduced in chapter 3. As a result, the outputs for the 24 HEs were obtained as shown in Table 4.1.

Table 4.1: Updated risk ranking index values of HEs from chapter 3

HE #	HEs	Risk Estimation			Ranking Index
		Low	Medium	High	
1.	Collision between Terminal Tractor (TT) and trailer.	8.5	25	66.5	69.1
2.	Collision between Rubber-Tired Gantry (RTG) crane and trailer.	17.75	25.25	57	59.7
3.	Collision between TT and RTG.	19.56	18.12	62.32	64.3
4.	Collision between quay crane and ship.	13.25	13.25	73.5	75
5.	Collision between two quay cranes.	18.75	8.5	72.75	73.8
6.	Crane breakdown due to human error.	23.5	5.5	71	71.8
7.	Moving the crane without raising the Boom of the gantry crane.	24.75	9.75	65.5	66.7
8.	Leakage/ emission of dangerous goods from a container.	41	11.25	47.75	49.3
9.	Ignition sources from equipment near dangerous goods premises.	35	27.5	37.5	40.6
10.	Person falls from height due to being too near to unprotected edges.	25.5	22.75	51.75	54.3
11.	Person falls from height due to non-provision / maintenance of safe access between adjacent cargo bays.	19	21	60	62.3
12.	Working on surfaces that are not even.	23	18.5	58.5	60.6
13.	Person slips, trips, and falls whilst working on surfaces with presence of leaking cargo.	22	11.25	66.75	68.1
14.	Person slips, trips, and falls whilst working on surfaces with presence of water/ ice.	25	15.25	59.75	61.5
15.	Person slips and falls whilst working on surfaces with presence of oils.	23.25	8.5	68.25	69.3
16.	Person struck by falling object.	28.5	22.5	49	51.5
17.	Person handling dangerous goods in container that has not been declared.	43.5	12.5	44	45.7
18.	Person struck by quay crane.	44.5	7.75	47.75	49
19.	Person struck by TT.	45.24	16	38.75	40.8
20.	Person struck by RTG.	43.5	15.75	40.75	49
21.	Person struck by trucks.	38.5	22	39.5	42
22.	Person crushed against a fixed object and ship / terminal structure.	41	16.25	42.75	44.8
23.	Person crushed against a fixed object and stacked containers.	37.75	23.25	39	41.7
24.	Person crushed by closing the twin lift container spreaders.	53	16.25	30.75	32.9

The HEs associated with container terminal operations may vary, depending on the unique safety characteristics of an individual container terminal. For the investigated container terminal, the FRBN deliveries the results for all HEs' REs *locally* and Table 4.1 indicates that HE4 is the most significant event followed by HE5, HE6, HE15, and HE1, respectively.

Once the REs for individual HEs have been obtained, the second part is assigning the RE of each HE in the hierarchical structure to evaluate their RI to a port's safety system globally. They can be synthesised and aggregated collectively by using the ER algorithm. The IDS is a general-purpose multi-criteria decision analysis tool implementing the ER approach. As a result, the RI for CTOS can be described in a form of linguistic grades with DoB values of 60.37 High, 10.56 Medium, and 28.89 Low, as shown in Figure 4.3, and the utility value is calculated using Equation 4.22 as 0.6172, which indicates that the RI of the investigated CTOS is high.

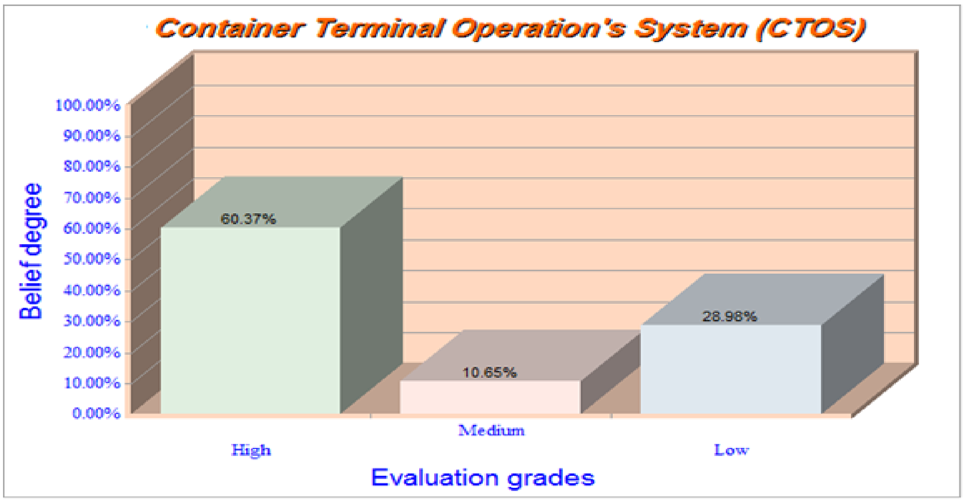

Figure 4.2: Risk Index of container terminal operation's system (IDS) software

The next step is to quantify the most significant HEs that influence the risk to a port's safety system *globally* by verifying the safety importance of each HE from a systematic perspective using the sensitivity analysis methods in Section 4.4.

The RI of the HEs globally on a port's safety system in the terminal operations is inevitable. Therefore, as explained in Section 4.4, this step develops a new sensitivity analysis approach through changing the DoBs of the risk parameters of each HE that allows us to measure the TRI of each HE risk inference on the container operational system and rank them accordingly. For instance, to evaluate the RI of HE.1, the DoB belonging to the linguistic variable "High" is increased to 100%, which leads to the increase of the utility value of the goal from 0.6172 to 0.6237 (i.e., HRI of 0.0065=

0.6237 - 0.6172). Then, the DoB belonging to the linguistic variable "Low" is increased to 100% which results in the goal utility value decreasing from 0.6172 to 0.5972 (i.e., LRI of 0.02= 0.6172 - 0.5972). Next, Equation 4.23 is used to calculate the TRI value of HE.1 as 0.01325$\left(=\frac{0.0065+0.02}{2}\right)$. Similarly, the TRI values for the 24 HEs are obtained and presented in Table 4.2.

Table 4.2: TRI for HEs on the CTOS

HE #	Utility Value / HEs	100% HIGH	100% LOW	High Risk Inference	Low Risk Inference	TRI
1.	Collision between Terminal Tractor (TT) and trailer.	0.6237	0.5972	0.0065	0.02	0.01325
2.	Collision between Rubber-Tired Gantry (RTG) crane and trailer.	0.6258	0.6002	0.0086	0.017	0.0128
3.	Collision between TT and RTG.	0.625	0.5992	0.0078	0.018	0.0129
4.	Collision between quay crane and ship.	0.6228	0.5962	0.0056	0.021	0.01333
5.	Collision between two quay cranes.	0.6232	0.5969	0.006	0.0203	0.0132
6.	Crane break down due to human error.	0.6477	0.5213	0.0305	0.096	0.0624
7.	Moving the crane without raising the boom of the gantry crane.	0.6521	0.5274	0.0349	0.0898	0.06215
8.	Leakage/ emission of dangerous goods from a container.	0.7044	0.5143	0.0872	0.1029	0.0951
9.	Ignition sources from equipment near dangerous goods premises.	0.7147	0.5252	0.0975	0.092	0.0948
10.	Person falls from height due to being too near to unprotected edges.	0.6392	0.5813	0.022	0.0359	0.0289
11.	Person falls from height due to non-provision / maintenance of safe access between adjacent cargo bays.	0.6357	0.5766	0.0185	0.0406	0.0296
12.	Working on surfaces that are not even.	0.6353	0.5773	0.0181	0.0399	0.029
13.	Person slips, trips, and falls whilst working on surfaces with presence of leaking cargo.	0.6228	0.6013	0.0056	0.016	0.01055

14.	Person slips, trips, and falls whilst working on surfaces with presence of water/ ice.	0.6238	0.6028	0.0066	0.0144	0.0105
15.	Person slips and falls whilst working on surfaces with presence of oils.	0.6227	0.6012	0.0055	0.016	0.01055
16.	Person struck by falling object/s.	0.6606	0.5598	0.0434	0.0574	0.0504
17.	Person handling dangerous goods in container that has not been declared.	0.6669	0.5684	0.0497	0.0488	0.04925
18.	Person struck by quay crane.	0.6472	0.5867	0.03	0.0305	0.03025
19.	Person struck by TT.	0.6512	0.5907	0.034	0.0265	0.03025
20.	Person struck by RTG.	0.6501	0.5896	0.0329	0.0276	0.03025
21.	Person struck by trucks.	0.6498	0.5892	0.0326	0.028	0.0303
22.	Person crushed against a fixed object and ship / terminal structure.	0.6591	0.5795	0.0419	0.0377	0.0398
23.	Person crushed against a fixed object and stacked containers.	0.6605	0.5808	0.0433	0.0364	0.0399
24.	Person crushed by closing the twin lift container spreaders.	0.6679	0.5888	0.0507	0.0284	0.0396

Accordingly, based on the results obtained in Table 4.2 the HEs can be prioritised in order of the important events in terms of risk impact on CTOS as shown in Figure 4.3 and the most important events can be listed as follows.

HE.8 Leakage/ emission of dangerous goods from a container.
HE.9 Ignition sources from equipment near dangerous goods premises.
HE.6 Crane break down due to human error.
HE.7 Moving the crane without raising the boom (lifting arm) of the gantry crane.
HE.16 Person struck by falling object/s.
HE.17 Person handling dangerous goods in containers that have not been declared.

In Figure 4.4, the risk magnitude of each HE is reflected by their associated TRIs through calculating the average of HRIs and LRIs.

In addition, another sensitivity test in the remainder of this section has been carried out to validate the reliability of the developed approach by investigating the RI magnitudes of the minor variation given to the DoB of the four risk parameters of HEs. The logicality and soundness of the results delivered in the proposed model are validated by the two axioms introduced in Section 4.4.1.

The HE of the most importance in terms of risk impact on CTOS (i.e., HE8 Leakage/ emission of dangerous goods from a container) is selected for the tests. The DoB associated with the linguistic term “High” is increased by 10% and simultaneously the DoB associated with the linguistic term “Low” decreased by 10% for the risk parameter L (i.e. the risk parameters L, P, C and I have been described in Section 3.3.1) the impact on the safety level of the CTOS will increase the RI from 0.6172 to 0.6223.

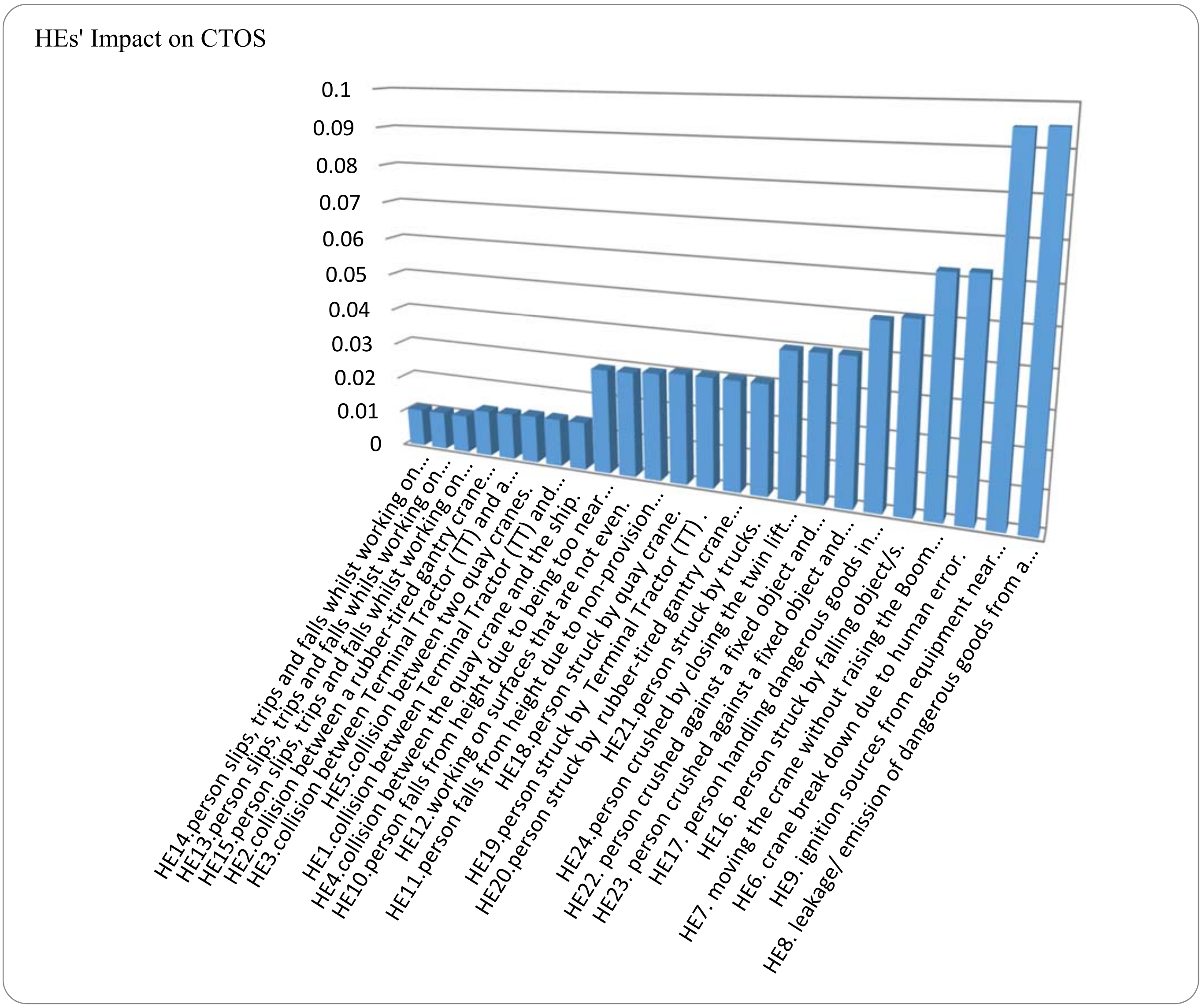

Figure 4.3: The most important HEs for CTOS

If the same DoB change (i.e., 10% increment in “High” and 10% decrement in “Low”) is applied to the other risk parameters such as P, C and I will certainly increase the RI of the CTOS. For instance, the impact of such changes on L and P combined is updated and the CTOS’s RI increases from 0.6172 to 0.6263. The sensitivity tests continue in the same manner. When the risk parameter C is combined with L and P, its impact to the CTOS' RI further increases from 0.6172 to 0.6312. When I is combined with L, P and C, the RI further increases from 0.66172 to 0.6361. The changes on the DoB of the risk parameters L, P, C and I are described in Table 4.3 for HE8, HE9 and HE6.

A similar sensitivity analysis was carried out to test "HE.9" and "HE.6" in Table 4.4.

Table 4.3: The DoB variation of the HEs

HE	**Prior Probability +10% "High"**	**Probability of HE/ Likelihood L**			**Probability of HE being undetected P**			**Consequences Severity C**			**Impact of an HE to the resilience of port operational systems I**		
		H	**M**	**L**	**H**	**M**	**L**	**H**	**M**	**L**	**H**	**M**	**L**
HE8 Leakage/ emission of dangerous goods from a container	Original	0.14	0.24	0.62	0.91	0.06	0.03	0.02	0.04	0.094	0.84	0.11	0.05
	L	0.24	0.24	0.52	0.91	0.06	0.03	0.02	0.04	0.094	0.84	0.11	0.05
	L & D	0.24	0.24	0.52	1	0	0	0.02	0.04	0.094	0.84	0.11	0.05
	L & D & C	0.24	0.24	0.52	1	0	0	0.12	0.04	0.84	0.84	0.11	0.05
	L & D & C & I	0.24	0.24	0.52	1	0	0	0.12	0.04	0.84	0.94	0.06	0
HE9 Ignition sources from equipment near dangerous goods premises	Original	0.24	0.28	0.48	0.74	0.24	0.02	0.2	0.27	0.53	0.32	0.31	0.37
	L	0.34	0.28	0.38	0.74	0.24	0.02	0.2	0.27	0.53	0.32	0.31	0.37
	L & D	0.34	0.28	0.38	0.84	0.16	0	0.2	0.27	0.53	0.32	0.31	0.37
	L & D & C	0.34	0.28	0.38	0.84	0.16	0	0.3	0.27	0.43	0.32	0.31	0.37
	L & D & C & I	0.34	0.28	0.38	0.84	0.16	0	0.3	0.27	0.43	0.42	0.31	0.27
HE6 A Crane breaks down due to human error	Original	0.82	0.15	0.03	0.05	0.04	0.91	0.82	0.14	0.04	0.93	0.06	0.01
	L	0.92	0.08	0	0.05	0.04	0.91	0.82	0.14	0.04	0.93	0.06	0.01
	L & D	0.92	0.08	0	0.15	0.04	0.81	0.82	0.14	0.04	0.93	0.06	0.01
	L & D & C	0.92	0.08	0	0.15	0.04	0.81	0.92	0.08	0	0.93	0.06	0.01
	L & D & C & I	0.92	0.08	0	0.15	0.04	0.81	0.92	0.08	0	1	0	0

The combined variation given to the DoB associated with the linguistic term “High” (i.e., 10% increment) for the risk parameters of “HE9”, “HE8”, and “HE6” has resulted in 125 RI values for CTOS as shown in Table 4.4. For instance, row#1, shows the values of HE6, HE8 and HE9 without any changes in the risk parameters (i.e. L, C, P and I), while in row#2, the variation is given to the DoB associated with the linguistic term “High” (i.e., 10% increment) for the risk parameter (L) of “HE9” only which resulted in an increment from 0.6172 to 0.6223. Next, in row#3, the variation is given to the DoB associated with the linguistic term “High” (i.e., 10% increment) for the risk parameter (P) of “HE9” with the given variation to (L) resulted in an increment from 0.6172 to0.6263. The sensitivity tests continue in the same manner to all DoB associated with the linguistic term “High” for all risk parameters (L) of “HE6, HE8 and HE9”.

Table 4.4: RI for CTOS and the variation on the HE risk parameters prior probabilities

#	HE6	HE8	HE9	ICTOS RI
1.	0	0	0	**0.6172**
2.	0	0	L	**0.6223**
3.	0	0	LP	**0.6263**
4.	0	0	LPC	**0.6312**
5.	0	0	LPCI	**0.6361**
6.	0	L	0	**0.622**
7.	0	L	L	**0.627**
8.	0	L	LP	**0.631**
9.	0	L	LPC	**0.6359**
10.	0	L	LPCI	**0.6407**
11.	0	LD	0	**0.6257**
12.	0	LD	L	**0.6306**
13.	0	LD	LP	**0.6346**
14.	0	LD	LPC	**0.6395**
15.	0	LD	LPCI	**0.6443**
16.	0	LDC	0	**0.6303**
17.	0	LDC	L	**0.6353**
18.	0	LDC	LP	**0.6392**
19.	0	LDC	LPC	**0.644**
20.	0	LDC	LPCI	**0.6487**
21.	0	LDCI	0	**0.6345**
22.	0	LDCI	L	**0.6394**
23.	0	LDCI	LP	**0.6433**
24.	0	LDCI	LPC	**0.6481**
25.	0	LDCI	LPCI	**0.6528**
26.	L	0	0	**0.6196**
27.	L	0	L	**0.6246**
28.	L	0	LP	**0.6287**

#	HE6	HE8	HE9	ICTOS RI
29.	L	0	LPC	**0.6336**
30.	L	0	LPCI	**0.6384**
31.	L	L	0	**0.6244**
32.	L	L	L	**0.6293**
33.	L	L	LP	**0.6333**
34.	L	L	LPC	**0.6382**
35.	L	L	LPCI	**0.643**
36.	L	LD	0	**0.628**
37.	L	LD	L	**0.633**
38.	L	LD	LP	**0.637**
39.	L	LD	LPC	**0.6418**
40.	L	LD	LPCI	**0.6466**
41.	L	LDC	0	**0.6327**
42.	L	LDC	L	**0.6376**
43.	L	LDC	LP	**0.6415**
44.	L	LDC	LPC	**0.6463**
45.	L	LDC	LPCI	**0.651**
46.	L	LDCI	0	**0.6369**
47.	L	LDCI	L	**0.6417**
48.	L	LDCI	LP	**0.6456**
49.	L	LDCI	LPC	**0.6504**
50.	L	LDCI	LPCI	**0.655**
51.	LD	0	0	**0.6225**
52.	LD	0	L	**0.6275**
53.	LD	0	LP	**0.6315**
54.	LD	0	LPC	**0.6364**
55.	LD	0	LPCI	**0.6412**
56.	LD	L	0	**0.6272**
57.	LD	L	L	**0.6322**
58.	LD	L	LP	**0.6361**
59.	LD	L	LPC	**0.641**
60.	LD	L	LPCI	**0.6458**
61.	LD	LD	0	**0.6309**
62.	LD	LD	L	**0.6358**
63.	LD	LD	LP	**0.6398**
64.	LD	LD	LPC	**0.6446**
65.	LD	LD	LPCI	**0.6493**
66.	LD	LDC	0	**0.6355**
67.	LD	LDC	L	**0.6404**
68.	LD	LDC	LP	**0.6443**
69.	LD	LDC	LPC	**0.6491**
70.	LD	LDC	LPCI	**0.6538**
71.	LD	LDCI	0	**0.6397**
72.	LD	LDCI	L	**0.6445**
73.	LD	LDCI	LP	**0.6484**
74.	LD	LDCI	LPC	**0.6531**
75.	LD	LDCI	LPCI	**0.6577**
76.	LDC	0	0	**0.6238**

#	HE6	HE8	HE9	ICTOS RI
77.	LDC	0	L	**0.6287**
78.	LDC	0	LP	**0.6327**
79.	LDC	0	LPC	**0.6376**
80.	LDC	0	LPCI	**0.6425**
81.	LDC	L	0	**0.6285**
82.	LDC	L	L	**0.6334**
83.	LDC	L	LP	**0.6374**
84.	LDC	L	LPC	**0.6422**
85.	LDC	L	LPCI	**0.647**
86.	LDC	LD	0	**0.6321**
87.	LDC	LD	L	**0.6371**
88.	LDC	LD	LP	**0.641**
89.	LDC	LD	LPC	**0.6458**
90.	LDC	LD	LPCI	**0.6505**
91.	LDC	LDC	0	**0.6368**
92.	LDC	LDC	L	**0.6416**
93.	LDC	LDC	LP	**0.6455**
94.	LDC	LDC	LPC	**0.6503**
95.	LDC	LDC	LPCI	**0.655**
96.	LDC	LDCI	0	**0.6409**
97.	LDC	LDCI	L	**0.6457**
98.	LDC	LDCI	LP	**0.6496**
99.	LDC	LDCI	LPC	**0.6543**
100.	LDC	LDCI	LPCI	**0.6589**
101.	LDCI	0	0	**0.6254**
102.	LDCI	0	L	**0.6304**
103.	LDCI	0	LP	**0.6344**
104.	LDCI	0	LPC	**0.6393**
105.	LDCI	0	LPCI	**0.6441**
106.	LDCI	L	0	**0.6302**
107.	LDCI	L	L	**0.6351**
108.	LDCI	L	LP	**0.639**
109.	LDCI	L	LPC	**0.6486**
110.	LDCI	L	LPCI	**0.6556**
111.	LDCI	LD	0	**0.6338**
112.	LDCI	LD	L	**0.6387**
113.	LDCI	LD	LP	**0.6426**
114.	LDCI	LD	LPC	**0.6474**
115.	LDCI	LD	LPCI	**0.6522**
116.	LDCI	LDC	0	**0.6384**
117.	LDCI	LDC	L	**0.6433**
118.	LDCI	LDC	LP	**0.6472**
119.	LDCI	LDC	LPC	**0.6519**
120.	LDCI	LDC	LPCI	**0.6566**
121.	LDCI	LDCI	0	**0.6425**
122.	LDCI	LDCI	L	**0.6474**
123.	LDCI	LDCI	LP	**0.6512**
124.	LDCI	LDCI	LPC	**0.6559**

#	HE6	HE8	HE9	ICTOS RI
125.	LDCI	LDCI	LPCI	**0.6605**

The first row in Table 4.4 shows the neutral RI for CTOS, and the rest of the table shows the updated RI by the given variation to the DoB associated with linguistic variable "High" for HE6, HE8, and HE.9 risk parameters locally and globally. Comparing any updated RI with the neutral RI can be concluded that the model is validated to be in line with Axiom 1.

According to Axiom 2, if the model reflects logical reasoning then the RI for CTOS associated with x factors (evidence) will always be greater than the one from x-y (y $\in$ x) factors (sub-evidence). This can be examined by comparing the RIs of the HEs with the reassigned DoB associated with linguistic variable "High" in each HE risk parameter prior probabilities, which can be specifically appointed by following the relationship between the evidence and sub-evidence.

The neutral RI for CTOS is chosen as the sub-evidence to investigate the accuracy of the model. All other RIs affected by the variation (i.e., increment) given to the DoB associated with linguistic variable "High" for HE8, HE9, and HE6 can be identified as evidence. Comparing the evidence and sub-evidence (i.e., the values in the first five rows in Table 4.4 are gradually increasing), it can be concluded that the model is validated to and in line with Axiom 2.

4.5. Results and Discussion

In accordance with the results obtained in Table 4.2 and the graph in Figure 4.3, the most significant HEs are those having a great risk impact on the CTOS listed as follows.

- Ignition sources from equipment near dangerous goods premises (HE9).
- Leakage/ emission of dangerous goods from a container (HE8).
- Crane break down due to human error (HE6).
- Moving the crane without raising the boom (lifting arm) of the gantry crane (HE7).
- Person struck by falling object/s (HE16).
- Person handling dangerous goods in containers that have not been declared (HE17).

The HEs investigated have been examined and validated for the sensitivity analysis in this study. Using the FRBN technique, each HE was assessed locally based on unique rational distribution of DoBs with linguistic terms and then ranked accordingly to evaluate the risk preference of the CTOS. While using the ER technique, other aspects are involved such as the TRI of each HE taking into account their specific risk estimations locally and their RI to a port's safety system globally, to facilitate the subjective safety based decision-making modelling for container terminal risk evaluation. The variations of TRI of the whole system due to the reallocation of DoB of any investigated HE to a level of 100% "High" (Max) and of 100% "Low" (Min) are averaged to calculate the aggregated effect of each HE to the safety performance of the whole system. The case study results confirm that the proposed method is capable of presenting sensitive and flexible risk results in real situations by simplifying the description of failure information, improving both the accuracy and visibility of FMEA, and providing a powerful risk evaluation tool for port safety management. ER provides a powerful tool for aggregation calculations, and is used to examine the identified HEs synthesis for the container terminal safety preferences ranking.

4.6. Conclusion

System safety analysis often requires the use of domain experts' knowledge when risk records are incomplete. The FRBN rationalises the DoB distribution of FRB by employing the same set of linguistic grades in both IF and THEN parts and applying that set to evaluate the HEs of a container terminal. The FRBN simplifies the communication between risk input and output based on DoBs and facilitates its implementation in CTOS in practice. The FRBN is integrated with the ER approach that has the ability of providing a powerful tool for aggregation calculations to synthesise the identified HEs for CTOS risk ranking. The FRBN technique is used to assess each HE locally while the ER approach is employed to take into account the risk impact of each HE to the safety of the investigated port system when evaluating their TRI globally. As a result, the integration of FRBN and ER provides an effective tool to incorporate subjective judgements for characterising a criticality analysis on prioritising failures in FMEA under uncertainty as well as the functional nonlinear relationship between outputs and inputs in the hierarchical evaluation process.

The HEs investigated in this study have been examined with new sensitivity analysis developed in two different approaches. Consequently, the ER technique determines the analysis of risk impact of each HE on the whole system. The case study results confirm that the proposed method is capable of presenting sensitive and flexible risk results in real situations by simplifying the description of failure information, improving both the accuracy and visibility of FMEA, and providing a powerful risk evaluation tool for port safety management. In addition, the proposed method highlights its potential in facilitating risk analysis of system design and operations in a wide context when the method is appropriately applied to study other seaports.

Sea ports and maritime terminals (i.e., infrastructures) are facing risk challenges from various perspectives including economic, operational, technical and environmental. This study mainly focused on the operational aspects including technical and personnel factors, leaving the other risk aspects to be addressed in future work. Other risk concerns influencing port safety, such as managerial, policy implications, natural, and political issues also need be investigated in order to provide a panoramic view of terminal risk analysis. Moreover, high quality representative computational modelling tools are required, not only to provide a user-friendly solution in the risk evaluation process that helps to predict the risk magnitude, explain the real safety performance, and develop a continuous risk management strategy for complex systems, but also to simplify the complex risk inference processes involved in the two steps in the developed methods. ANNs seem to be a promising solution to addressing this research problem. In addition, a risk-control option model can be developed to eliminate and/or mitigate the HEs in CTOS and to enhance the system operational efficiency.

Chapter 5 — Integrated container port system risk analysis and probabilistic safety assessment simulations using ANNs

Summary

This study proposes a novel, modified FMEA approach using Artificial Neural Networks (ANNs) to predict container terminal operation risks, which can complement the two models—Fuzzy Bayesian and Bayesian ER—discussed in Chapters 3 and 4 respectively. This study proposes three new models based on ANNs to enhance the performance of FMEA by overcoming its incapability in tackling uncertainty in data and at the same time ease the evaluation process on the stakeholders from handling a complex large amount of data to measure, predict, and improve their system safety and reliability performance. It simplifies the complex risk inference processes involved in the two developed methods. The first is Bayesian Network ANN (BNANN) that incorporates BNs with ANNs to facilitate risk prediction of each HE identified in Chapter 3. The second model is Evidential Reasoning ANN (EvRANN), which uses ANNs to simulate the FRBER method from Chapter 4 to ease the aggregation of all 24 HEs. The final model is Artificial Neural Networks-Bayesian Network-Evidential Reasoning (AnBnEvR) integrates the two ANN models into a single model; it simplifies risk prediction, analyses processes, and realises real-time risk prediction of ports at HE or whole system levels. The proposed ANN based models produced smaller deviations that exhibited superior predictive accuracy with satisfactory determination coefficients (i.e., the Regression) (R^2) of 0.999 with the corresponding Minimum Mean Squared Errors (MSE) of 0.000001334 for simulating BNANNs and R^2 of 0.997, with the corresponding MSE of 0.0001344 for simulating EvRANNs and forecasting container terminal operation risk evaluation. The proposed ANN-based approach provides an excellent evaluation and prediction tool for complex systems, such as container terminal operation activities that could be easily modelled in a feasible, versatile, and accurate manner.

5.1. Introduction

Technological effort, risk management development, and HE-driven risk mitigation have resulted in strengthened safety standards, as evidenced by practical applications and research over the years. New concepts involving efficient operation and design should be developed and implemented in order to achieve optimum evaluation, control, and safety management performance in maritime port operation. High quality models of accuracy and reliability assurance can help risk evaluation predict risk magnitude, explain real safety performance, and develop a continuous risk management strategy for complex systems. Many types of technologies can develop such models, but numerous Artificial Neural Networks (ANNs) applications have been successfully applied for real-time risk prediction in various sectors over the past decade, due to their reliable, robust, and salient capturing of non-linear relationships between complex system variables (i.e., multi-input/output). On the other hand, FMEA is one of the most widely applied hazard identification and risk analysis methods, due to its visibility and ease. ANNs, a method based on uncertainty treatment theory, can enhance FMEA performance by overcoming its incapability of tackling data uncertainty; at the same time, it can ease stakeholders' burden of handling a complex large amount of data to measure, predict, and improve system safety and reliability performance. ANNs are computational modelling tools that many disciplines use to model complex problems. Research has shown that ANNs have powerful pattern classification and recognition capabilities. Inspired by biological systems, particularly research into the human brain as a large-scale nonlinear drive system, ANNs offer a computational paradigm that learns and generalises from experience. It also has many egregious functions, such as adaptive learning, real time operation, self-organisation, thinking and reasoning, judging and memory, and fault tolerance (Widrow et al., 1994; Kumar and Ravi, 2007). Since the 1980s, research on ANNs has made remarkable developments, and has been successfully applied for many different tasks in a wide variety of domains, such as science, industry, business—including accounting and finance, marketing, engineering, and manufacturing—and health and medicine to model complex real-world problems, as evidenced by literature.

In the last decade, however, a few studies examined risk assessment using ANNs, including medical (Sadatsafavi et al., 2005; Wang et al., 2011; Tsujita et al., 2014), financial (Lacerda et al., 2005; LIN, 2009; Wang et al., 2011; De Andres et al., 2011; Oreski et al., 2012; Henry et al., 2013), and civil engineering studies (Gómez & Kavzoglu, 2005; Brack et al., 2005; Chen et al., 2007; Moseley et al., 2007; Ying et al., 2008; Schuhmacher et al., 2009). However, very few studies use ANN in risk analysis for maritime-related systems. Ung et al., (2006) applied ANNs to predict the risk level of sea-lane navigation within port areas by incorporating fuzzy set theory and ANNs. Although, showing a unique conception in the idea essence of applying ANNs in the maritime port industry, however, the approach has only considered the fuzziness, incapable of modelling the other types of uncertainties in data, which releases a significant research gap. In addition, since then the development on ANNs and its application capability in various fields of study is remarkable, in which allow providing a mature risk assessment-modelling scheme for maritime port industry with high accuracy.

This chapter aims to develop an integrated container port system risk analysis and probabilistic safety assessment simulations, using ANNs that predict and evaluate the criticality of hazardous events in a container terminal. The ANN approach is used to model two methodologies introduced in previous chapters: the FRBN technique from Chapter 3 and FRBER in Chapter 4. Furthermore, the ANN approach implements Experimental Data (ED) that is used to train ANNs in rational structure and develops an applicable, new risk-based decision support tool for effective seaport risk prediction.

The two models simulated in this chapter have proven their ability to evaluate risk in container terminals. However, the complexity of handling a large amount of data dealing with two different software methodologies could burden stakeholders who must navigate non-user-friendly processes to measure, predict, and improve system safety and reliability performance, motions, and action planning. It is noteworthy to mention that, due to optimisation required for the five risk assessment attributes with their fuzzy parameters introduced in Chapters 3 and 4 (i.e., the inputs and outputs) with evaluations tasks applied cause the amount of calculation to be tremendous in the FRBN and FRBER interface, however, it can be overcome by applying the ANN approach.

In order to clearly map and explain the proposed models, this study is divided into three parts that develop a safety analysis approach using a hybrid of fuzzy, BN, ER, and ANNs. The first part simulates FRBN, evaluating the criticality of each HE for the identified 24 HEs locally in a container terminal (see Chapter 3). The second part simulates FRBER, evaluating the criticality of risk associated with the most significant HEs of the identified 24 global HEs for a container terminal (see Chapter 4). The final part presents the integrated AnBnEvR model, which predicts the risk index for each HE and provides a risk management system on OSP in a container terminal system.

This chapter begins with a broad overview of the history and definition of ANNs history, particularly concerning their principals, characteristics, and general application as carried out in Section 5.2. Section 5.3 describes the methodology of a novel ANN framework, capable of simulating two different models to evaluate the risk associated with the 24 global and local HEs in container terminals. Section 5.4 examines the development of ANN modelling in maritime ports. Section 5.5 describes the construction of BNANN models to simulate FRBN for individual HE risk evaluations. Section 5.6 describes the construction of model ERANN that simulate FRBER for aggregated HEs. Section 5.7 presents the integrated AnBnEvR, and Section 5.8 concludes the chapter.

5.2. Artificial Neural Networks (ANNs) Overview

5.2.1. ANN history

In 1942, McCulloch and Pitts proposed modelling neural nets as a single neuron form in terms of the computational “nervous activity” model; this model describes the neuron as a linear threshold-computing unit with multiple inputs and a single output to solve character recognition problems (Basheer & Hajmeer, 2000). In 1949, Hebb built the missing link between single neurons and network in his classic book *The Organization of Behaviour*. Rosenblatt developed a network in 1958 using McCulloch and Pitts’ model, based on a unit called the “perceptron” (Lippmann, 1987).

Widrow and Hoff (1960), Rosenblatt (1962), and others explored and developed many types of perceptron-based ANNs in the 1960s. The topic rapidly faded in the 1970s, however, because of two main problems: firstly, the practical difficulties of solving many real-world problems; and secondly, the results of Minsky and Papert’s 1969 study, which identified serious limitations among perceptrons and could not be solved by simply adding neuron layers. It was also determined that the perceptron was incapable of representing simple, linearly inseparable functions, as in the famous “exclusive or” (XOR) problem (Minsky & Papert, 1987; Marini et al., 2008). However, the primary problem was the absence of any learning algorithm to train such networks.

Hence, the era of the artificial neural network seemed to come to an end. However, Hopfield (1982) poured new life into this field by introducing two key concepts that overcame all of Minsky and Papert’s identified limitations: first, the nonlinearity between total input received by a neuron and its produced output; second, the possibility of feedback coupling outputs with inputs (Marini et al., 2008).

Since then, ANNs have seen an explosion of interest, together with a paradigm change in recent years. They were intensively and extensively used as problem solving algorithms for application development, rather than accurate representations of the human nervous system (Liao & Wen, 2007; Marini et al., 2008). They are successfully applied across an extraordinary range of domains, in areas as diverse as finance, medicine, engineering, chemistry, geology, and physics. More information about the history of ANNs development can be found in several existing studies (Anderson & Rosenfeld, 1988; Pollack, 1989; Nelson & Illingworth, 1990; Eberhart & Dobbins, 1990; Priddy & Keller, 2005; Yegnanarayana, 2009).

5.2.2. ANN concept

ANNs are computational modelling tools with flexible structures that capture and simulate complex input/output relationships. They are comprised of densely interconnected adaptive and simple processing elements, capable of performing massive parallel computations for data processing and knowledge representation (Dawes, 1991; Schalkoff, 1997; Liao & Wen, 2007). The ANN terminology has been developed from a biological model that uses artificial neurons to imitate the learning process of the human brain (i.e., natural neurons) to a system that processes nonlinear and complex data, even when the data are imprecise and noisy. However, solving complex problems requires knowledge of biological network functionality rather than a replication of biological system operation (Basheer & Hajmeer, 2000; Liao & Wen, 2007).

The human nervous system consists of billions of neurons of various types and lengths relevant to their location in the body (Schalkoff, 1997). Figure 5.1 shows a schematic of simplified biological neurons with three major functional units: dendrites, cell bodies, and axons. The cell body has a nucleus that contains information about hereditary traits, as well as plasma that holds the molecular equipment used for producing material needed by the neuron (Jain et al., 1996). The dendrites receive signals from other neurons and pass them to the cell body. The axon, which branches into collaterals, receives signals from the cell body and carries them through synapses to the neighbouring neurons' dendrites (Zupan & Gasteiger, 1993).

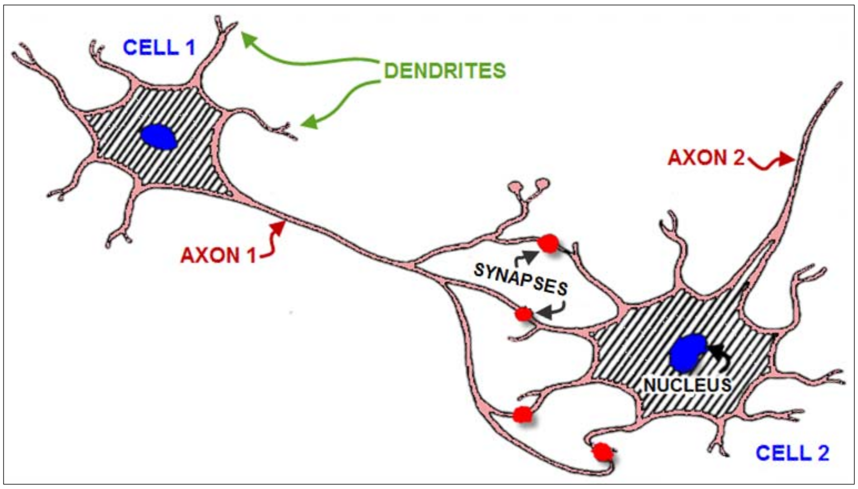

Figure 5.1: Natural neurons

An impulse, in the form of an electric signal, travels within the dendrites and through the cell body towards the synapse's synaptic membrane. Next, if the signals received are strong enough (surpassing a certain threshold), the neuron activates and emits a signal through the axon that might be sent to another synapse or activate other neurons (Grossberg, 1982; Rosenzweig et al., 1999). A schematic illustration of the signal transfer between two neurons through the synapse is shown in Figure 5.2.

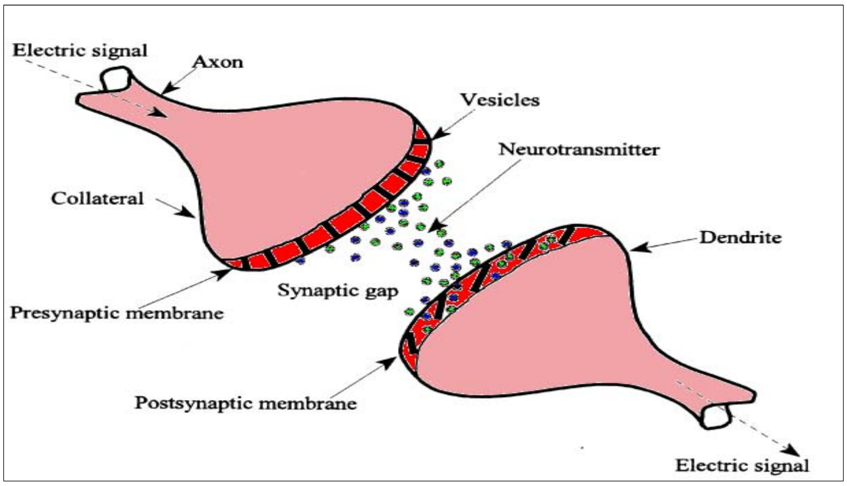

Figure 5.2: Natural neurons signal transfer

5.2.3. ANN principles

The complexity of real neurons is highly abstracted when modelling artificial neurons. ANNs consist of inputs (synapses), which are multiplied by weights (strength of respective signals), and then computed by a mathematical function, which determines the activation of the neuron; then another function (possibly identity) computes the artificial neuron's output. As a result, ANNs' mechanisms combine all artificial neurons to process information.

The greater an artificial neuron's weight, the stronger its input. A neuron's computation depends on weights and differs if the weight changes, because weight is multiplied by input. By adjusting an artificial neuron's weights, the output can be obtained as desired for specific inputs. However, when an ANN consists of hundreds or thousands of neurons, manually finding all the necessary weights is complicated; algorithm weights can find and adjust ANN weights in order to obtain desired network output. This process of weight adjustment is called learning or training (Haykin, 1999).

A complex system may be deconstructed into simpler elements in order to understand and handle it. Simple elements may be gathered to produce a complex system; networks are one approach for achieving this (Bar, 2003).

There are many network types, but they all contain the following components:

- A set of nodes: nodes can be seen as computational units. They receive and process inputs to obtain an output. This processing may be very simple (summing the puts) or quite complex (a node might contain another network).
- Connections between nodes: connections determine information flow between nodes and can be unidirectional, when information flows only in one sense, and bidirectional, when information flows in either sense.

Node interactions through connections lead to a network's global behaviour, which cannot be observed through the network's elements. This global behaviour is described as "emergent," meaning that the networks abilities supersede those of its elements, making networks a very powerful tool (Haykin, 1999).

A neuron is a real function of the input vector$(x_1 \dots x_j)$. The output y is obtained as

$$f(y_j) = f\left(\alpha + \sum_{i=1}^{k} w_{kj} x_j\right) \qquad (5.1)$$

where f is a function (functions will be explained in detail in Section 5.3.1),

$x_1, x_2, x_3, \dots x_j$ are the input signals,

$w_{k1}, w_{k2}, w_{k3}, \dots w_{kj}$ are the synaptic weights of neuron k , and

α is the bias

A graphical presentation of a neuron is given in Figure 5.3. Mathematically, a Multi-Layer Perceptron network is a function consisting of compositions of functions' weighted sums corresponding to neurons (Haykin, 1999).

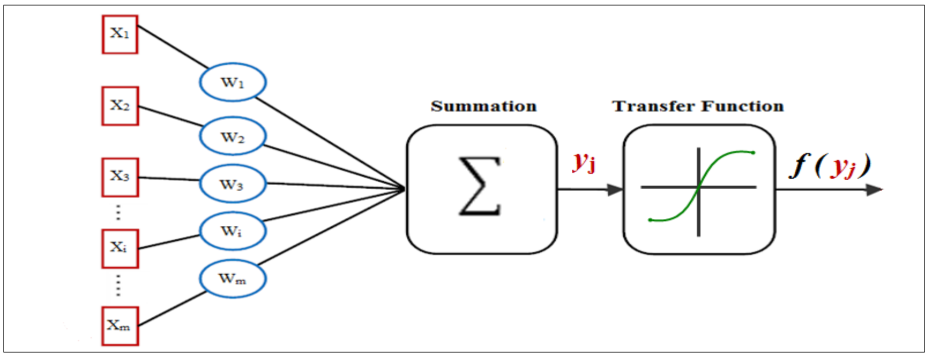

Figure 5.3: A single neuron

ANNs as a data processing system consist of a large number of simple, highly interconnected processing elements in an architecture inspired by the brain's cerebral cortex structure, and there are several architecture ANN types. Simpson (1990) lists 26 different types of ANNs, Maren (1991) lists 48, and Pham (1994) estimates more than 50. Some networks are more proficient in solving perceptual problems, while others are more suitable for data modelling and functional approximation, but feed forward networks (i.e., Back-Propagation network (BP) and recurrent networks are the most widely used (Basheer & Hajmeer, 2000).

In Figure 5.4, the BP information flows in one direction along connecting pathways, from the input layer via the hidden layers to the final output layer. There is no feedback (i.e., all links are unidirectional and there are no same layer neuron-to-neuron connections), and the output of any layer does not affect that same or preceding layer. These networks are the most widely used types and are considered the workhorse of ANNs because of their flexibility and adaptability in modelling a wide spectrum of problems in many application areas (Widrow et al., 1994).

The recurrent network in Figure 5.5 differs from feed forward network architectures in that there is at least one feedback loop. Thus, these networks have one layer with feedback connections; they may also have neurons with self-feedback links (i.e., a neuron's output is fed back into itself as input).

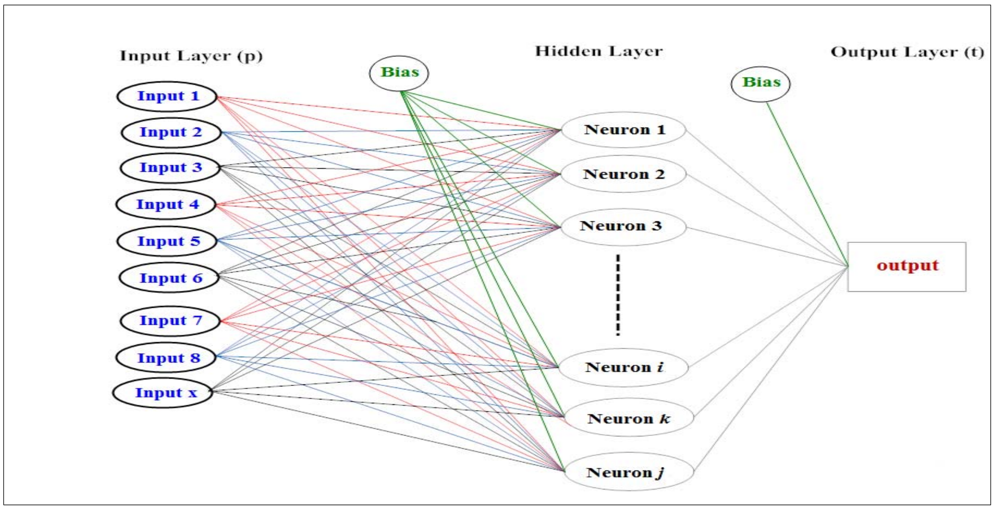

Figure 5.4: Feed forward network

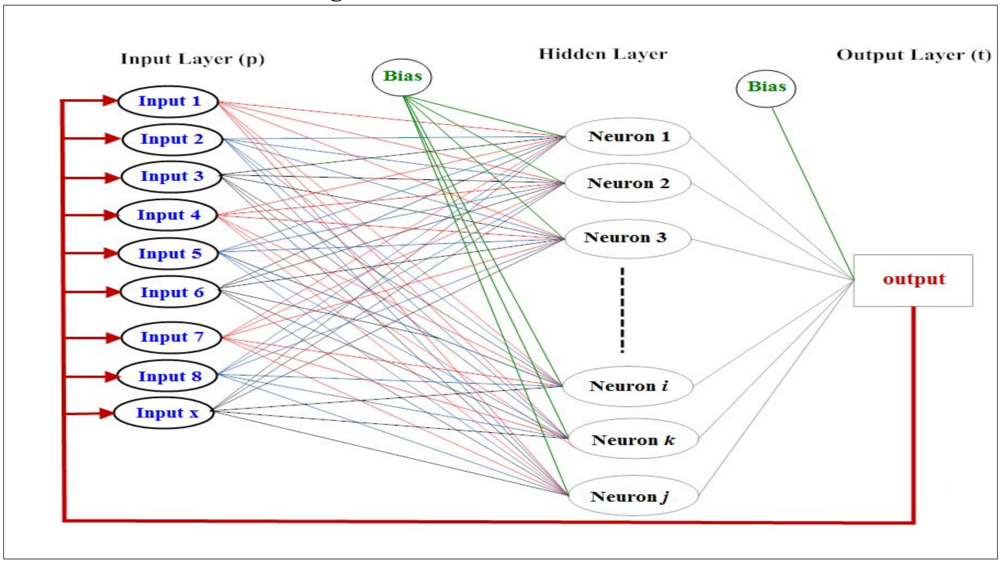

Figure 5.5: Recurrent network

This study uses BP because of three main factors: its ability to learn mapping from one data space to another using examples; high accuracy in capturing data's nonlinearity in (i.e., the relationship between inputs and outputs); and the simplicity in searching, accelerating, and stabilising the training process. BP is detailed in the next to expand the understanding of ANNs, identifying these systems and how to design them.

5.2.4. Characteristics of ANNs

ANNs are very sophisticated, nonlinear computational tools, capable of modelling extremely complex functions. Specifically, any given functional relation between a set of inputs and corresponding set of outputs can be represented by an opportunely chosen ANN architecture (Marini et al., 2008). ANNs have a remarkable result whenever there are problems of prediction, classification, or control. This sweeping success can be attributed to a few key factors listed as follows (Siegel *et al.,* 1998; Haykin, 1999; Etheridge *et al.,* 2000; Taha, 2012):

1. ANNs exhibit can map input patterns to their associated output patterns.

2. ANNs learn by example. Thus, ANN architectures can be “trained” with known examples of a problem before they are tested for their inference capability on unknown instances of the problem, and can therefore identify new objects.

3. ANNs possess the capability to generalize. Generalisation refers to the ANNs producing reasonable outputs for inputs not encountered during training (i.e., learning). Thus, they can predict new outcomes from past trends.

4. ANNs have flexibility and maintenance ease, as they adapt to environmental changes; they can also learn by experience and realise the relationship between variables to improve performance.

5. ANNs are robust, fault tolerant systems. Therefore, they can recall full patterns from incomplete, partial, and/or noisy patterns.

6. ANNs can solve new kinds of difficult problems. This has opened new fields for decision support applications that were difficult or impossible to be programmed in computers.

7. ANNs can deal with incomplete, confused, or not well-determined data, and can deal with unexpected conditions (much like the human brain). They can also deal with a large amount of data to create models in case there are no certain, known rules, and they provide accurate results when accurately built.

8. ANNs can process information in parallel and distributed manners at high speed, as they consist of a large number of processing elements that communicate with each other.

9. ANNs do not sufficiently test research hypotheses and give no important input variables. This makes it difficult to interpret results, and needs a long time to be learned.

10. ANNs use past data patterns for future predictions, meaning that they assume the future will be as the past. When change occurs in an environment or surrounding circumstances, network patterns are not better predictors than are statistical conventional patterns, unless they are reconstructed.

5.2.5. ANNs Applications

The types and uses of ANNs are very diverse; since McCulloch and Pitts' (1943) first neural model, hundreds of different ANN models have been developed. They differ in function, accepted values, topology, and/or learning algorithms (Haykin, 1999).

A review by Liao and Wen (2007), based 10,120 articles about ANN methodologies and application developments from 1995 to 2005, uses data mining to disclose the wide range of ANN applications in many fields of study. Other researchers have explored the use of hybrid ANNs with deferent methods, such as neuro-fuzzy for time series modelling (Nayak et al., 2004), neuro-fuzzy rule-based for stock market decision support modelling (Kuo et al., 2001), Bayesian neural networks for medicine (Caballero & Fernandez, 2008), and Dempster-Shafer neural network for navigation technology (Aggarwal et al., 2013).

In addition, ANNs have been used for a wide variety of applications where statistical methods or Expert Systems (ES) are traditionally employed. They have been used in classification problems—such as identifying underwater sonar currents—recognising speech, and predicting the secondary structure of globular proteins. In time-series applications, ANNs have been used to predict stock market performance, discriminate analysis, logistic regression, Bayes analysis, multiple regression, and Autoregressive Integrated Moving Average (ARIMA) time-series models. It is, therefore, time to recognise neural networks as a powerful tool for data analysis (Turban et al., 2011).

ANNs' success increases as a problem's dimensionality and/or increases, because traditional regression statistical methods often fail to produce accurate approximations. Accordingly, ANNs may be employed for modelling with low data dimensionality or for approximating simple functions when higher accuracy is desired. Moreover, ES is a computer program that mimics the human reasoning process, which relies on logic, belief, rules of thumb, opinion, and experience. However, unlike ANNs, ES suffer from major limitations, mainly their hypersensitivity to incomplete and/or noisy data (i.e., uncertainty), and some human knowledge cannot be expressed explicitly by rules (Fu, 1995). As a result, ANNs are more robust and often outperform other computational tools in solving a variety of problems.

Literature contains many examples of ANNs models, demonstrating that ANNs have a broad field of successful applications in mapping, regression, modelling, clustering, and classification. They are flexible, which makes them adaptable to different kinds of problems and customizable for nearly any data representation design.

5.2.6. ANN software

ANNs' software is used for different kinds of problems, and software choice depends on the problem's classification and features, the type of learning algorithm, and affordability. the software's can be described as follows.

5.2.6.1. Commercial software

Multiple types of neural network software have been developed, and are not limited to commercial software: Environment for Computer Aided Neural Software Engineering (ECANSE) (Blaško, 2000); Matlab: Neural Network Toolbar (MATLAB, 2013); Neuroshell 1 and 2 (WSG, 2007); and Statistica Neural Network (Statistica NN, 1998).

5.2.6.2. Freeware software

Other examples but not limited to the freeware software including: Net II, Spider Nets Neural Network Library, NeuDC, Binary Hopfield Net with free Java source, Neural shell, PlaNet, Valentino Computational Neuroscience Work bench, Neural Simulation language version-NSL, and Brain neural network Simulator.

Among ANN software, Matlab is a high-level language and interactive environment for numerical computation, visualisation, and programming that allows for analysing data, developing algorithms, and creating models and applications. Matlab computer language, tools, and built-in math functions can explore multiple approaches and reach a solution faster than with spreadsheets or traditional programming languages. It also has the functions to integrate based algorithms with external applications and other programming languages.

The proposed Failure Modes and Effects Analysis ANNs (FMEANNs) approach constructs two multilayer perceptron neural network models, namely BNANNs and

EvRANNs, which are independently designed then integrated into the AnBnEvR model. In order to achieve the goal and based on the aforementioned, the Neural Network Toolbox Version 7.8 of MATLAB® mathematical software predicts risk evaluation for a container terminal.

5.3. Methodology

The FRBN and FRBER methods were developed and tested using the 24 HEs identified in Chapters 3 and 4 respectively. However, their complex inference process has been criticised in practical applications. The proposed models using ANNs are constructed to ease the risk inference analysis of ports in both HE and system levels. As a result, it was found that HE6, HE7, and HE16 greatly influence the risk index on a container terminal, both locally and globally.

A multilayer perceptron neural network model design is mostly composed of an ED set collection used for model training and testing, followed by network creation and configuration based on pre-processing and analysis of the data set. Next comes network training and validation, and finally, simulations and predictions (Eren et al., 2012).

The three parts for developing novel FMEANNs and modelling FRBN and FRBER using the ANN approach are outlined as follows.

1. Design the BNANNs model to simulate the FRBN method in chapter 3 (Alyami et al., 2014). FRBN has 12 inputs based on the four risk parameters and the linguistic terms for each risk parameter (i.e., each risk parameter; L, C, P, and I, have three inputs of High, Medium, and Low). The risk evaluation output for each HE identified has three linguistic terms (i.e. High, Medium and Low).

2. Design the EvRANNs model to simulate the FRBER method, which has nine inputs based on three HE risk evaluations resulting from BNANNs (i.e., in each BNANNs output, each HE has three outputs of High, Medium, and Low), with only one output processed in FRBER.

3. Construct the AnBnEvR model by integrating the above models, creating a risk prediction tool that provides a panoramic view of the safety management system of a container terminal's operation performance.

5.3.1. Methodology algorithms

5.3.1.1. Algorithms of modelling performance criteria

In a typical ANN, the input layer is composed of the ED *(X_i)*, which is associated with the input layer's neurons *(1, 2…, i,… m)*. The input signals are fed into the input layer, then transferred to the hidden layers' neurons *(1, 2…, j,… n),* where processing takes place by multiplying connection weights *(w_{ij})* between two neurons and using the summation function to deliver output signals to the output layers *(1, 2…, k,… p)* (Bilgili et al., 2007).

Each layer's input data is processed to outputs using an activation (i.e., transfer) function, a nonlinear mathematical function known as a "transfer function." The most widely used transfer functions are *tansig*, logarithmic sigmoid *(logsig)*, and *purelin*, described respectively below and illustrated in Figure 5.6. The *tansig* activation function offers slightly better predictions than the others and most commonly used in the hidden layer with *purelin* activation function in the output layer (Kaveh et al., 2008; Magharei et al., 2012; Mashhadi et al., 2013).

$$f(x) = \frac{1}{1+e^{-x}} \tag{5.2}$$

$$f(x) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}} \tag{5.3}$$

$$f(x) = x \tag{5.4}$$

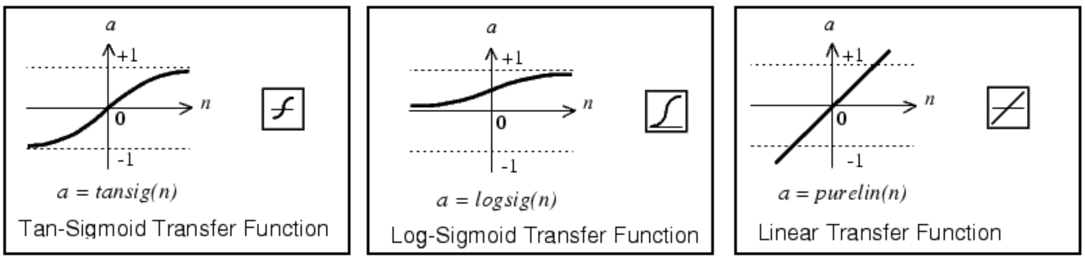

Figure 5.6: Graphical representation for activation (transfer) functions

The data flow process for a single neuron in the network starts with each input streaming multiplied by a weight (*w*) and summed using the summation function. Then, this single value is processed through a transfer function to produce the output value of a neuron, as illustrated in Figure 5.7 (Kaveh et al., 2008).

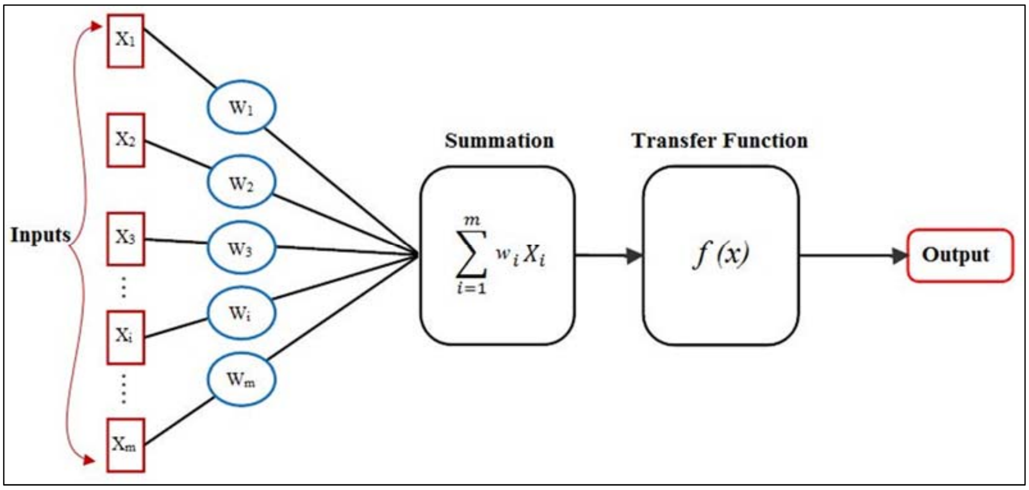

Figure 5.7: Data flow process in a neuron

Selecting a training algorithm and activation function is of crucial importance for robust ANN model performance. In general, linear functions are used for input and output layers, and nonlinear transfer functions for hidden layers (Yetilmezsoy & Demirel, 2008).

Levenberg Marquardt Back Propagation (LMBP) is the most widely used optimisation algorithm for a variety of ANN problems. It is preferred for its speed and stability in training the ANN models. Literature discloses that LMBP is the best algorithm, producing minimum errors between predicted outputs and corresponding targets, and it is associated with the highest regression (i.e., the relationship between ED and model predictions in the testing phase) compared to other BP algorithms in several domains (Yetilmezsoy & Demirel, 2008; Elmolla et al., 2010; Eren et al., 2012; Süt and Çelik, 2012; Reynaldi et al., 2012; Jeffrey et al., 2014; Abushammala et al., 2014). The LMBP network training function (*trainlm*) updates weight and bias values according to LMBP algorithm optimisation and is often the fastest BP algorithm in the MATLAB toolbox; it is highly recommended as a first choice supervised algorithm, although it requires more memory than other algorithms (MATLAB, 2013).

The LMBPA optimisation is a standard technique for nonlinear, least square problems, and was applied in this study to simulate actual risk estimation values for constructing a risk prediction system. It was independently developed by Kenneth Levenberg and Donald Marquardt and modified with the Gauss Newton method it is the steepest descendent method for providing a numerical solution to a problem of minimising a nonlinear function, and has stable convergence (Haykin, 1999). The LMBPA data training algorithm procedure is as follows (Najjar et al., 1997; Basheer & Hajmeer, 2000; Jeffrey et al., 2014):

1. Initialise the weights and thresholds in the hidden and output layer, often in the range of [−1, 1].

2. Calculate the hidden layer y value:

$$y_j(p) = tansig\left[\sum_{i=1}^{n} x_i(p) w_{ij}(p) - \theta_j\right] \tag{5.5}$$

where *tansig* is the transfer function

n is the number of neurons in the hidden layer,

x_i is the number of inputs,

w_{ij} is the weights, and

θ is the threshold value.

3. Calculate the output layer y value:

$$y_k(p) = tansig\left[\sum_{j=1}^{n} x_{ik}(p) w_{jk}(p) - \theta_k\right] \tag{5.6}$$

where m is the number of neurons in the hidden layer and θ is the threshold value.

4. Calculate the output layer error:

$$\delta_k(p) = y_k(p)[1 - y_k(p)]e_k(p) \tag{5.7}$$

$$e_k(p) = y_{d,k}(p) - y_k(p) \tag{5.8}$$

5. Correct the output layer weight w:

$$\Delta w_{jk}(p) = \alpha y_j(p)\delta(p) \tag{5.9}$$

$$\Delta w_{jk}(p+1) = w_{jk}(p) + \Delta w_{jk}(p) \tag{5.10}$$

6. Calculate the hidden layer error δ:

$$\delta(p) = y_j(p)[1 - y_j(p)]\sum_{k=1}^{1}\delta_k(p)w_{jk}(p) \tag{5.11}$$

7. Correct the hidden weight *w*:

$$\Delta w_{ij}(p) = \alpha x_i(p)\delta_j(p) \tag{5.12}$$

$$w_{ij}(p+1) = w_{ij}(p) + \Delta w_{ij}(p) \tag{5.13}$$

The steepest descendent method has a very fast convergence speed; however, when the optimal point is reached due to a decreasing gradient, the convergence speed slows. Therefore, the Newton method is integrated with the steepest descendent method to obtain excellent convergence effects when approaching the optimal point (Jeffrey et al., 2014). Accordingly, the performance function has the form of a square sum and represents the Hessian matrix, which is as follows:

$$H = J^T J \tag{5.14}$$

$$g = J^T e \tag{5.15}$$

where *J* is the Jacobian matrix, containing the first order differentiation of the network error against weight and partial weight, and

e is the network error vector and *g* is the gradient.

The basic principles of the Newton Method are:

$$X_{k+1} = X_k - A_k^{-1} g_k \tag{5.16}$$

where A_k is the Hessian matrix, namely, the second order differentiation of the performance function in the weights and partial weights.

$$A_k = \nabla^2 f(X) \tag{5.17}$$

$$g_k = \nabla f(X) \tag{5.18}$$

The LMBP Algorithm uses the Hessian matrix the value to correct the Newton method:

$$X_{k+1} = X_k - \left[J^T + \mu I\right]^{-1} J^T e \qquad (5.19)$$

where parameter μ ensures that matrix inversion will always produce a result, and this parameter will depend on evaluation of sum of squared errors.

The LMBP algorithm has characteristics of the steepest descendent method; consequently, it has a positive relationship with value, so if the error is large, the value will be also in order to increase convergence speed, and vice versa (Jeffrey et al., 2014). The complete derivation of the algorithm can be found elsewhere (Zupan and Gasteiger, 1993; Haykin, 1999; Jeffrey et al., 2014), and a clear systematic derivation is given by Najjar et al., (1997).

5.3.1.2. Algorithms of modelling assessment criteria

Output values *(Y1,…Yk,…Yp)* are compared with target values *(Z1,…Zk,…Zp)* (i.e., experimental results) to assess model predictions. The differences between predicted values and target values are evaluated against the modelling performance criteria established within the ANN algorithm. Hence, it is necessary to reprocess output values if modelling performance criteria are not met (Bilgili et al., 2007; Kaveh et al., 2008).

The MSE and the R^2 value are the most common performance criteria for the ANN model performance evaluation (Erena et al., 2012).

The optimum number of neurons was determined by the minimum MSE value from the training and prediction dataset. The MSE represents the difference between an approximating function $F(w,x_i)$ of the adjustable weight (w) for the predicted values and target values (i.e., the error) with a range from 0 to 1 where the lower values of MSE are preferable (Kaveh et al., 2008; Elmolla et al., 2010; Sütand Çelik, 2012). It is computed as follows.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_{model,i} - y_{obs,i})^2}{n}} \qquad (5.20)$$

where n is the number of target values and $y_{obs,i}$ and $y_{model,i}$ are target values and their corresponding predicted value, respectively.

R^2 shows the percentage of variability between ED and predicted data. R^2 values range between zero and one, in which $R2 \text{ value} \approx 1$ means a greater correlation and stronger relationship between predicted and actual values (Kaveh et al., 2008). It can be computed as:

$$R^2 = \left[\frac{n\sum_{i=1}^{n} y_{obs,i}\, y_{\mathrm{mod}\ el,i} - \left(\sum_{i=1}^{n} y_{obs,i}\right)\left(\sum_{i=1}^{n} y_{\mathrm{mod}\ el,i}\right)}{\sqrt{\left(n\sum_{i=1}^{n} y_{obs,i}^2 - \left(\sum_{i=1}^{n} y_{obs,i}\right)^2\right) \times \left(n\sum_{i=1}^{n} y_{\mathrm{mod}\ el,i}^2 - \left(\sum_{i=1}^{n} y_{\mathrm{mod}\ el,i}\right)^2\right)}} \right]^2 \qquad (5.21)$$

The MSE and R^2 values provide information on general error ranges between predicted and target values.

The above criteria are commonly used for validating models and their predictions. Notably, however, the ED quality is an essential requirement for modelling work; otherwise, the results of statistical tests and model predictions will be inaccurate (Erena, 2012; Hezave et al., 2012).

5.4. Development of ANN Modelling in Maritime Ports

The FRBN introduced in chapter 3 individually evaluates the criticality of the 24 HEs in a container terminal, using four risk parameters: HE occurrence probability (L), HE consequences/severity (C), HE impact on the resilience of port operational systems (I), and the probability of HE being undetected (P). The four risk parameters are constructed to form the IF part, while the RE of failures is presented in the THEN part associated with three linguistic grades. DoB of High (H), Medium (M), and Low (L) are employed to describe L, C, P, I, and R. The degrees of the parameters, calculated by the Bayesian networks method for each HE, are based on knowledge accumulated from past events, taking into account domain experts' judgements. The process is illustrated in Figure 5.8.

$$\begin{bmatrix} L_{H_X} \\ C_{H_X} \\ P_{H_X} \\ I_{H_X} \end{bmatrix} \xrightarrow{FRBN} [H_X] \qquad \begin{bmatrix} L_{M_X} \\ C_{M_X} \\ P_{M_X} \\ I_{M_X} \end{bmatrix} \xrightarrow{FRBN} [M_X] \qquad \begin{bmatrix} L_{L_X} \\ C_{L_X} \\ P_{L_X} \\ I_{L_X} \end{bmatrix} \xrightarrow{FRBN} [L_X]$$

Figure 5.8: FRBN process

where (*X=1,2...24)* is the HE number.

FRBEvR uses the results from FRBN and the evidential reasoning method to aggregate the 24 HEs and evaluate their collective criticality in a container terminal. The Risk level of the System (RoS) is a single value for a container terminal, shown in Figure 5.9.

$$\begin{bmatrix} H_1 & M_1 & L_1 \\ H_2 & M_2 & L_2 \\ \vdots & \vdots & \vdots \\ H_X & M_X & L_X \end{bmatrix} \xrightarrow{FRBEvR} RoS$$

Figure 5.9: FRBEvR process with ANNs

Two three-layers ANN models were developed to predict risk evaluation of a container terminal operation for each HE individually and aggregated collectively. The ANN architecture simulates the FRBN and FRBER methods. They consist of an input layer, hidden layer, and output layer. Optimal network architecture was determined as one hidden layer with 40 neurons using the LMBP algorithm, with transfer function *tansig* at the hidden layer and transfer function *purelin* at the output layer.

Although the two models have the same features, they differ in trajectories concerning input and the output structures. The number of neurons in the input layer is twelve and nine, while the number of neurons in the output layer is three and one for BNANNs and EvRANNs respectively. As a result, the network architecture for BNANNs and EvRANNs is constructed as (12 - 40 - 3) and (9 - 40 - 1) respectively. It is noteworthy that there are no clear guidelines for choosing an appropriate number of neurons in the hidden layer; this is generally optimised by trial and error (Bilgili et al., 2007; Dogan et al., 2008; Yetilmezsoy and Demirel, 2008; Kaveh et al., 2008; Turp et al., 2011; Süt and Yahya, 2012; Eren et al., 2012; Hezave et al., 2012; Magharei et al., 2012; Sudhakaran et al., 2013; Mashhadi et al., 2013).

AnBnEvR is an integration of BNANNs and EvRANNs, and it completes the prediction of a container terminal operation's risk evaluation in a panoramic safety performance view.

5.4.1. Experimental data processing

The EDs in this study are partially obtained (i.e., actual data for testing) from previous chapters (i.e., Chapters 3 and 4). As aforementioned, the relationship between the FRBBN and FRBEvR is that the outputs of the former are used as inputs for the latter.

The total dataset used in this research consists of 24 HEs, although, it was attempt to use the same dataset in this study. However, as aforementioned, ANNs are constructed based on risk inference analysis of the FRBBN and FRBER HEs which disclosed that HE6, HE7, and HE16 have a great influence on a container terminal's risk index from both perspectives, individually and aggregated collectively among other HEs. It is noteworthy that BNANNs can process each HE, since the evaluation is individually conducted, while EvRANNs cannot because the HEs have to be processed collectively due to the ER technique's aggregation feature. Therefore, HE6, HE7, and HE16 are used for the EvRANNs' model architecture.

The previous chapters' EDs are relatively inadequate for training the ANN model, since the FRBN method's actual data is classified as 12 inputs, with three outputs for each HE. The FRBER method is classified as 72 inputs with one output as one set for the aggregated HEs, which is modified based on the above conditions to be nine inputs with one output; this is mainly because the ED generated for ANN architecture and training should cover the region of predicted results.

The ED has to be large, although its size creates a greater computational burden; on the other hand, it eliminates the ANN model's propensity for over fitting (Yetilmezsoy & Demirel, 2008; Dhar et al., 2013). The simulated processes cannot be outside the input variables' domain, as ANN modelling is not comprehensive; this is an important aspect for providing a viable predicting tool (Abushammala et al., 2014).

As ED has a great influence on ANN modelling performance's accuracy, a generation of a suitable EDs was conducted for modelling FRBN and FRBER methods. Although it was challenging to obtain the required EDs for training ANNs due to lack of objective failure data in container terminals, EDs were created and obtained using the Python program (Lutz, 1996; Ong et al., 2013). The generated EDs' objective is to make the relationship between inputs and outputs maximally informative, while ensuring that the EDs adequately cover the region between zero and one with plausible inference intervals and maintaining each model's characteristics. Above all, the constructed models based on generated EDs makes them applicable for any other maritime container terminal for risk evaluation and prediction. More details on generating EDs, BNANs, and EvRANNs are in Sections 5.5.1 and 5.6.1.

5.5. Bayesian Network ANNs (BNANNs) Model Design

The BNANN model consists of 12 inputs representing the four risk parameters—L, C, P, and I—and three outputs representing the RE in FRBN (i.e., ANN target). The simulation of FRBN using ANNs uses the following steps.

1. ED analysis
2. BNANNs model optimisation
3. Results validation

5.5.1. Experimental data analysis

As mentioned in Section 5.4, The four risk parameters are constructed to form the IF part, while the RE of failures is presented in the THEN part associated with three linguistic grades. DoB of High (H), Medium (M), and Low (L) are employed to describe L, C, P, I, and R. Therefore, it can be classified as 12 inputs with 3 outputs for each HE in FRBN. The actual data obtained from chapter 3, Section 3.4.3.4 for the 24 HEs cannot adequately train the ANN model as previously concluded in Section 5.4.1, mainly because the ED set amount is insufficient. As a result, ED needs to be generated.

For the generated ED to train and test the ANN model with the best prediction results, the simulated processes (i.e., predicted input and output values) should be inside the variables' domain, meaning that every possible risk parameter assessment should be included. In other words, if the predicted input and output values are not inside the trained ANN variables domain, the predicted results will be inaccurate or incorrect.

A 0.2 inference interval is applied among DoB in each risk grade for each risk parameter and the reason behind that is to cover the region between zero and one (i.e. 0-1); this not only narrows the range of deviation between input and consequently output values, but also adequately increases the training dataset.

The number of ED sets depends on the number of risk parameters. Transferring the inference interval of 0.2 from zero to one resulted in 21 possible combinations between the four risk parameters with the associated grades and DoB. Accordingly, the sum of all possible combinations is calculated as (21×21×21×21= 194481).

As a result, the ED containing 194,481 sets, with 12 inputs and three outputs in each set, is obtained and partially shown in Table 5-1.

Table 5.1: BNANNs experimental datasets generated

	BNANNs Model Inputs												**ANNs Model Outputs**		
Risk Parameters	**L**			**C**			**P**			**I**			**RE**		
Risk Grades / No.	**H**	**M**	**L**	**H**	**M**	**L**	**H**	**M**	**L**	**H**	**M**	**L**	**H**	**M**	**L**
1	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0
2	1	0	0	1	0	0	1	0	0	0.8	0.2	0	0.95	0.05	0
3	1	0	0	1	0	0	1	0	0	0.8	0	0.2	0.95	0	0.05
4	1	0	0	1	0	0	1	0	0	0.6	0.4	0	0.9	0.1	0
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
194478	0	0	1	0	0	1	0	0	1	0	0.6	0.4	0	0.15	0.85
194479	0	0	1	0	0	1	0	0	1	0	0.4	0.6	0	0.1	0.9
194480	0	0	1	0	0	1	0	0	1	0	0.2	0.8	0	0.05	0.95
194481	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1

5.5.2. BNANN model optimisation

After selecting *trainlm* as the best training algorithm for the BNANN model and having analysed the ED set, the optimal BNANN model architecture and its parameter variation is determined; this is accomplished by selecting the optimum number of neurons in the hidden layer based on the minimum MSE value and the observed and predicted training and testing set values.

There is no specific rule regarding the amount or percentage of data for training or testing and validation. The general guideline is that training data should be more than the testing and validation data (Kaveh et al., 2008; Sudhakaran et al., 2013).

Hence, out of the total ED set (i.e., 194,481) that was randomly divided by *trainlm*, 70% (i.e., 136,137) was used for training, 15% (i.e., 291,72) for testing, and 15% (i.e., 291,72) for validation. In optimising the network, 15 neurons were used in the hidden layer as an initial guess, then the number of neurons was changed by increasing 10 neurons in each trial.

The preliminary trials indicated that the learning and prediction ability of 25 neurons in the hidden layer networks was better than that of 15 neurons. This was realised after several attempts to gradually increase the number of neurons and observe their effect on the predicted value; the training data error decreased, while that of validation data increased. Six local minimum MSE values were observed at neuron numbers of 15, 25, 35, 38, 40, and 45.

However, the neural network architecture with 40 hidden neurons reached the minimum MSE when training, validating, and testing the BNANN model. Thus, 40 neurons were chosen as the optimum number for the hidden layer. The network structure was 12-40-3 (12 neurons in the input layer, 40 in the hidden layer, and three in the output layer).

The optimal BNANNs, together with a flowchart of the LMBP algorithm, are shown in Figure 5.10, a three-layer ANNs of 12 neurons at input layer with *tansig* transfer function at hidden layer with 40 neurons and a *purelin* transfer function at output layer.

The training ended after 1,000 iterations (*trainlm*, Epoch 1000) for the LMBP, because the differences between training and validation errors started to increase.

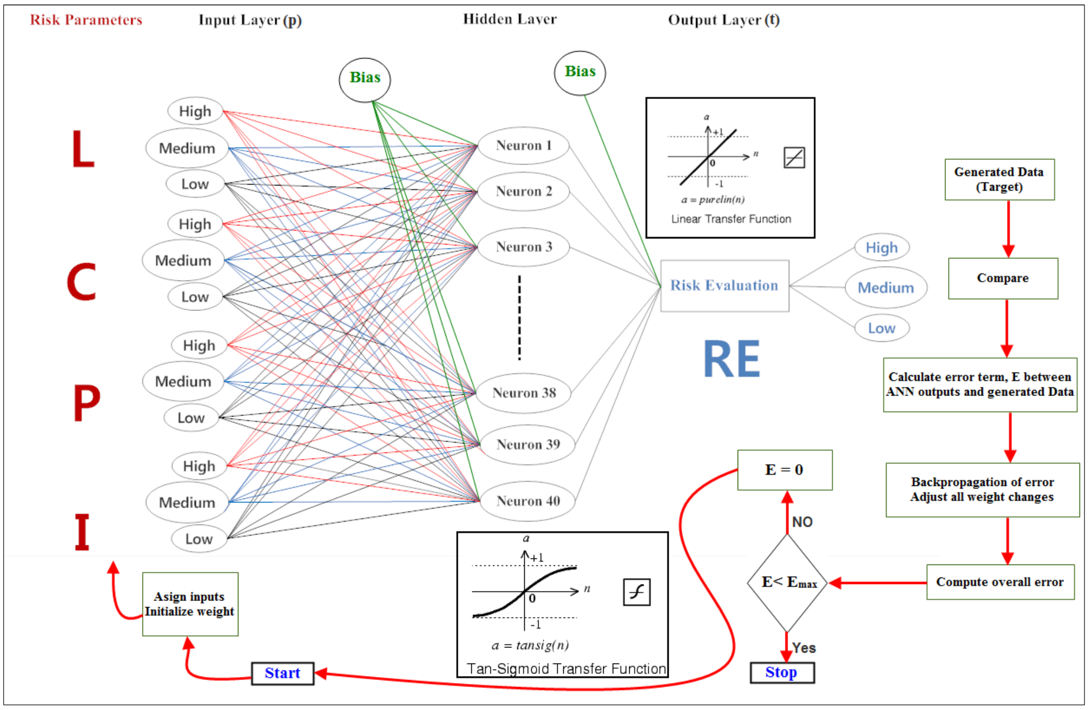

Figure 5.10: Optimal BNANN structure with a flowchart of the LMBP

5.5.3. Results validation

The network's MSE was very high, with 15 hidden neurons (MSE 0.0524618), and it decreased significantly to (MSE 0.0017914) with 25 hidden neurons. The number of neurons then increased from 25 to 35, and a gradual decrease was observed in the (MSE 0.00002151). Next, the 35 hidden neurons slightly increased to 45 among the (MSE 0.001394). Then, 40 neurons were tested, and the MSE reached its minimum value of 0.000001334. The neural network containing 40 hidden neurons (MSE 0.000001334) was chosen as the best case. When the number of neurons was less than 40, the MSE showed a slight increase from 0.000001334 to 0.000002164 at 38 neurons, as depicted in Figure 5.11. This increment can be attributed to the characteristics of this study's MSE performance index and input vector, and it shows the dependence between MSE and number of hidden layer neurons for the LMBP.

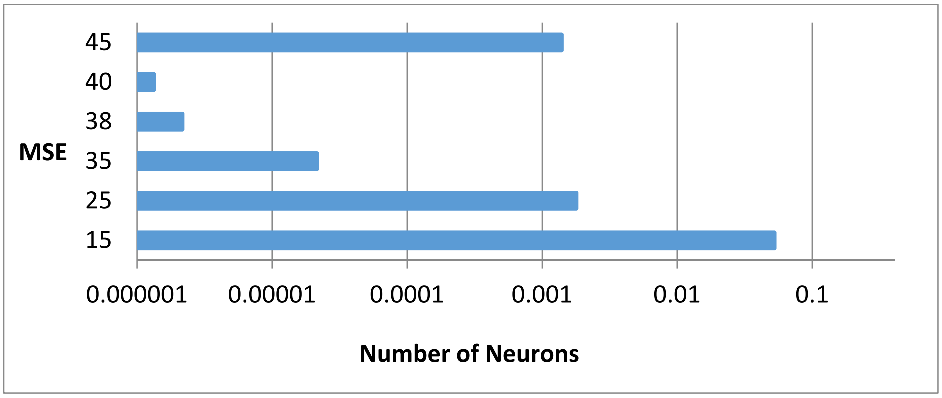

Figure 5.11: MSE for BNANN tuning

The training, validation, and test's mean squared errors for the BNANNs using the LMBP algorithm are illustrated in Figure 5.12; it shows that, with 40 neurons, the effect on training data error decreased while that on validation data increased.

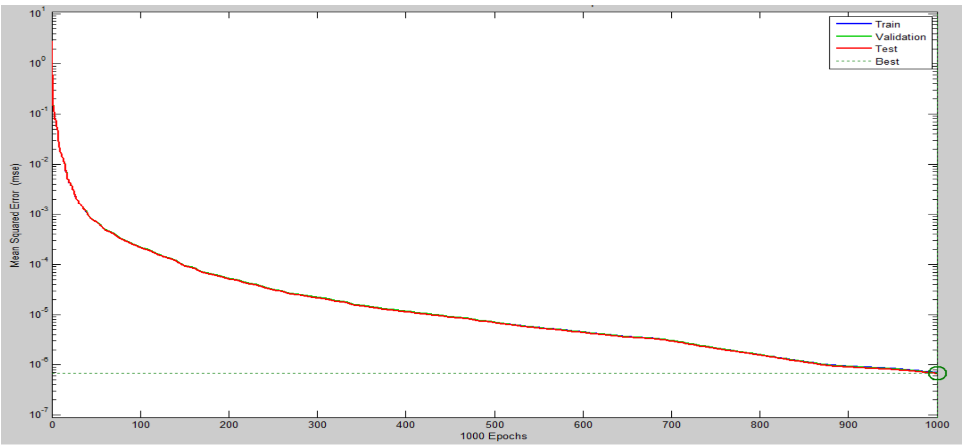

Figure 5.12: Training, validation, and test's mean squared errors for BNANNs

The regression analysis of the network response between BNANN outputs and the corresponding targets was performed. The graphical output of the plotted network outputs versus the targets as open circles is illustrated in Figure 5.13. Taking into account the data's non-linear dependence, linear regression shows a perfect agreement between BNANN outputs (predicted data) and the corresponding targets (i.e., ED). The solid red, blue, green, and black lines—which respectively represent test, training, validation, and combination of all three— indicate the perfect linear fit that $R^2 \approx 1$.

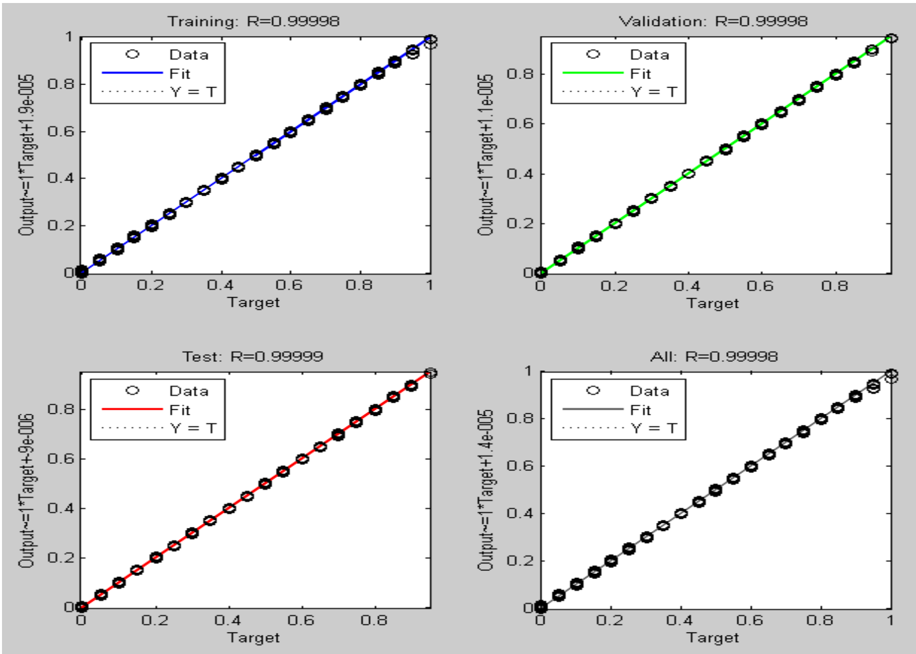

Figure 5.13: BNANN regressions

The previous statistical analysis shows that BNANN model predictions are very close to the ED. In addition, to confirm the developed model's robustness and predictive capability, the optimal BNANN model's performance was evaluated using another data set consisting of the actual data obtained in chapter 3, which was not used in the training stage. Consequently, a simulink model of the BNANNs was constructed, as shown in Figure 5.14. Table 5.2 shows that the results, along with the correlation coefficient between the actual and predicted datasets, provide a high accuracy and a perfect match.

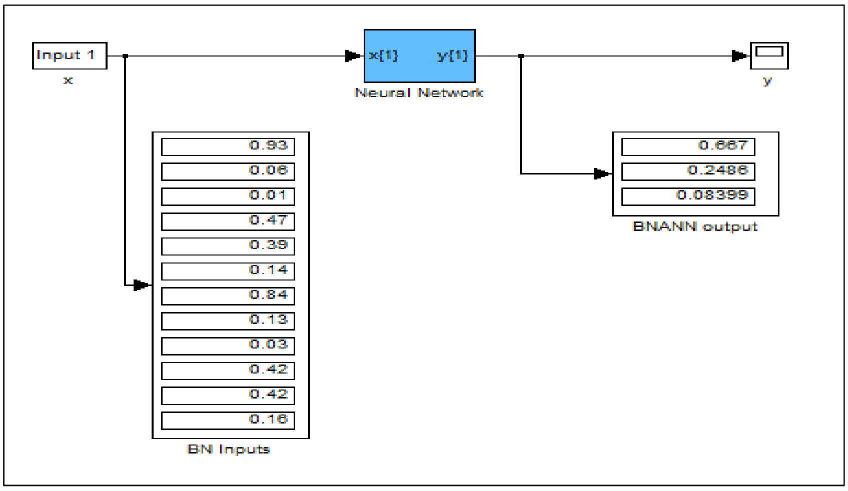

Figure 5.14: The simulink model of the BNANNs

Table 5.2: BNANN correlation coefficient

No.	FRBN output				BNANNs output		
	High	Medium	Low		High	Medium	Low
1	0.665	0.25	0.085		0.667	0.249	0.084
2	0.57	0.2525	0.1775		0.57	0.2519	0.1769
3	0.5875	0.1625	0.25		0.588	0.1617	0.25
4	0.735	0.1325	0.1325		0.7363	0.132	0.132
5	0.7275	0.085	0.1875		0.728	0.085	0.187
6	0.71	0.055	0.235		0.7099	0.056	0.235
7	0.655	0.0975	0.2475		0.655	0.0977	0.2477
8	0.5975	0.1125	0.29		0.5966	0.1134	0.289
9	0.375	0.275	0.35		0.375	0.275	0.35
10	0.5175	0.2275	0.255		0.5172	0.2275	0.2551
11	0.6	0.21	0.19		0.5997	0.2103	0.1898
12	0.585	0.185	0.23		0.5845	0.1854	0.2299
13	0.6675	0.1125	0.22		0.666	0.1137	0.22
14	0.5975	0.1525	0.25		0.5972	0.1527	0.25
15	0.6825	0.085	0.2325		0.6816	0.0855	0.2328
16	0.49	0.225	0.285		0.4896	0.2248	0.2853
17	0.44	0.125	0.435		0.44	0.1248	0.4344
18	0.4775	0.0775	0.445		0.4788	0.07729	0.4448
19	0.3875	0.16	0.4524		0.388	0.16	0.4521
20	0.4075	0.1575	0.435		0.4079	0.1575	0.4349
21	0.395	0.22	0.385		0.3947	0.22	0.3848
22	0.4275	0.1625	0.41		0.4276	0.1628	0.4098
23	0.39	0.2325	0.3775		0.39	0.2321	0.3775
24	0.3075	0.1625	0.53		0.308	0.1623	0.5298
Correlation					0.999983	0.999961	0.999995

5.6. Evidential Reasoning ANNs (EvRANNs) Model Design

As aforementioned, FRBEvR model inputs are taken directly from the FRBN model. The previous section's BNANN model describes the simulation of the FRBBN model. Therefore, the EvRANNs model is based on results directly taken from the BNANNs model. Only taking the top three HEs that influencing the risk index individually and aggregated collectively on a container terminal. Accordingly, the EvRANNs model consists of nine inputs representing the risk evaluation R (i.e., BNANN results) for HE6, HE7, and HE16, and one output representing the risk evaluation of a container terminal's entire system. The ER simulation using ANNs is described as follows:

1. Experimental data analysis
2. EvRANN model optimisation
3. Results validation

5.6.1. Experimental data analysis

The reason for having an insufficient ED set in designing BNANNs applies here; therefore, the exact criteria and logic for inference intervals were used for generating ED sets to train and test the EvRANN model as previously conducted in Section 5.5.1. However, it is three risk parameters instead of four and the sum of all possible combinations between the three HEs with the associated grades and DoB is calculated as (21×21×21= 9261). Therefore, the EDs contained 9261 sets with nine inputs and one output in each set. This is obtained and partially shown in Table 5-3.

Table 5. 3: EvRANN experimental datasets generated

No.	EvRANNs Model Inputs									ANNs Model Outputs
	HE 1			HE 2			HE 3			
	High	Medium	Low	High	Medium	Low	High	Medium	Low	RI
1	1	0	0	1	0	0	1	0	0	1
2	1	0	0	1	0	0	0.8	0.2	0	0.9778
3	1	0	0	1	0	0	0.8	0	0.2	0.9556
4	1	0	0	1	0	0	0.6	0.4	0	0.9529
...	....	.....	.....	.....	.....	.....	.....	.....	.....	.....
9258	0	0	1	0	0	1	0	0.6	0.4	0.075
9259	0	0	1	0	0	1	0	0.4	0.6	0.0471
9260	0	0	1	0	0	1	0	0.2	0.8	0.0222
9261	0	0	1	0	0	1	0	0	1	0

5.6.2. EvRANNs model optimisation

The same training algorithm used for the BNANN model was also used with EvRANNs (i.e., *trainlm*), including the same performance and assessment criteria with typical process and sequence of neurons number trails selection, which started with 15 neurons.

During several preliminary trial attempts to gradually increase the number of neurons and observe their effect on the predicted value, the training data error decreased and validation data error increased; this indicated that the learning and prediction ability of 25 neurons in the hidden layer networks was better than that of 15 neurons. Six local minimum MSE values were observed at neuron numbers of 15, 25, 35, 38, 40, and 45. However, the neural network architecture with 40 hidden neurons reached the minimum MSE when training, validation, and testing the EvRANN model. Consequently, 40 neurons were chosen as the optimum number for the hidden layer. Finally, the structure of the network was 9-40-1 (nine neurons in the input layer, 40 in the hidden layer, and one in the output layer).

The optimal EvRANNs, together with a flowchart of the LMBP algorithm, is shown in Figure 5.15. It shows a three-layer ANN of nine neurons at the input layer with a *tansig* transfer function at hidden layer, and 40 neurons and a *purelin* transfer function at output layer.

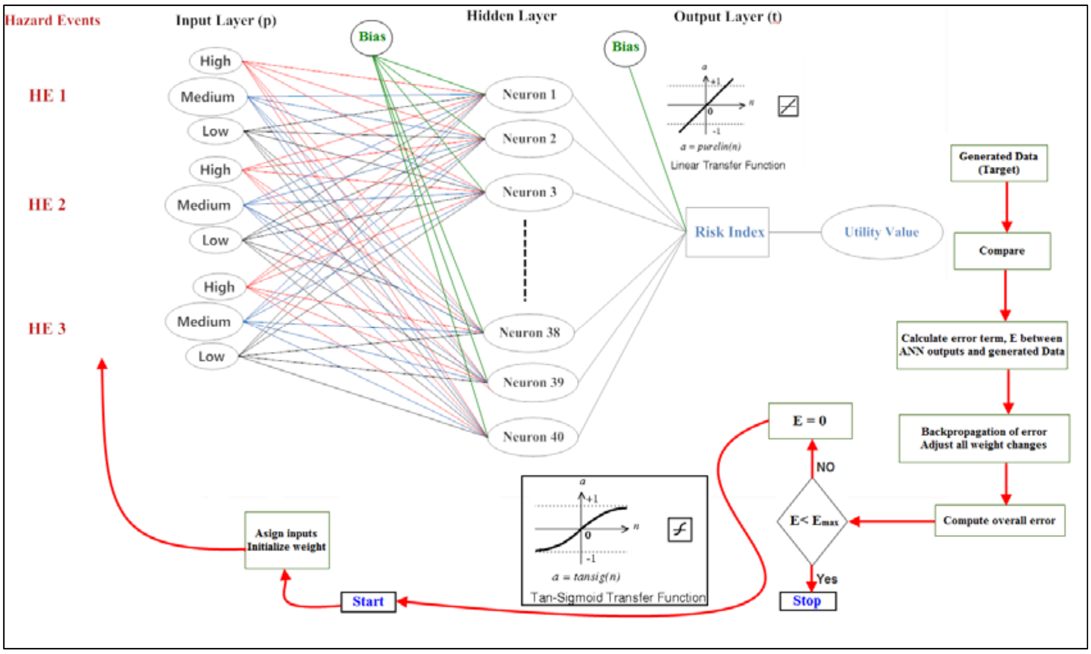

Figure 5.15: Optimal EvRANN structure, with a flowchart of the LMBP

The LMBP training ended after 51 iterations (*trainlm*, Epoch 51) because the differences between training and validation error started to increase.

As previously stated, there is no specific rule regarding the amount/percentage of data for training or testing and validation. The general guideline is that training data should be more than testing and validation data. Hence, out of the total dataset (i.e., ED, 9,261) that was randomly divided by *trainlm*, 70% (i.e., 6,483) was used for training, 15% (i.e., 1,389) for testing, and 15% (i.e., 1,389) for validation.

5.6.3. Results validation

The network's MSE was very high for the 15 hidden neurons (MSE 0.556) and decreased significantly from 25 to (MSE 0.0000679). Then, as the number of neurons increased from 25 to 35, the (MSE 0.0000617) decreased. Next, the (MSE .516) increased from 35 hidden neurons to 45. Therefore, 40 neurons were tested, and the MSE reached its minimum value of 0.00001344. Therefore, the neural network containing 40 hidden neurons (MSE 0.00001344) was chosen as the best case. When the number of neurons was less than 40, MSE slightly increased from 0.000001334 to 0.000019 with 38 neurons, as depicted in Figure 5.16. This increment can be attributed to the characteristics of this study's MSE performance index and input vector, and it shows the dependence between MSE and number of hidden layer LMBP neurons.

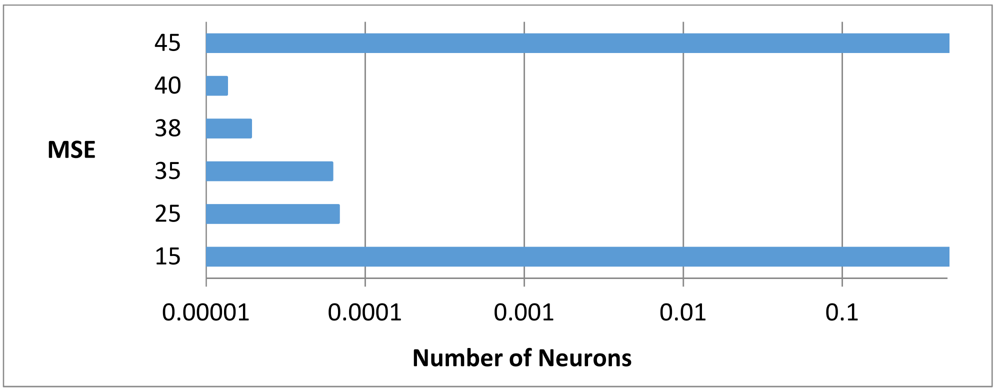

Figure 5.16: MSE for EvRANN optimisation

The BNANN training, validation, and test's mean squared errors for using the LMBP algorithm are illustrated in Figure 5.17. It clearly shows that, with 40 neurons, the effect on training data error's effect decreased, while that of validation data increased.

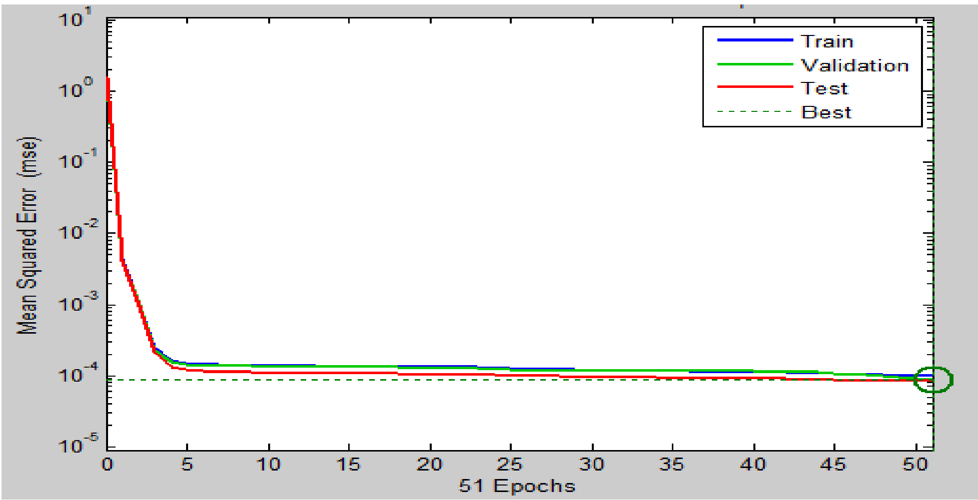

Figure 5.17: Training, validation, and test mean's squared errors for the EvRANNs

The regression analysis of the network response between EvRANN outputs and corresponding targets was performed. The graphical output of the plotted network outputs versus the targets as open circles is illustrated in Figure 5.18. Taking into account the data's non-linear dependence, linear regression shows a perfect agreement between EvRANNs outputs (i.e., predicted data) and corresponding targets (i.e., ED). The solid red, blue, green, and black lines—which respectively represent the test, training, validation, and combination of all three—indicate the perfect linear fit that $R^2 \approx 1$.

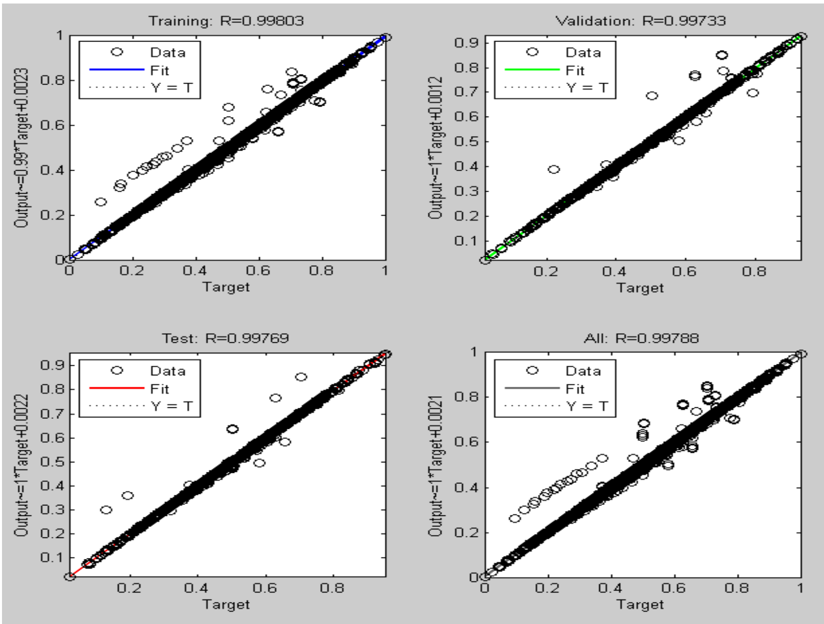

Figure 5.18: EvRANN regressions

The previous statistical analysis shows that the EvRANN model predictions are very close to the ED. In addition, to confirm the developed model's robustness and predictive capability, the performance of the optimal EvRANN model was evaluated using another data set consisting of the actual data obtained in chapter 4, which was not used in the training stage. Consequently, a simulink model of the EvRANN network was constructed, as shown in Figure 5.19, and the results—along with the correlation coefficient between actual and predicted datasets respectively—provided a very high accuracy and perfect match, as presented in Table 5-4.

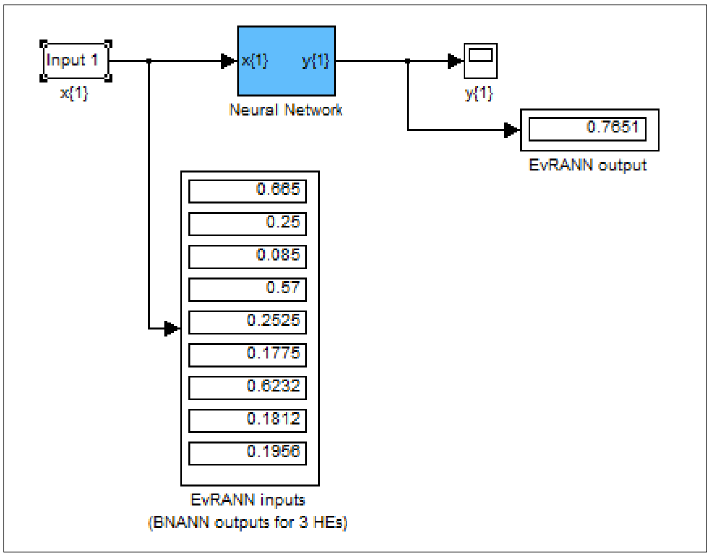

Figure 5.19: simulink model of the EvRANN network

Table 5.4: EvRANN correlation coefficient

	FRBER outputs	**EvRANNs output**
	0.7668	0.7651
	0.8102	0.8126
	0.6002	0.6024
	0.7011	0.702
	0.7443	0.7469
	0.55	0.5511
	0.4834	0.4837
	0.4613	0.4608
Correlation	0.999941	

5.7. Integrated ANNs Bayesian Networks Evidential Reasoning (AnBnEvR)

The previous sections described the BNANN and EvRANN models, which can be integrated to predict risk evaluation of a container terminal operation and provide a panoramic view on risk inference, either individually or collectively aggregated. The integration of the simulated Bayesian Networks and Evidential Reasoning using Artificial Neural Networks was created within dynamic system simulation for MATLAB. Consequently, the simulink model of the AnBnEvR network was constructed as illustrated in Figure 5.20.

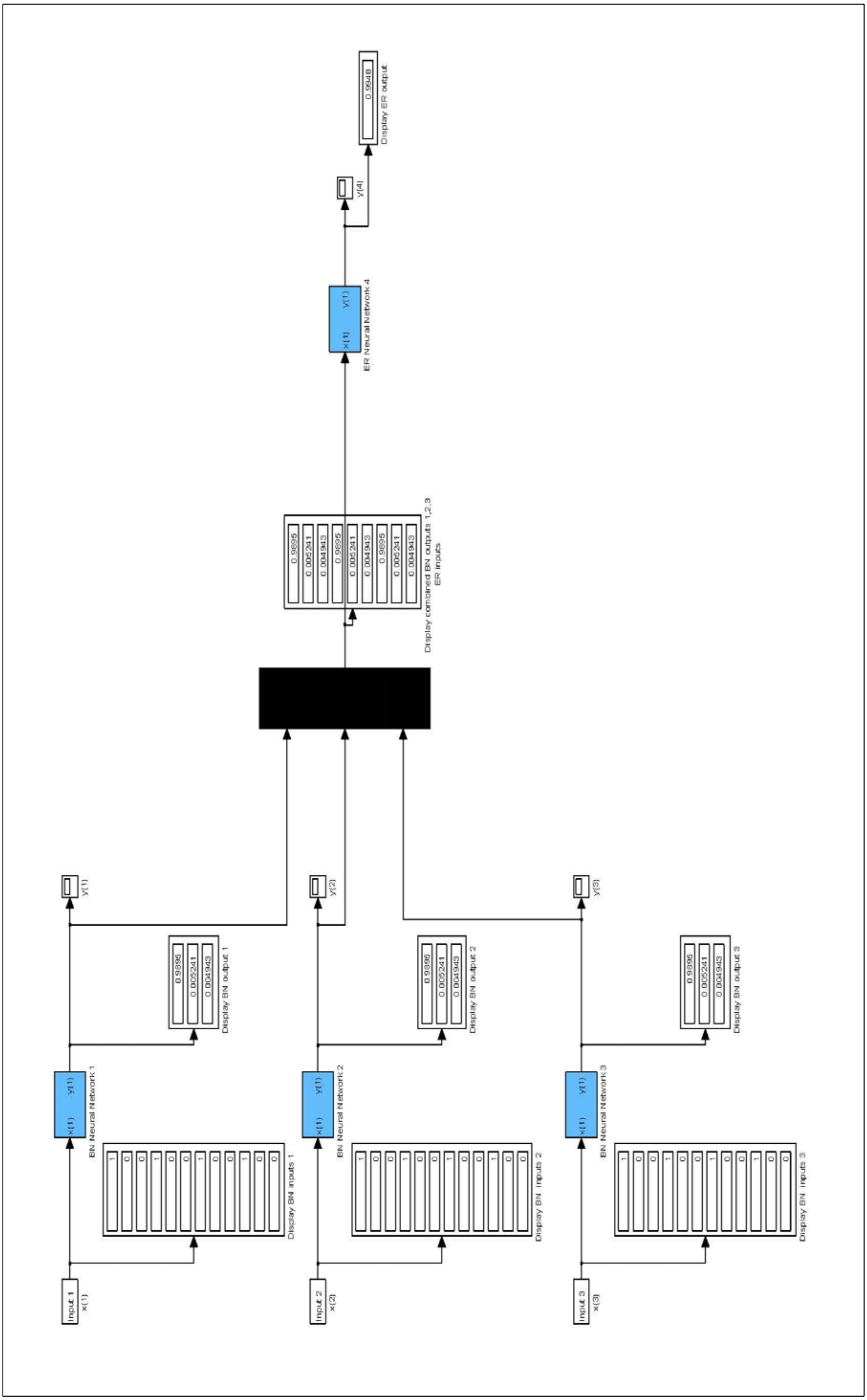

Figure 5.20: Simulink model of the AnBnEvR network

5.8. Conclusion

This study develops a novel FMEANN approach for evaluating and predicting the criticality of HEs in a container terminal system; at the same time, it provides a panoramic view on maritime container terminal safety performances. This study applied an ANN to container terminal systems to investigate the applicability of ANN as a tool for predicting risk inference of complex container terminal operation activity systems.

Two three-layer BP neural networks were optimised to evaluate and predict the maritime container terminals' operation safety. The configuration of the BP neural network that giving the smallest MSE is constructed using LMBP training algorithm of *tansig* transfer function at hidden layer with 40 neurons and a *purelin* transfer function at output layer. The optimal architecture for BNANN and EvRANN models were optimised as twelve and nine neurons in the input layers with three and one in the output layers. The two three-layer ANN-based models showed precise and effective predictions with very satisfactory determination coefficients for testing sets R^2 of about 0.999 and 0.997, with corresponding MSE of 0.000001334 and 0.0001344 respectively for simulating BNANs and EvRANNs. The simulation of FRBN and FRBEvR using ANNs, with the presented results, showed that neural network modelling can effectively simulate and predict container terminal operation safety.

The integration of the two models (i.e., AnBnEvR network) provides an excellent evaluation and prediction tool for complex systems, such as container terminal operation activities, in which BNANNs evaluate and predict individual HEs within the system while EvRANNs deal with HEs aggregated collectively. Based on these findings, this study concludes that a highly complex and dynamic system, such as a maritime container terminal, could be easily modelled in a feasible, versatile, and accurate manner using the proposed ANN-based approach. Considering the advantages of artificial intelligence methodology, the present modelling strategy will be expanded to full scale to evaluate real-time operation activities and control risk in a cost-effective manner from the viewpoint of safety and security. However, the model cannot be used with different input values outside the range of trained data.

Chapter 6 — Decision Support System for Optimal Container Port Safety Performance Plan Selection

Summary

This chapter aims to present a fuzzy decision-making approach to tackle the selection of Risk Control Options (RCOs) and operational safety strategies under uncertainty in container terminals. The selection of an appropriate strategy to ensure the OSP in container terminals is a crucial decision for many stakeholders including terminal managers, ship-owners, surveyors, and safety engineers. In such a process of complex group MCDM, ambiguous and incomplete data are usually presented in different quantitative and qualitative forms. AHP and the FTOPSIS have been merged to formulate a hybrid approach to assess the costs and benefits associated with operational safety strategies. In order to evaluate the benefits, such as risk reduction, this chapter also introduces a novel port operational risk analysis technique incorporating Bayesian Evidential Reasoning (BER). The contributory findings through the application of the approach in the real world are twofold. First, the newly proposed approach can deliver results similar to the ones obtained using the existing safety control decision-making methods when the input data is completed. The new approach can also provide solutions, while the traditional ones cannot when the uncertainty in decision input data is high. Secondly, the most preferred safety control measures are those capable of addressing both operational efficiency and risk reduction in container terminals, such as automation solutions.

6.1. Introduction

For many decades, containerised trade has been the fastest growing market segment. The total volume of containers handled per year has steeply increased and is expected to continue increasing in the future (UNCTAD, 2013). As a result, container terminals are continuously challenged to increase their throughput capacity, introducing innovations regarding its design, material handling equipment, and safety research applications on container terminal safety operations.

Most of the Decision Making Problems (DMP) in container terminal operation are dealing with optimisation in transport operations: comparing vehicle types; determining the number of vehicles; routing; dispatching; collision and deadlock avoidance (Héctor et al., 2014); terminal operation including deriving and comparing dispatching policies

(Stahlbock & Voß, 2008; Steenken et al., 2004); port efficiency (Gonzalez & Trujillo, 2009; Panayides et al., 2009); operations management (Meredith et al., 1989); logistics (Mentzer & Kahn, 1995); and supply chain management research (Sachan & Datta, 2005; Burgess et al., 2006). Hardly any papers focus on OSP within container terminals. This chapter presents a new classification scheme using FTOPSIS to ensure the optimal OSP strategy with respect to the following decision problems criteria: (1) Risk reduction; (2) Actual benefits in term of operational efficiency; (3) Cost; and (4) Technical difficulties on OSP strategy application, while the weights of all the criteria is obtained by using AHP.

The ratings of various alternatives versus various aforementioned subjective and objective criteria and the weights of all criteria are assessed in linguistic variables represented by fuzzy numbers to resolve the ambiguity of concepts that are associated with human being's judgments using the application of AHP and FTOPSIS to provide solutions for effective risk control and safety management in container ports in real-world practice.

This research aims to ensure that the OSP in maritime container terminals maximise the safety measures by offering the best risk-control options and strategies through developing a number of integrated models under high uncertainty. To achieve this aim, this chapter is organised as follows. A brief review of the AHP technique is provided in Section 6.2. An analytical overview of TOPSIS and an extended TOPSIS using FL in several domains is carried out in Section 6.3. The procedures required for developing these integrated models with various types of information at various stages through conducting an appropriate literature review, and human knowledge base and expertise have been explained in Section 6.4. Section 6.5 describes the methodology of MCDM to cope with the container terminal OSP decision problem and strategies selection using AHP-FTOPSIS that can define the positive and negative ideal solutions. Moreover, a brief introduction of a hybrid BER approach to conduct risk analysis of operations in container terminals has been provided. A particular test case regarding container terminal safety performance evaluation is investigated to demonstrate the feasibility of the new methodology in Section 6.6. Section 6.7 develops a discussion based on the results obtained. Section 6.8 concludes the chapter. The new approach can provide solutions to rational selection of risk control measures in situations where the relevant data is incomplete.

6.2. Research Background

6.2.1. A brief review on MCDM

The MCDM provides a systematic structured approach for a decision-making process that involves a decision problem with six elements, to the achievement or best performance of each decision alternative on criteria defined, which is described by Malczewski (1999) as follows.

1. Value is something a person cares deeply about.
2. Goal is the formulation of values in a given problem context.
3. Objective is the specification of a goal in terms of the desired property of the problem solution.
4. Decision Maker is a single person or a group of people, or the whole organisation, responsible for making decisions.
5. Decision Alternatives are the feasible solutions to a decision problem.
6. Criteria are the basis for evaluating decision alternatives. It has two types: attributes that measure the performance of an objective/s, and an objective that is a statement for the desired level of goal achievement.

There are two basic techniques to MCDM approach: MADM and Multiple Objective Decision Making (MODM).

The MADM technique provides a selection to be made among decision alternatives described by their attributes. It assumes that the problem has a predetermined number of decision alternatives based on its attributes, while in the MODM technique the decision alternatives are not given. Instead, MODM provides a mathematical framework for designing a set of decision alternatives and once the decision alternatives are identified, each alternative is judged by how suitable it is in satisfying the objective (Malczewski, 1999).

There are three generic types of MCDM problem as follows:

- Selection is finding a set of decision alternatives to be chosen from.
- Sorting is assigning each alternative to one of the predefined criteria based on relative differences of decision alternatives along a criterion.
- Ranking is establishing a prioritised list of alternatives.

It is noteworthy to mention that MADM problems require sorting and ranking, while MODM problems only require selection.

The process of MCDM begins with identifying the problem and then recognising the decision problem through a series of steps (Malczewski, 1999) as follows and presented in Figure 6.1.

- Set of criteria/attributes is the evaluation criteria that represent the measures for achieving those criteria.
- Set of alternatives is the nature of decision alternatives to choose from, whether these potential alternatives are feasible or not.
- Criterion scores represent the achievement of decision alternatives on evaluation criteria.
- Decision table represents the collection of criterion scores and thus provides the basis for the comparison of decision alternatives.
- Decision maker preferences are expressed in term of weights that express relative importance of the evaluation criteria under consideration.
- Aggregation functions are the decision rule. They compute an overall assessment measure of each decision alternative by integrating the decision maker's preferences with criterion scores.
- Sensitivity analysis tests the stability of an assessment measure of each decision alternative when weights and criterion scores are varied. If small changes in the weights or criterion scores produce significant changes in the order of ranked decision alternatives, then the ranking of decision alternatives is sensitive.
- Final recommendation is the choice of the most appropriate decision alternatives

In respect to the model presented in this chapter, it has been decided to follow the MADM technique in MCDM approach because the scope of this research is to select from a predetermined number of decision alternatives on a set of attributes for a defined objective.

There are some commonly known methods which use the MCDM approach to make decisions, which are briefly described in the following subsections.

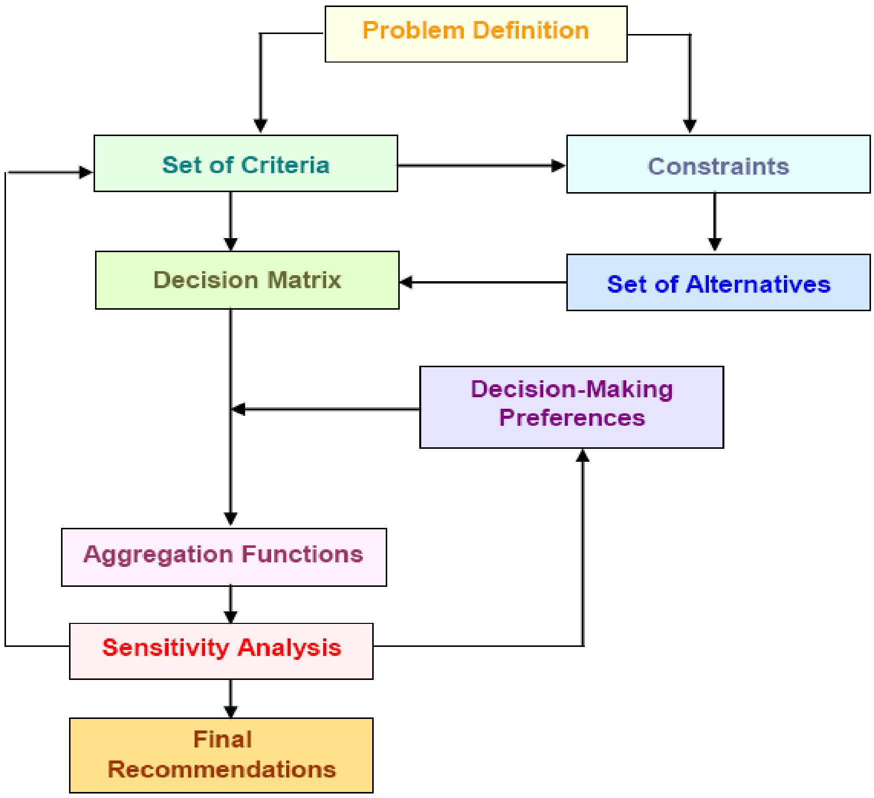

Figure 6.1: The process of Multiple Criteria Decision Making (MCDM)

6.3. Development of the MADM model

Yoon and Gyutal (1989) defined MADM as "technical decision aids for evaluating alternatives which are characterised by multiple attributes". Most critical situations that use MADM problems in engineering practice are characterised by both quantitative and qualitative attributes with various types of uncertainties. In many circumstances, the attributes, especially in qualitative forms, may only be properly assessed by human judgment, which is subjective in nature and is inevitably associated with uncertainties. It is mainly caused by two occurrences; first is a human's inability to provide complete judgments, or the lack of information that is referred to as "ignorance" (incompleteness); second, the vagueness of meanings about attributes and their assessments that is referred to as "fuzziness" (vagueness) (Guo et al., 2009).

For decades, many MADM methods have been developed due to the two aforementioned phenomena, AHP (Saaty, 1980) and MAUT (Keeney & Raiffa, 1993; Belton & Stewart, 2002) and others mentioned in the previous sections as well as their extensions (Moore, 1979) especially in the weight evaluation process (Arbel &Vargas, 1992; Islam et al., 1997). In those methods, MADA problems are modelled using decision matrices, in which an alternative is assessed on each attribute by either a single real number or an interval value. However, in many decision situations using a single number or interval to represent a judgment proves to be difficult and may be unacceptable. This is because the information may be lost or distorted in the process of pre-aggregating different types of information, such as a subjective judgment, a probability distribution, or an incomplete piece of information (Guo et al., 2009).

Fuzziness or vagueness can be well treated using the fuzzy set theory (Zadeh, 1975; Carlsson & Fuller, 1996). Regarding the fuzziness of MADA problems, a large community of researchers have proposed fuzzy MADA methods in the literature, such as fuzzy hierarchical aggregation methods, conjunction implication methods (Laarhoven & Pedrycz, 1983; Bellman & Zadeh, 1970; Yager, 1981) weighted average aggregation methods (Baas & Kwakernaak, 1977; Tseng & Klein, 1992) and weighted average aggregation with criteria-assessment methods (Yager, 1988). Ultimately, these pure fuzzy MADA approaches are mostly based on traditional evaluation methods and are unable to handle probabilistic uncertainties such as ignorance (Guo et al., 2009).

6.3.1. A Brief Review of Analytical Hierarchy Process (AHP)

Conventional techniques such as FTA, ETA, Failure Mode, FMECA and Bow-Tie have been widely used in reliability analysis of critical systems and have vastly enrich the risk analysis literature. However, most of the aforementioned approaches have prescribed setbacks which affect their application for quantitative risk analysis and management due to their inability to account for uncertainties associated with the system operation. As a result, methods such as the fuzzy set theory, the AHP and other preliminary assessment methods are nowadays widely used in many industrial sectors to overcome the previously drawbacks mentioned (John et al., 2014).

In addition, he AHP technique is suitable for dealing with complex systems that require making a choice from among several criteria, which provides a comparison of the considered options, first developed by Saaty (1980). The AHP is based on the subdivision of the problem in a hierarchical structure and helps to organise the rational analysis of the problem by dividing it into its smaller constituent parts. The analysis then supplies an aid to the decision makers, who call for simple pair-wise comparison judgements to develop priorities and who can appreciate the influence of the considered elements in the hierarchical structure (Saaty & Vargas, 2012). The AHP is a tool that can give a preference list of the considered alternative solutions and can be used for analysing different kinds of social, political, economic, and technological problems using both qualitative and quantitative variables (Chang & Chen, 2011).

The fundamental principle of the analysis is the possibility of connecting information based on knowledge to make decisions or previsions. The different contexts in which the AHP can be applied include the creation of a list of priorities, the process of choosing the best policy, the optimal allocation of resources, the prevision of results and temporal dependencies, the assessment of risks, and planning (Nezarat et al., 2015).

Fundamentally, the AHP works by developing priorities for alternatives and/or the criteria used to judge the alternatives. First, priorities are derived for the criteria in terms of their importance to achieve the goal, then priorities are derived for the performance of the alternatives on each criterion. These priorities are derived based on pair-wise assessments using judgments, or ratios of measurements from a scale if one exists. Finally, a weighting and adding process is used to obtain overall priorities for the alternatives as to how they contribute to the goal. Therefore, this chapter proposes the use of AHP for determining the weights of the main criteria.

The AHP is used to obtain the various weights of the multi-criterion of the model. The AHP method is implemented, as it is a comprehensive framework to cope with intuitive, rational, and irrational data when dealing with multi-objective, multi-criterion and multi-actor decisions with and without certainty for any number of criteria and/or alternatives. The FTOPSIS method is used to find the optimal alternative, which is the closest to the ideal solution and farthest away from the negative ideal solution with a description of accurate Euclidean distance. Therefore, the combination of the AHP and FTOPSIS methods provides more informative results in the reliability analysis and decision making to ensure the optimal OSP strategy.

6.3.2. The Technique for Order Preference by Similarity to Ideal Solution

DMP is the process of finding the best option from all of the feasible alternatives. In day-to-day life many decisions are being made based on various criteria by providing weight to each criterion and all the weights are obtained from human judgments. There are not only very complex issues involving multiple criteria, but there is also the need for all of the alternatives to have common criteria that clearly lead to more acquainted and better decisions, in order to get the optimal solution (Aruldoss et al., 2013). The problem becomes more complex when many criteria are involved for the alternatives. Therefore, the MCDM approach pertains to structure and planning problems involving multiple criteria to solve real world decision problems.

MCDM is a full-grown branch of operation research related to mathematical design and computational tools, which supports the subjective evaluation of decision alternatives under a number of performance criteria by a group or a single decision maker (Lootsma, 1999). MCDM uses knowledge from many fields, including mathematics, behavioural decision theory, economics, computer technology, software engineering, and information systems. Since the 1960s, MCDM has been an active research area and has produced many theoretical and applied papers and books (Roy, 2005). MCDM methods have been designed to designate a preferred alternative, classify alternatives in a small number of categories, and/or rank alternatives in a subjective preference order. Among numerous MCDM methods developed to solve real-world complex issues involving multiple criteria decision problems, TOPSIS continues to work satisfactorily in diverse application areas (Behzadian et al., 2012). It was originally proposed by Hwang and Yoon (1981) to help select the best alternative with a finite number of criteria as a simple ranking method in conception and application. As a remarkable classical MCDM method, the review of literature revealed that TOPSIS has received a strong interest from researchers and practitioners and the global interest in the TOPSIS application has grown exponentially (Shiha et al., 2007; Boran et al., 2009; Behzadian et al., 2012; Aruldoss et al., 2013).

TOPSIS makes full use of attribute information, provides a cardinal ranking of alternatives, and does not require attribute preferences to be independent (Chen & Hwang, 1992; Yoon & Hwang, 1995). The standard TOPSIS method attempts to choose alternatives that simultaneously have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. While the positive ideal solution maximises the benefit criteria and minimises the cost criteria, the negative ideal solution maximises the cost criteria and minimises the benefit criteria.

A survey on MCDM methods and its applications conducted by Aruldoss et al., (2013) indicated that the TOPSIS technique is applied mostly in many applications among other MCDM methods, such as Elimination EtChoix Traduisant la REalite (ELECTRE), AHP, Grey Theory and VIKOR. In addition, a literature survey on TOPSIS applications and methodologies is published by Behzadian et al., (2012) and includes 266 papers published in 103 scholarly journals since 2000, and discloses that the TOPSIS methodology has been successfully applied to a wide range of application areas and industrial sectors with varying terms and subjects, and intensively applied in the following fields: Supply Chain Management and Logistics; Design, Engineering and Manufacturing Systems; Business and Marketing Management; Health, Safety and Environment Management; Human Resources Management; Energy Management; Chemical Engineering; Water Resources Management; Medicine; Agriculture; Education; Design; Government; and Sports. The top two categories are Supply Chain Management and Logistics, and Design, Engineering and Manufacturing Systems, containing with over 50% of the total published applications, while few applications have been devoted to Chemical Engineering or Water Resources Management. However, MCDM requires a broader emphasis on interdisciplinary and social decision problems.

6.3.3. A brief review of extended TOPSIS using fuzzy logic

The conventional TOPSIS method applies the criteria weights and the alternatives ratings as crisp values. However, in practical situations it is often difficult and very challenging for decision makers to evaluate the precise weights of criteria and the ratings of alternatives under investigation. Therefore, an extended FTOPSIS approach was developed, which incorporated FL that uses linguistic variables represented by fuzzy numbers to address the imprecision that is inherent with the evaluation problems of complex and interdependent systems (Kuo et al., 2006; Yang & Hung, 2007; Chen & Tsao, 2008; Ashtiani et al., 2009; Ebrahimnejad et al., 2009; Roghanian et al., 2010; Aydogan, 2011; Jolai et al., 2011; Awasthi et al., 2011; and Yang et al., 2011).

Mentes and Helvacioglu (2012) proposed a fuzzy multiple-attribute decision support model for the selection of the most appropriate spread mooring system. The model was developed using fuzzy AHP and FTOPSIS methods for selecting the spread mooring system of gas companies situated near Yarimca on the Eastern Marmara Sea Region of Turkey. Lavasani et al., (2012) developed a fuzzy multi-attribute decision making (FMADM) method for ranking offshore well barriers' systems. The research uses fuzzy AHP and FTOPSIS for treating the well barriers as group decision-making problems in a fuzzy environment.

Singh and Benyoucef (2011) proposed a FTOPSIS technique with a mechanism for determination of fuzzy linguistic value attributes using an entropy method to enumerate the weights of various attributes without involvement of decision makers, while Liao and Kao (2011) proposed an integrated FTOPSIS and Multi-Choice Goal Programming

(MCGP) approach to solve the supplier selection problem. Torlak et al., (2011) used a FTOPSIS multi-methodological approach in the Turkish domestic airline industry to facilitate the selection/evaluation problem.

Many researchers with numerous studies attempting to handle this impression and subjectivity have been carried out by means of FTOPSIS (Chen, 2000; Jahanshahloo, Lotfi, & Izadikhah, 2006; Wang & Lee, 2007; Yang et al., 2009; Yang et al., 2011). This is mainly because fuzzy logic provides the flexibility needed to represent the ambiguous information resulting from the lack of data or knowledge, whereas TOPSIS can reasonably deal with the multiplicity of criteria. Chen (2000) used extreme fuzzy numbers (1, 1, 1) and (0, 0, 0) as basic elements of defining the Fuzzy Positive Ideal Solutions (FPIS) and Fuzzy Negative Ideal Solutions (FNIS) in FTOPSIS. The advantages of Chen's (2000) approach can be listed as follows:

i. The logic is rational and understandable.
ii. The computation processes are straightforward.
iii. The synthesis of multiple expert assessments is taken into account.
iv. The concept of newly defined positive and negative ideal solutions based on (1, 1, 1) and (0, 0, 0) permits the pursuit of the best alternatives for each criterion depicted in a simple mathematical form.
v. The importance weights of criteria are incorporated into the decision procedures.

However, the method has potential problems, including the following (Deng et al., 2000; Kuo et al., 2006; Lin & Chang, 2008; Wang & Lee, 2007; Yang et al., 2011):

i. Fuzzy ratings of cost criteria must not include zero values.
ii. Single linguistic variable assessment constrains the flexibility of using expert knowledge.
iii. Both quantitative and qualitative data requires to be expressed using the pre-defined fuzzy ratings and consequently, information may be lost in the transformation process.
iv. Evaluation results may be affected by the inter-dependency of criteria and inconsistency of subjective weights.
v. Multiplication between fuzzy ratings and weights will produce approximate (instead of precise) triangular fuzzy numbers.

vi. A crisp relative closeness for each alternative provides only one possible solution to a fuzzy MCDM problem, but cannot reflect the whole picture and all of its possible solutions.

A wide range of studies managing incomplete information and linguistic modelling have been proposed in the literature to deal with the above drawbacks, such as Alonso et al., (2009), Cabrerizo et al., (2010), and Xu (2007). Although showing much attractiveness by providing better solutions to dealing with imprecise and incomplete information for MCDM, the previous research involved complex algorithms that might mathematically burden the users in real-world applications.

Yang et al., (2011) proposed an approximate FTOPSIS to facilitate the development of a reliable vessel selection model under a fuzzy environment. The research uses the concept of belief degrees to increase the flexibility and confidence of experts in evaluating the performance of each alternative to model the system and overcome some of the aforementioned drawbacks when using classical FTOPSIS methods. Furthermore, objective quantitative data is directly used as input via a linear normalisation programme to avoid information loss in the inference process and different positive and negative ideal solutions for benefit and cost criteria will also be defined to eliminate the influence of zero values associated with cost criteria and to avoid the necessity of normalising the decision matrix.

6.4. Development for Modelling OSP in Container Terminals

Integrating safety performance into the design and operation of container terminals systems can be potentially costly (Mansouri et al., 2009). However, experience has shown that severe disruptions driven by HEs occurrence could lead to a long term consequence and subsequently losing the entire service delivery. Therefore, decision makers encounter a high level of strategic decisions that involve uncertainty and major resource implications regarding investment in appropriate OSP strategies that aim at bolstering the effectiveness of their operations.

The evaluation of cost-effectiveness in this respect requires systematic and efficient cost-benefit analysis based on the utilisation of a risk management algorithm which takes into account the complex and operational uncertainty of the system (Wang & Trbojevic, 2007). More importantly, the decision processes are challenging due to the fact that numerous events need to be considered and a major source of decision complexity is the inter-relationship among choices.

Strategic decisions' selection involves different levels of granularity and conditions for achieving an optimum level of strategic decisions on capital systems, such as container terminals, through an understanding of the system and the attributes influencing their performance (Mostashari et al., 2011).

Consequently, exploring different decision-making processes for structuring a robust and flexible decision making approach based on a wide range of elements related to infrastructural design, planning, and management helps to optimise the operational efficiency of the systems (Omer et al., 2012; Rao & Davin, 2008).

Since the main objective of any collaborative decision-making process is to obtain the optimum combination of criteria for rational decision making, effort needs to be tailored towards identifying, developing, and structuring those criteria that influence alternatives selection in an effective manner. The selection of the best alternatives enhances the container port OSP under high uncertainty.

6.4.1. Data collection methods

This research aims to obtain the optimal container port safety performance plan selection through developing a number of integrated models under high uncertainty. It classifies the goals and scope of the problem, and obtains relevant information through a robust literature review and brainstorming session with the various experts involved in container terminals operation. Different data are needed for identifying, analysing and developing such models, so as to integrate them into one strategic safety performance approach. The selection of Risk Reduction (RR) criterion that was obtained by incorporating BER approach results from chapter 3 and 4 is one of the benefits criteria.

The data collection method in this study, adopting both qualitative and quantitative data sets, namely experts' judgements, in which different survey questionnaires (in the form of a comparison matrix) were given to experts to ascertain their expert judgments. These questionnaires use qualitative linguistics variables to help experts to express their judgements easily under uncertain environments. Then, the obtained linguistics variables were transformed into quantitative data in the form of triangular fuzzy numbers to be used in the implementation procedures. Some other criteria use quantitative data sets that were obtained by examining the investigated container terminal records, such as cost and RR that are normalised and assigned directly to the model.

With respect to cost, the investigated terminal offered their financial records related to some alternatives that had already been implemented, which were used to rate the alternatives with respect to the quantitative cost criteria in this study. The needed data for other alternatives that was introduced by this research, namely the automation solutions, are collected by a careful literature review carried out and presented in a brainstorming session with a group of domain experts and by survey questionnaires.

6.4.2. Experts selection

The preliminary study of determining the criteria and alternatives took place in July 2015 in the United Kingdom, with seven safety/security officers, port managers and scholars. Moreover, in September 2015, another meeting took place in the Kingdom of Saudi Arabia with four safety/security officers and port managers to further study the investigated data set. The experts selected, based on their experience which is shown in Section 3.3.2, Table 3.3.

6.5. Methodology for Modelling OSP Strategies in Container Terminals

The main procedure for the AHP-FTOPSIS method can be described in a stepwise manner as follows.

1) Estimate RR criterion using the BER approach.
2) Identify the alternatives and other criteria.
3) Evaluate the ratings of alternatives with respect to each criterion.
4) Normalise the ratings of alternatives with respect to the quantitative criteria.
5) Calculate the weights of all criteria using an AHP approach.
6) Define FPIS and FNIS with respect to benefit and cost criteria.
7) Calculate the distance Closeness Coefficients (CCs) of all alternatives.
8) Determine the weighted distance CCs of all alternatives.
9) Calculate the CCs of all alternatives.
10) Model validation.

6.5.1. Estimate the RR criterion using BER approach

Port operational risk analysis models incorporating BER produced for collaborative modelling in chapters 3 and 4 of this thesis can be used as a transitional object or complement object (i.e., criteria used to provide cognitive decision support such as risk reduction and overall system risk assessment) for this analysis. This allows decision makers to integrate their previous risk assessment of the system elements and share their strategic concerns, increase their understanding of the system, and appreciate the potential impact of different alternatives before subsequently arriving at a decision for OSP improvement and management of the system.

The identification of the DMP is based on the 24 HEs investigated in chapter 3 of this research, in which the significant HEs were identified through a careful literature review, and human knowledge base and expertise with reference to Section 3.3.2. All 24 HEs were evaluated on two stages; in the first stage, the specific risk estimations for each HE were evaluated locally by using the FRBN method introduced in chapter 3 (Alyami et al., 2014), while in the second stage, by assigning the results obtained from BN, they were evaluated globally by calculate their risk influence to a port's safety system using FRBER introduced in chapter 4 (Alyami et al., 2016). The risk evaluation for HEs using BER provided a panoramic view of container operation risk management by assessing the HEs risk and ranking them accordingly, and estimating the RR that allows decision makers to enhance their OSP by implementing the best RCOs for each DMP.

6.5.2. Identify the alternatives and criteria

The first step is setting up a decision-making matrix format by assigning the relevant alternatives and criteria associated with a decision scenario that are appropriately identified and expressed. The alternatives are a set of actions that are required in order to achieve the decision objective. The set of criteria are used as functions that distinguish the alternatives. The decision-making target is to prioritise all alternatives by assessing them using input data with respect to each criterion.

The decision processes often require both qualitative (i.e., vague information based on subjective judgments) and quantitative (i.e., databases or objective calculations) data and, in order to avoid the loss of information in the transformation between data with different natures, it is beneficial to develop a framework that is capable of accommodating both data sets. Therefore, the established decision-making matrix format D can be expressed as follows:

$$
D = \begin{array}{c} \\ A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array}
\begin{array}{c} X_1 \quad \cdots \quad X_j \quad \cdots \quad X_n \\
\begin{bmatrix} X_{11} & \cdots & X_{1j} & \cdots & X_{1n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ X_{i1} & \cdots & X_{ij} & \cdots & X_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ X_{m1} & \cdots & X_{mj} & \cdots & X_{mn} \end{bmatrix}
\end{array} \qquad (6.1)
$$

where A_i, i = 1, 2, . . ., m represents the alternatives considered; X_j, j= 1, 2, . . ., n means the qualitative or quantitative criteria used to determine the performance of alternatives; X_{ij} indicates alternative ratings, which can be described by either a triangular fuzzy number $\widetilde{X_{ij}} = (a_{ij}, b_{ij}, c_{ij})$ or a real number $\widetilde{X_{ij}}$.

6.5.3. Evaluate the ratings of alternatives with respect to each criterion

It is beneficial to collect raw data as precisely as possible, therefore, the ratings of alternatives can be evaluated by different sets of linguistic variables used to describe the individual criteria, when the relevant objective data is unavailable. Fuzzy set theory is well-suited to model such subjective linguistic variables and deal with the discrete problem. Decision makers use the predefined linguistic rating variables in Table 6.2 to evaluate the alternatives with respect to each criterion (Chen, 2000; Chang et al., 2012). The sets of questionnaires presented in Appendix II-2 were prepared and implemented.

Table 6.1: FTOPSIS Linguistic variables and their TFN Values

Linguistic Terms	TFN
Very High (VH)	(0.75, 1.0, 1.0)
HIGH (H)	(0.5, 0.75, 1.0)
MEDIUM (M)	(0.25, 0.5, 0.75)
LOW (L)	(0.0, 0.25, 0.5)
Very LOW (VL)	(0.0, 0.0, 0.25)

Once fuzzy alternative ratings are obtained, they require to be transformed into the form of Triangular Fuzzy Numbers (TFN) for further analysis in the FTOPSIS framework. Both the performance score (x) and the membership degree (μ_x) are in the range of 0 and 1 as presented in Figure 6.2.

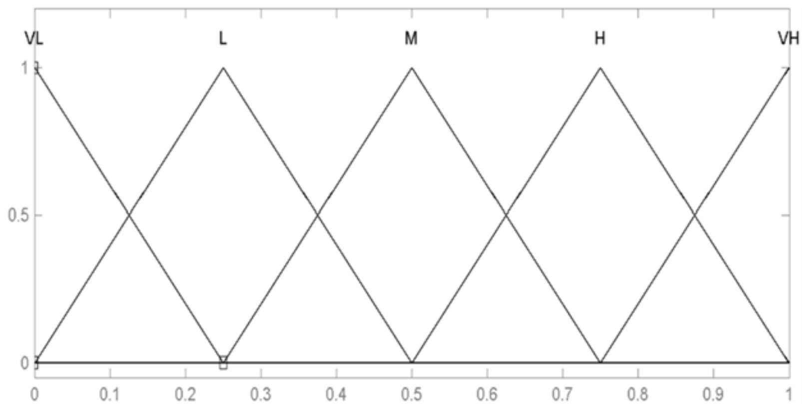

Figure 6.2: Membership degree for Linguistic Rating

Triangular fuzzy numbers are usually used to describe the linguistic variables based on a common interval [0, 1] due to their easiness (Yang et al., 2011). Various evaluations based on triangular fuzzy numbers can be appropriately modelled, transformed and expressed by the predefined linguistic variables using a Max–Min fuzzy similarity function (Liu et al., 2005). In this process, a linear utility function (Yang et al., 2009) is often used to transform the fuzzy number definitions of different sets of linguistic variables based on various universes onto the common space [0, 1] to convert linguistic evaluations into TFN and aggregate the fuzzy ratings and weights from multiple decision makers. Assume that K experts are involved into the MCDM analysis. Then the importance of the criteria and the rating of the alternatives with respect to each criterion can be calculated as follows.

$$\tilde{X}_{ij} = \frac{1}{K}\left[\tilde{X}_{ij}^{1}(+) \ldots (+)\tilde{X}_{ij}^{1}(+) \ldots (+)\tilde{X}_{ij}^{K}\right] \qquad (6.2)$$

where $\tilde{X}_{IJ}^{1}$ is the *i*th alternative rating with respect to the *j*th criterion and the importance weight of the *j*th criterion is estimated by the *l*th $(1 \in K)$ from Equation 6.1.

6.5.4. Normalise the ratings of alternatives with respect to the quantitative criteria

The linear scale function is used to transform the quantitative criteria scales into a comparable scale to avoid the complicated normalisation formula used in classical TOPSIS. The feasibility of the linear function is evidenced and supported by the fact that all the criteria in TOPSIS are categorised into either the benefit or cost group having a single direction distribution feature (Yang et al., 2011). Therefore, the normalised decision matrix denoted by R can be obtained as follows:

$$R = [r_{ij}]_{m \times n} \qquad (6.3)$$

where r_{ij} can be any of $\overline{r_{ij}}$, representing the normalised ratings of the alternatives with respect to quantitative criteria. The quantitative ratings can be computed as

$$\bar{r}_{ij_{cost}} = \frac{\bar{V}_J^-}{\tilde{X}_{ij}} \qquad (6.4)$$

$$\bar{r}_{ij_{\text{Benefit}}} = \frac{\bar{V}_J^*}{\tilde{X}_{ij}} \qquad (6.5)$$

where $\bar{V}_J^*$ and $\bar{V}_J^-$ are the highest and lowest values obtained of the *j*th quantitative criterion.

It is noteworthy that fuzzy alternative ratings do not require further normalisation given that they have been defined on a common interval [0, 1] by normalising their original universes and the averaged ratings matrixes of alternatives with respect to the criteria that can be obtained. That is, $\tilde{r}_{ij} = \tilde{X}_{ij}$, where $\tilde{r}_{ij}$ means the normalised fuzzy rating of the *i*th alternative evaluation with respect to the *j*th criterion (Yang et al., 2011).

6.5.5. Calculate the weights of all criteria using an AHP approach

The classical FTOPSIS technique takes into account the importance weights of criteria, however, it does not provide the assurance of the assessment consistency between decision criteria (Nezarat et al., 2015). An AHP approach (Saaty, 1980) is well suited to measuring the relative weights between the criteria and increasing the reliability of expert's assessment through the investigation of the consistency ratio of all pair-wise weight comparisons.

The AHP procedure to calculate the relative weights of criteria can be described in a series of steps as follows (Lee et al., 2008):

I. *Pair-wise comparison.*
II. *Estimate the relative weights.*
III. *Check the consistency.*
IV. *Obtain the overall rating.*

I. Pair-wise comparison

It first requires the pair-wise weight assessments matrices between the criteria at the same level of a decision hierarchy as follows:

$$A=\begin{bmatrix} 1 & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & 1 \end{bmatrix} \quad (6.6)$$

where A = comparison pair-wise matrix,

w_1 = weight of element 1,

w_2 = weight of element 2, and

w_n = weight of element n.

In order to determine the relative preferences for two elements of the hierarchy in matrix A, an underlying semantical scale is employed with values from 1 to 9, as shown in Table 6.3.

Table 6.2: The Relational Scale for Pair-wise Comparisons

Scale of importance	Preferences expressed in linguistic variables
1	Equally important
3	A little important
5	Important
7	Very important
9	Extremely important
2,4,6,8	Intermediate values of important

II. Estimate the relative weights

Let $I_{jk,I}$ be the relative importance judgement on the pair of the same level criteria C_j and C_k by the *I*th expert. Then the synthesised pair-wise weight comparison between $C_j$and $C_k$from k experts can be calculated as:

$$I_{jk} = \frac{1}{k}\left[I_{jk,1}(+)\ldots(+)I_{jk,I}(+)\ldots(+)I_{jk,k}\right] \quad (6.7)$$

Next, an approximation of the *j*th criterion weight can be computed as follows (Pillay & Wang, 2003):

$$w_j = \frac{1}{n}\sum_{k=1}^{n}\frac{I_{jk}}{\sum_{j=1}^{n} I_{jk}} \qquad (6.8)$$

III. Check the consistency

The AHP method provides a measure of the consistency for pair-wise comparisons by introducing a Consistency Ratio (CR) (Nobre et al., 1999). In this step, the consistency of matrices is checked to ensure that the judgments of decision makers are consistent and some pre-parameter is needed. First, the Consistency Index (CI) is calculated as:

$$CI = \frac{\frac{\sum_{j=1}^{n}\frac{\sum_{j=1}^{n} w_j I_{kj}}{w_k}}{n} - n}{\text{n}-1} \qquad (6.9)$$

The CI of a randomly generated reciprocal matrix shall be called to the Random Index (*RIx*) provided by Saaty (1980) shown in Table 6.4.

Table 6.3: Random inconsistency indices (Saaty, 1980)

Matrix Size (n)	2	3	4	5	6	7	8	9	10
RIx	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The last ratio that has to be calculated is the *CR*. Generally, if the CR is less than 0.1, the judgments are consistent, so the derived weights can be used (Yang et al., 2011). The formulation of CR is as follows:

$$CR = \frac{CI}{RIx} \qquad (6.10)$$

IV. Obtain the overall rating

In the last step, the relative weights of decision elements are aggregated to obtain an overall rating for the alternatives as follows (Vahidnia et al., 2008):

$$W_i^s = \sum_{j=1}^{j=m} w_{ij}^s\, w_j^a \qquad i = 1, \ldots, n \qquad (6.11)$$

where W_i^s= total weight of site i,

w_{ij}^s= weight of alternative (site) i associated to attribute (map layer) j,

w_j^a= weight of attribute j,

m = number of attribute, and

n= number of site.

6.5.6. Define FPIS and FNIS with respect to benefit and cost criteria

FPIS is defined as the vector involving the best normalised scores for each criterion and FNIS is defined as the vector involving the worst normalised scores for each criterion. In this study, FPIS and FNIS are defined as follows:

$$A^* = r_1^*, r_j^*, \dots, r_n^*$$

$$A^- = r_1^-, r_j^-, \dots, r_n^-$$

where if *B* and *C* indicate the sets of Benefit and Cost criteria respectively, then

$$r_j^* = (1,1,1) \quad , r_j^* = (0,0,0) \quad (j \in B) \text{ and}$$

$$r_j^* = 0,0,0) \ , r_j^* = (1,1,1) \qquad (j \in C) \qquad (6.12)$$

6.5.7. Calculate the distance CCs of all alternatives

Since the FPIS is (1,1,1) and FNIS is (0,0,0) the calculation of the distance CCs of all alternatives can be calculated by deducting the FPIS from averaged ratings matrixes of alternatives with respect to the criteria for B category criteria and deducting the averaged ratings matrixes of alternatives with respect to the criteria from FNIS.

6.5.8. Obtain the weighted distance CCs of all alternatives

This is achieved by multiplying the distance CCs of all alternatives by the weights of the criteria obtained in step ***IV***.

6.5.9. Calculating the CCs of all alternatives

In order to rank all the alternatives, the alternative with the highest *CCi* is the best alternative (shortest distance to the best condition and longest distance to the worst condition):

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-} \qquad i = 1,2,\dots,m \qquad (6.13)$$

6.5.10. Model validation

The soundness of the model is validated through a sensitivity analysis test to ensure its applicability and reliability for OSP in container terminal applications. Sensitivity analysis refers to analysing how sensitive the result would be (i.e., outputs) to minor change in inputs. Sensitivity analysis is conducted by increasing the weight of each criterion individually according to the results obtained from AHP implementation, then FTOPSIS steps are performed and the new results are observed for decision-making processes (Chang et al., 2007; Buyukozkan & Cifci, 2012).

The final output results are dependent on the subjective judgements of the decision makers, and sensitivity analysis is an essential aspect that would reflect different views on the relative importance of the best solution for specific HE that provide managerial focus during container operation on safety and system performance. A slight increment/decrement in the weight associated with criterion will certainly result in the effect of a relative increment/ decrement in the CCs of the criterion variable and the alternatives ranking output accordingly, therefore, a careful review of the weights is recommended, if the ranking order is highly sensitive to small changes in the criteria weights.

In order to determine the sensitivity, the weight associated with one criterion is increased separately by 10%, 20% and 30%, respectively. It is noteworthy to mention that for increasing the criterion weight by “m”, simultaneously the weights associated with other criteria are decreased by “m” to compensate the increment percentage on the increased criterion. However, if the weight is becoming less than “m”, then the remaining weight can be divided on the remaining criteria and this process continues until "m" is consumed.

6.6. A real case study on container port operational safety performance (OSP)

The procedure shown in Section 6.5 was applied on an anonymous container terminal in the real world that was selected to conduct a case study to demonstrate the feasibility of the proposed AHP-FTOPSIS method.

6.6.1. Estimate RR criterion using BER approach

The HEs associated with container terminal operations may vary, depending on the unique safety characteristics of an individual container terminal. For the investigated container terminal, the specific RE for each HE was evaluated locally by applying the

FRBN method introduced in chapter 3 (Alyami et al., 2014) and the results are shown in Table 6.5 indicating that HE.4 is the most significant event followed by HE.5, HE.6, HE.15, and HE.1 respectively.

Table 6.4: Risk ranking index values of hazardous events (HEs) (Alyami et al., 2014)

HE#	HEs	Risk Estimation			
		Low	Medium	High	Ranking Index
1.	Collision between Terminal Tractor (TT) and trailer	8.5	25	66.5	69.1
2.	Collision between Rubber-Tired Gantry (RTG) crane and trailer.	17.75	25.25	57	59.7
3.	Collision between TT and RTG.	19.56	18.12	62.32	64.3
4.	Collision between quay crane and ship.	13.25	13.25	73.5	75
5.	Collision between two quay cranes.	18.75	8.5	72.75	73.8
6.	Crane breakdown due to human error.	23.5	5.5	71	71.8
7.	Moving the crane without raising the boom of the gantry crane.	24.75	9.75	65.5	66.7
8.	Leakage/ emission of dangerous goods from a container.	41	11.25	47.75	49.3
9.	Ignition sources from equipment near dangerous goods premises.	35	27.5	37.5	40.6
10.	Person falls from height due to being too near to unprotected edges.	25.5	22.75	51.75	54.3
11.	Person falls from height due to non-provision / maintenance of safe access between adjacent cargo bays.	19	21	60	62.3
12.	Working on surfaces that are not even.	23	18.5	58.5	60.6

13.	Person slips, trips, and falls whilst working on surfaces with presence of leaking cargo.	22	11.25	66.75	68.1
14.	Person slips, trips, and falls whilst working on surfaces with presence of water/ ice.	25	15.25	59.75	61.5
15.	Person slips and falls whilst working on surfaces with presence of oils.	23.25	8.5	68.25	69.3
16.	Person struck by falling object/s.	28.5	22.5	49	51.5
17.	Person handling dangerous goods in container that has not been declared.	43.5	12.5	44	45.7
18.	Person struck by quay crane.	44.5	7.75	47.75	49
19.	Person struck by TT.	45.24	16	38.75	40.8
20.	Person struck by RTG.	43.5	15.75	40.75	49
21.	Person struck by trucks.	38.5	22	39.5	42
22.	Person crushed against a fixed object and ship / terminal structure.	41	16.25	42.75	44.8
23.	Person crushed against a fixed object and stacked containers.	37.75	23.25	39	41.7
24.	Person crushed by closing the twin lift container spreaders.	53	16.25	30.75	32.9

Next, assign the RE results of each HE obtained from the FRBN method into the hierarchical structure depicted in Figure 4.2 to evaluate their RI to a port's safety system globally. As a result, by applying FRBER in chapter 4, the RI can be described in a form of linguistic grades with DoB values of 60.37 High, 10.56 Medium, and 28.89 Low, and can be transformed to a utility value as 0.6172, which indicates that the RI for the investigated container terminal is consider to be high and would jeopardise the terminal operations. A series of unique sensitivity analysis tests in chapter 4 (Alyami et al., 2016) reveals the HEs that have greater risk influence than others do, and that HE.9 is the most significant event followed by HE8, HE6, HE7, HE16 and HE17.

Based on the results obtained from applying the BER method in Alyami et al., (2014; 2016) it is obvious that HE.6 has a great risk influence on the port OSP in both locally and globally risk management perspective (i.e. it is ranked as the second most significant HE in FRBN and as third most significant HE in FRBER. Therefore, HE.6 was assigned as the DMP in this study that needs to be addressed.

The RR criterion needs to be estimated using the BER approach before the AHP-FTOPSIS process. Therefore, the DMP (i.e., "HE6 Crane break down due to human error") is re-evaluated after implementing the alternatives by using the BN approach in order to obtain the updated RE. Next, the RR can be calculated by subtracting the updated RE from the original RE obtained in chapter 3. The second stage commences by assigning the new RE for DMP in a form of linguistic grades with DoB to re-estimate the RI globally by using the FRBER approach in chapter 4 (Alyami et al., 2016). Consequently, the RI values for DMP after implementing the alternatives are obtained and RR is calculated.

Taking the RR for A1 as an example, First, with reference to FRBN in chapter 3, Section 3.4.3.1, Section 3.4.3.2 and Section 3.4.3.3, the experts are asked to express their judgment and reassess DMP (i.e.HE6) after implementing A1, the feedback received from the experts is first combined (by conducting an average calculation) to produce DMP input values in terms of the four risk parameters. Next, Given the Equation 3.4, the prior probabilities of the four nodes can be obtained and converted to obtain *p* (*Rh*|*Li, Cj, Pk, Il*) then the RE (i.e. Risk Evaluation) of DMP can be calculated using Equation 3.5 as *p* (*Rh*) = {(93.89% Low, 0.94% Medium, 5.17% High)}. Equation 3.6 is used to calculate the risk ranking index value of DMP as 6.2 (= 93.89% × 1 + 0.94% × 10 + 5.17% × 100). The calculation can be computerised using the *Hugin* software. It can be noticed that the local risk of HE6 as is reduced from 71.8 to 6.2 after applying A1 as shown in Table 6.6.

Table 6.5: RR on DMP by implementing A1

ALTERNATIVE	Experts	Probability of failure/ Likelihood			probability of failures being undetected			Consequences /severity			Impact of the HE on the resilience of port operational systems			New RE	Original risk from BN 71.8
		H	M	L	H	M	L	H	M	L	H	M	L		Risk Reduction
Hiring highly qualified crane driver	A	20	25	55	10	25	65	35	0	65	15	25	60	6.2	
	B	20	25	55	15	25	60	20	20	60	20	20	60		
	C	25	15	60	25	25	50	30	5	65	25	25	50		
	D	30	15	55	20	15	65	20	10	70	30	0	70		
	Prior Probability	20	25	55	10	25	65	35	0	65	15	25	60		65.6

It is clearly observed that the risk inference decreased dramatically after implementing A1, from 71.8 to 6.20, and the RR can be calculated as 65.6. Similarly, the new RE and RR for DMP after implementing the other alternatives are presented in Table 6.7.

Table 6.6: RR on DMP by implementing the alternatives

A#	Alternatives Implemented	New Risk Evaluation	Risk Reduction
A1	Hiring highly qualified crane driver	6.20	65.6
A2	Hiring qualified crane driver	23.47	48.33
A3	Requiring situation awareness training programme for quay crane drivers	24.82	46.98
A4	Requiring situation awareness training programme for yard crane drivers	28.7	43.1
A5	Requiring situation awareness training programme for transportation drivers	19.59	52.21
A6	Requiring intensive safety and security checks	22.09	49.71
A7	Requiring intensive crane maintenance programme	15.23	56.57
A8	Appling automated crane operations on quay area	9.18	62.62
A9	Appling automated crane operations on yard area	7.19	64.61
A10	Appling automated crane operations on transportation area	9.04	62.76
A11	Appling fully automated crane operations	3.81	67.99

Second, with reference to CTOS model using ER in chapter 4, Section 4.4, the new RE for HE6 is updated in Table 4.1. Next, assigning the RE of all other HEs in the hierarchical structure to be synthesised and aggregated collectively by using the ER algorithm. The IDS is a general-purpose multi-criteria decision analysis tool implementing the ER approach. As a result, the RI (i.e. Risk Index) for CTOS can be described in a form of linguistic grades with DoB values of 51.49 High, 10.66 Medium, and 37.85 Low and the utility value is calculated using Equation 4.22 as 0.5682. it can be noticed that the global risk inference of HE6 among other HEs is reduced from 0.6172 to 0.5682 after applying A1 as a risk control option. Finally, the RR can be calculated as 0.049 (= 0.6172 – 0.5682). Having obtained the RR for HE6 after applying the alternatives, it is normalised using Equation 6.5 as shown in Table 6.8.

Table 6.7: RR on DMP by implementing A1

A#	DMP RI	RR	Normalised RR
A1	0.5777	0.0490	0.9533
A2	0.6	0.0172	0.3346
A3	0.6378	0.0195	0.2860
A4	0.6369	0.0069	0.1342
A5	0.5905	0.0267	0.5195

A6	0.5989	0.0183	0.3560
A7	0.6204	0.0220	0.6128
A8	0.576	0.0412	0.8016
A9	0.5771	0.0401	0.8132
A10	0.5751	0.0421	0.8191
A11	0.5658	0.0514	1

6.6.2. Identify the alternatives and other criteria

In order to derive the other criteria and their assessment grades, this step of the analysis involves a structured interview that has been conducted and presented to the safety/security officers and port managers, previously introduced in Section 6.5.2. A careful literature review is carried out and presented in a brainstorming session with the same group of experts to identify the most suitable criteria and the most preferred safety control measures capable of addressing both operational efficiency and risk reduction in container terminals such as automation solutions alternatives.

As a result, the hierarchy is constructed in Figure 6.3 with four levels of criteria and eleven alternatives. The RR criterion estimated in the previous step from incorporating results obtained with BER approach, is included as one of the benefits criteria.

The eleven alternatives can be listed as follow:

A1 Hiring highly qualified crane driver
A2 Hiring qualified crane driver
A3 Requiring situation awareness training programme for quay crane drivers
A4 Requiring situation awareness training programme for yard crane drivers
A5 Requiring situation awareness training programme for transportation drivers
A6 Requiring intensive safety and security checks
A7 Requiring intensive crane maintenance programme
A8 Appling automated crane operations on quay area
A9 Appling automated crane operations on yard area
A10 Appling automated crane operations on transportation area
A11 Appling fully automated crane operations

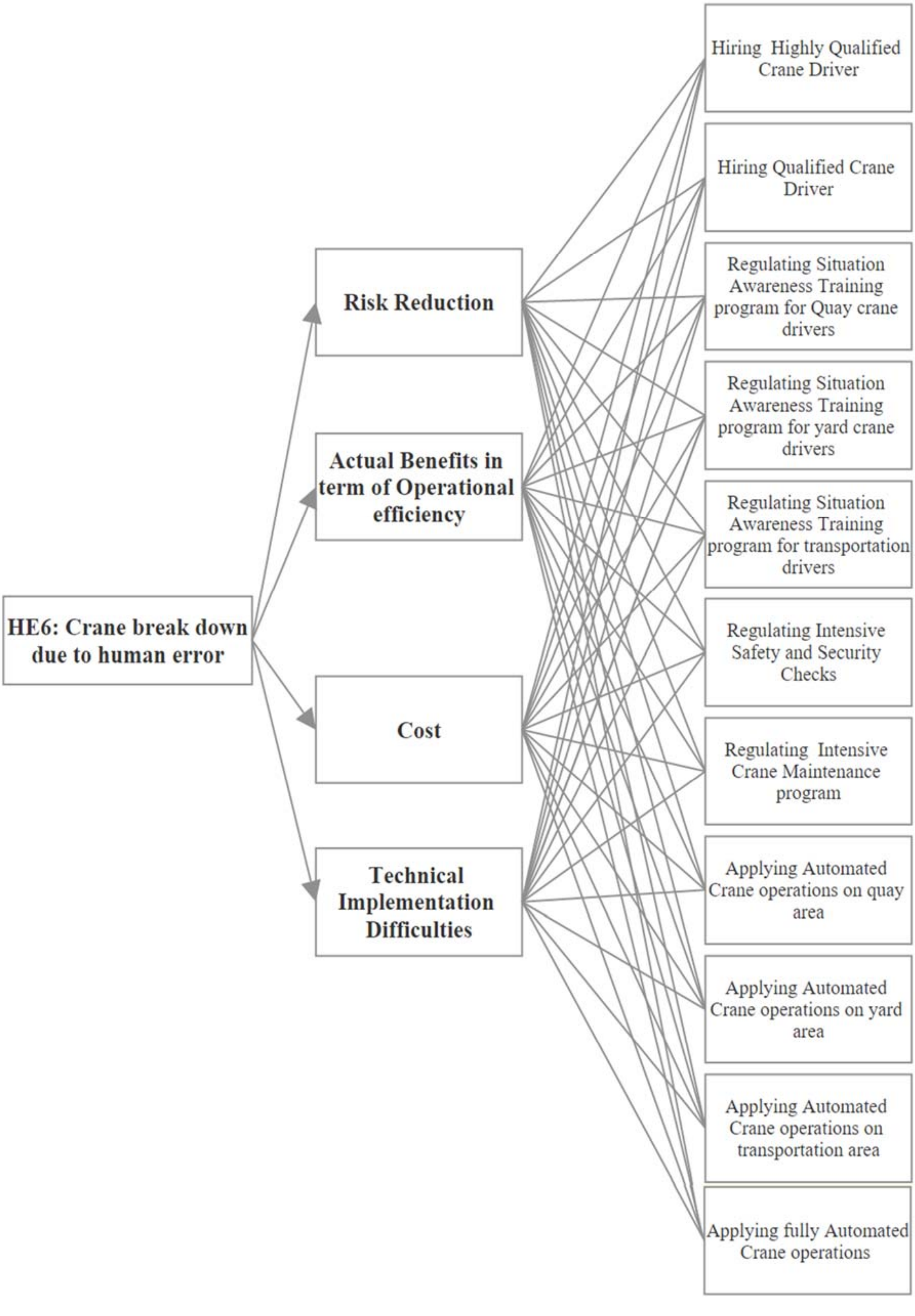

Figure 6.3: Hierarchical structure of container port operational safety performance

The criteria and alternatives that are critical to enhancing the container port OSP are assigned based on expert opinions and/or through a careful literature review as described in Table 6.9.

Table 6.8: Referencing alternatives and criteria

		Type of Reference	Reference
Criteria	Risk Reduction	Experts	
	Actual Benefits in term of Operational efficiency	Experts	
	Cost (£)	Literature and Experts	Mansouri et al., 2010; Vugrin et al., 2011
	Technical Implementation Difficulties	Experts	
Alternatives	Hiring Highly Qualified Crane Driver	Literature and Experts	ILO, 1977; HSE, 2014
	Hiring Qualified Crane Driver	Literature and Experts	ILO, 1977; HSE, 2014
	Regulating Situation Awareness Training program for Quay crane drivers	Literature and Experts	Hetherington et al., 2006
	Regulating Situation Awareness Training program for yard crane drivers	Literature and Experts	
	Regulating Situation Awareness Training program for transportation drivers	Literature and Experts	
	Regulating Intensive Safety and Security Checks	Experts	
	Regulating Intensive Crane Maintenance program	Experts	
	Applying Automated Crane operations on quay area	Literature	Hoshino and Ota, 2007
	Applying Automated Crane operations on yard area	Literature	
	Applying Automated Crane operations on transportation area	Literature	
	Applying fully Automated Crane operations	Literature	

The criteria used for the selection procedure are divided into two main categories: cost (C) (the lower the value, the more effective the alternative) and benefit (B) (the higher the value, the more resilient or effective the alternative) as described in Table 6.10.

Table 6.9: The Criteria for container port operational safety performance

Criteria	Description of criteria	Type of Assessment	Definition	Category
C1	Risk Reduction	Real Data	Enhance the safety by evaluating HEs and estimate the risk inference.	B
C2	Actual Benefits in term of Operational efficiency	Linguistic Assessment	Improvement on operational efficiency (i.e., TEU movements, crane turning journey, etc.)	B
C3	Cost (£)	Real Data	Capital required to apply the alternative.	C
C4	Technical Implementation Difficulties	Linguistic Assessment	The ability of applying the required alternative accurately and dependably.	C

6.6.3. Evaluate the ratings of alternatives with respect to each criterion

In order to effectively evaluate the alternatives, the criteria assessment grades (i.e., linguistic variables or numerical grades) have been obtained in the interview process. They have been set in a way that the experts can feel confident in using their domain knowledge as previously discussed in Section 6.5.3. Each subjective criterion is assessed with respect to each alternative by a group of four experts in leading port in KSA (i.e., experts number 7, 8, 9, and 12 in Section 6.4.1) using the linguistic terms in Table 6.2. while the RR criteria (i.e. C1) is obtained from Section 6.6.1. The assessments of all alternatives with respect to both qualitative and quantitative criteria are presented in Table 6.11.

Table 6.10: Assessments of alternatives with respect to criteria

Alternatives	Experts	C1	C2	C3	C4
A1	**Exp1**	0.0490	VH	27000	L
	Exp2		H		VL
	Exp3		VH		L
	Exp4		VH		L
A2	**Exp1**	0.0172	VH	20000	VL
	Exp2		H		L
	Exp3		VH		L
	Exp4		H		L
A3	**Exp1**	0.0147	H	20000	L
	Exp2		VH		VL
	Exp3		VH		L
	Exp4		VH		L
A4	**Exp1**	0.0069	VH	15000	VL
	Exp2		VH		L
	Exp3		H		L
	Exp4		VH		L

A5	**Exp1**	0.0267	VH	30000	L
	Exp2		H		L
	Exp3		H		L
	Exp4		VH		VL
A6	**Exp1**	0.0183	VH	25000	VL
	Exp2		H		L
	Exp3		VH		L
	Exp4		VH		L
A7	**Exp1**	0.0315	VH	95000	M
	Exp2		VH		L
	Exp3		VH		M
	Exp4		VH		M
A8	**Exp1**	0.0412	VH	300000000	H
	Exp2		VH		VH
	Exp3		VH		H
	Exp4		VH		H
A9	**Exp1**	0.0418	VH	300,000,000	H
	Exp2		VH		VH
	Exp3		VH		H
	Exp4		VH		H
A10	**Exp1**	0.0421	VH	200,000,000	H
	Exp2		VH		VH
	Exp3		VH		H
	Exp4		VH		H
A11	**Exp1**	0.0514	VH	500,000,000	H
	Exp2		VH		VH
	Exp3		VH		H
	Exp4		VH		H

6.6.4. Normalise the ratings of alternatives with respect to the quantitative criteria

There are two criteria that need to be normalised then transformed to TFN, namely, cost and RR. As previously mentioned in Section 6.5.4, some ratings of alternatives with respect to the cost quantitative criteria were used and need to be normalised. Therefore, all objective cost criteria were normalised by using Equation 6.4, where, the objective criteria (i.e., RR) were normalised by using Equation 6.5.

With respect to the cost criterion, all values obtained are British Pound Sterling (BRP £) units in one year. The values of cost and RR criteria with the normalised values are presented in Table 6.12.

Table 6.11: Normalised values for cost and RR criterion

Cost per year £	Normalised Cost	RR	Normalised RR
27000	0.56	0.0490	0.95
20000	0.75	0.0172	0.33
20000	0.75	0.0147	0.38
15000	1	0.0069	0.13
30000	0.5	0.0267	0.52
25000	0.6	0.0183	0.36
95000	0.1579	0.0315	0.43
300000000	0.00005	0.0412	0.80
300000000	0.00005	0.0418	0.81
200000000	0.000075	0.0421	0.82
500000000	0.00003	0.0514	1.00

After normalising the objective criteria, other subjective criteria are directly transformed to TFN and all the matrixes are averaged. Taking A1 for example, Table 6.13 shows the normalised objective criteria and the transformed criteria in the form of TFN.

Table 6.12: Normalised ratings of alternatives with respect to the criteria

Alternatives	Experts	C1			C2			C3			C4		
A1	**Exp1**	0.95	0.95	0.95	0.75	1.00	1	0.6	0.6	0.6	0	0.25	0.50
	Exp2	0.95	0.95	0.95	0.50	0.75	1	0.6	0.6	0.6	0	0.00	0.25
	Exp3	0.95	0.95	0.95	0.75	1.00	1	0.6	0.6	0.6	0	0.25	0.50
	Exp4	0.95	0.95	0.95	0.75	1.00	1	0.6	0.6	0.6	0	0.25	0.50

Next, Table 6.14 shows the averaged ratings matrixes of alternatives with respect to the criteria.

Table 6.13: Averaged ratings of alternatives with respect to the criteria

Alternatives	C1			C2			C3			C4		
A1	0.830	0.953	0.953	0.688	0.938	1	0.6	0.6	0.6	0	0.188	0.438

6.6.5. Calculate the weights of all criteria using an AHP approach

AHP has been used to estimate the weights of all the criteria in Figure 6.3. Taking Expert (A) as an example, the steps to obtain the weight for all criteria are as follows:

i. *Pair-wise comparison*

The pair-wise importance comparison between criteria Risk Reduction, Actual Benefits in terms of Operational Efficiency, Cost and Technical Implementation Difficulties is carried out by the four experts using Equation 6.6.

ii. Estimate the relative weights

The weighting vectors representing the priority of the four criteria in the pair-wise comparison matrix is obtained by using Equation 6.8 as (0.6025, 0.2305, 0.0768, and 0.0901).

iii. Check the consistency

The consistency of matrices is checked to ensure that the judgments of decision makers are consistent. The *CI* is calculated using Equation 6.9 and the *RI* is obtained from Table 6.4. As a result, the consistency of the judgements has been verified by calculating CR = 0.0161 (<0.1) using Equations 6.10 and 6.11. The results are shown in Table 6.15.

Table 6.14: Expert A weights pair-wise comparison for all criteria

Risk Reduction	Actual Benefits in term of Operational efficiency	Cost	Technical Difficulties	Weight	CI	CR
1	3	9	5	0.6025	0.0145	0.0161
0.3333	1	3	3	0.2305		
0.1111	0.3333	1	1	0.0768		
0.2	0.3333	1	1	0.0901		

iv. Obtain the overall rating

Similarly, the weights of the other criteria in the hierarchy shown in Figure 6.3 can be computed and the average weight for all experts' ratings with respect to all criteria can be obtained as shown in Table 6.16. Such weights only present relative importance between the criteria.

Table 6.15: Expert A weights pair-wise comparison for all criteria

CRITERIA WEIGHT	
C1	0.648
C2	0.195
C3	0.075
C4	0.082

6.6.6. Define FPIS and FNIS with respect to benefit and cost criteria

Having identified the nature of the criteria in Table 5.6, the FPIS and FNIS can be defined using Equation 6.12 as follows:

$$A^* = [r_1^* = (1,1,1), r_2^* = (1,1,1), r_3^* = (0,0,0), r_4^* = (0,0,0)]$$

$$A^{-} = [r_1^{-} = (0,0,0), r_2^{-} = (0,0,0), r_3^{-} = (1,1,1), r_4^{-} = (1,1,1)]$$

6.6.7. Calculate the distance CCs of all alternatives

Since the FPIS is (1,1,1) and FNIS is (0,0,0) the calculation of the distance CCs of all alternatives are presented in Table 6.17.

Table 6.16: The distance CCs of all alternatives

Alternatives		C1	C2	C3	C4
1	**d^***	0.170	0.313	0.400	1.000
	d^-	0.953	1.000	0.600	0.438
2	**d^***	0.665	0.250	0.250	1.000
	d^-	0.335	1.000	0.750	0.438
3	**d^***	0.714	0.250	0.250	1.000
	d^-	0.286	1.000	0.750	0.438
4	**d^***	0.866	0.500	0.000	1.000
	d^-	0.134	1.000	1.000	0.438
5	**d^***	0.481	0.500	0.500	1.000
	d^-	0.519	0.750	0.500	0.438
6	**d^***	0.644	0.375	0.444	1.000
	d^-	0.356	1.000	0.556	0.438
7	**d^***	0.387	0.250	0.842	0.813
	d^-	0.613	1.000	0.158	0.688
8	**d^***	0.198	0.250	1.000	0.250
	d^-	0.802	1.000	0.000	1.000
9	**d^***	0.187	0.250	1.000	0.250
	d^-	0.813	1.000	0.000	1.000
10	**d^***	0.181	0.250	1.000	0.250
	d^-	0.819	1.000	0.000	1.000
11	**d^***	0.000	0.250	1.000	0.250
	d^-	1.000	1.000	0.000	1.000

6.6.8. Obtain the weighted distance CCs of all alternatives

This is achieved by multiplying the distance CCs of all alternatives by the weights of the criteria obtained in step ***IV***. The weighted distance CCs of all alternatives are presented in Table 6.18.

Table 6.17: The weighted distance CCs of all alternatives

WEIGHTED		C1	C2	C3	C4	SUM
1	**d^***	0.1105	0.0611	0.0298	0.0820	0.2833
	d^-	0.6179	0.1954	0.0447	0.0359	0.8938
2	**d^***	0.4313	0.0488	0.0186	0.0820	0.5807
	d^-	0.2169	0.1954	0.0559	0.0359	0.5040
3	**d^***	0.4628	0.0488	0.0186	0.0820	0.6122

	d^-	0.1854	0.1954	0.0559	0.0359	0.4725
4	**d^***	0.5611	0.0977	0.0000	0.0820	0.7408
	d^-	0.0870	0.1954	0.0745	0.0359	0.3927
5	**d^***	0.3115	0.0977	0.0373	0.0820	0.5284
	d^-	0.3367	0.1465	0.0373	0.0359	0.5563
6	**d^***	0.4174	0.0733	0.0331	0.0820	0.6057
	d^-	0.2308	0.1954	0.0414	0.0359	0.5034
7	**d^***	0.2509	0.0488	0.0627	0.0666	0.4291
	d^-	0.3972	0.1954	0.0118	0.0563	0.6607
8	**d^***	0.1286	0.0488	0.0745	0.0205	0.2724
	d^-	0.5195	0.1954	0.0000	0.0820	0.7969
9	**d^***	0.1211	0.0488	0.0745	0.0205	0.2649
	d^-	0.5271	0.1954	0.0000	0.0820	0.8044
10	**d^***	0.1173	0.0488	0.0745	0.0205	0.2611
	d^-	0.5309	0.1954	0.0000	0.0820	0.8082
11	**d^***	0.0000	0.0488	0.0745	0.0205	0.1438
	d^-	0.6482	0.1954	0.0000	0.0820	0.9255

6.6.9. Calculating the CCs of all alternatives

The distance closeness coefficient (CC_i) of all alternatives can be calculated by using Equation 6.13. Taking A1 as an example, CC_{A1} can be calculated as follows.

$$CC_{A_1} = \frac{0.8938}{0.8938 + 0.2833} = 0.7439$$

The CC_i of the other alternatives can be computed and ranked accordingly in a similar way and their results are shown in Table 6.19.

Table 6.18: CC results and ranking order of container port safety performance plan selection

Alternatives	d^*	d^-	CC	Rank
A1	0.3077	0.8938	0.7439	5
A2	0.5807	0.5040	0.4647	8
A3	0.6122	0.4725	0.4356	10
A4	0.7408	0.3927	0.3465	11
A5	0.5284	0.5563	0.5129	7
A6	0.6057	0.5034	0.4539	9
A7	0.4291	0.6607	0.6063	6
A8	0.2724	0.7969	0.7452	4
A9	0.2649	0.8044	0.7523	3
A10	0.2611	0.8082	0.7558	2
A11	0.1438	0.9255	0.8655	1

Based on the results shown in Table 6.19, the most suitable solutions for the investigated container port that provides the optimum safety performance plans with respect to HE.6 (Crane break down due to human error) are those implementing automated operation.

The best is A11 (Appling fully automated crane operations) followed by A10 (Appling automated crane operations on transportation areas), A8. (Appling automated crane operations on quay area), A9 (Appling automated crane operations on yard area), and A1 (Hiring highly qualified crane driver) as depicted in Figure 6.4.

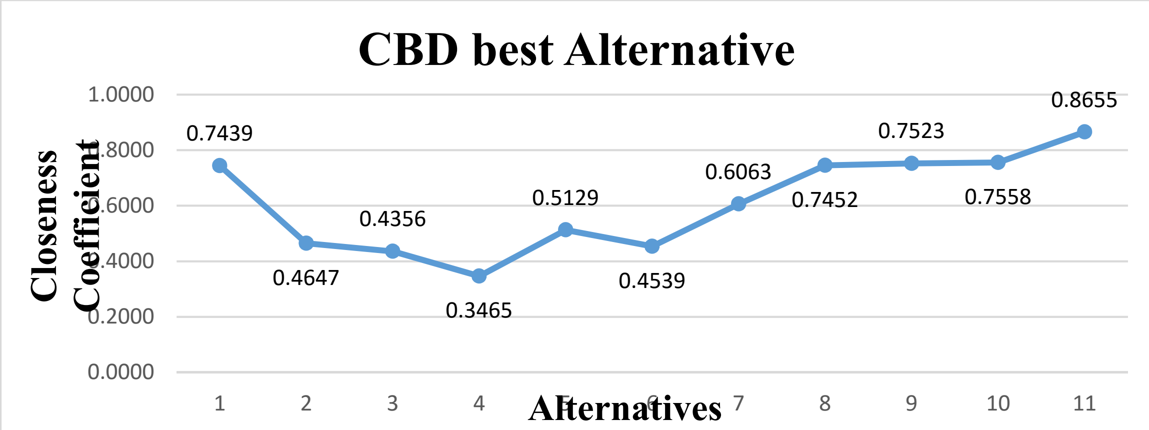

Figure 6.4: Ranking order for container port operational safety performance plan

6.6.10. Model validation process

The logicality and soundness of the results delivered in the proposed model is tested by the sensitive analysis. As described in Section 6.5.10, the weight associated with one criterion is increased separately by 10%, 20% and 30%, while simultaneously the weights associated with other criteria are decreased by compensating the increment percentage on the increased criterion, and the final ranking of the alternatives are observed. The sensitivity of the alternatives has been analysed when cost is increased separately by 10% first, then 20%, and finally 30%. The result obtained is presented in Figure 6.5.

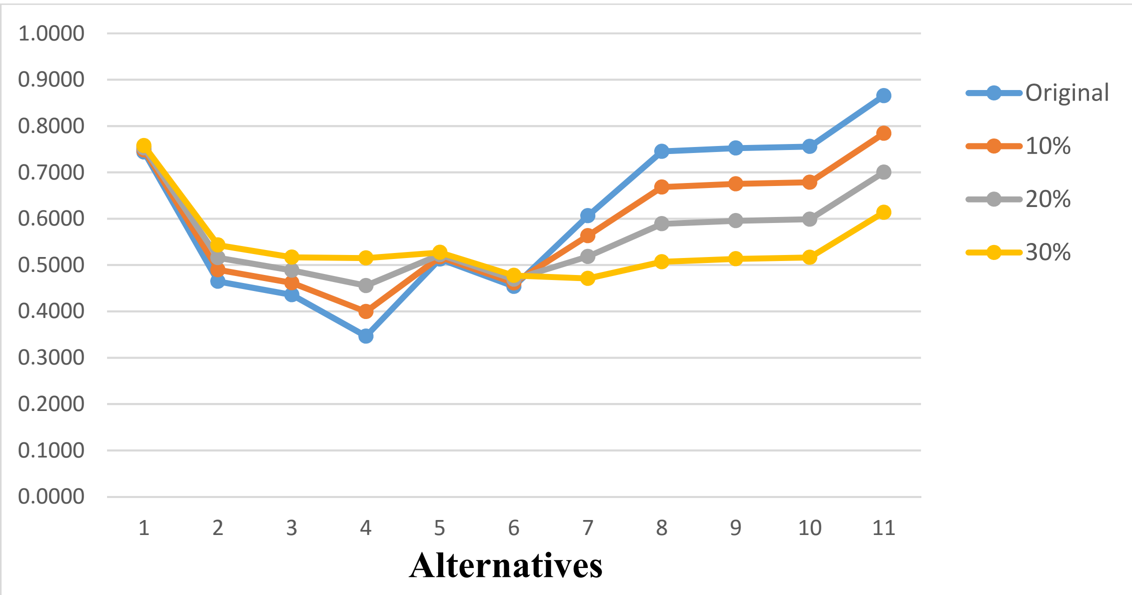

Figure 6.5: Cost weight increments analysis

6.7. Results and Discussion

Sensitivity analysis is conducted to analyse the effect in the output data given a slight change in the cost weight. Based on Figure 6.5, it can be seen that automation operation installation provides the optimum solution for DMP. Furthermore, the analysis revealed that the cost weight increment by 10%, 20% and 30% has not affected the final ranking of the best alternatives for the investigated container port OSP. The slight change on the CC of A11, A10, A8, A9 and A1 can be observed clearly in Table 6.20.

Table 6.19: Cost weight increment effect on the alternatives

A#	Alternatives	Original Cost Weights	10%+	20%+	30%+
A11	Appling fully Automated Crane operations	0.8655	0.78421	0.70033	0.61372
A10	Appling Automated Crane operations on transportation areas	0.7558	0.67854	0.59879	0.51645
A9	Appling Automated Crane operations on yard area	0.7523	0.67513	0.59551	0.51331
A8	Appling Automated Crane operations on quay area	0.7452	0.66831	0.58896	0.50703
A1	Hiring Highly Qualified Crane Driver	0.7439	0.74824	0.75281	0.75767

Based on the result obtained from this analysis, the investigated container port OSP can be improved by automation operation installation. However, since the investigated container port has future plan for automation operation installation which has not been implemented yet, it is beneficial to implement A1, hiring a highly qualified crane driver, as the best solution for DMP.

6.8. Conclusion

This chapter has presented a collaborative modelling and strategic fuzzy decision-making approach that can be implemented for the selection of appropriate operational safety strategies by tackling the selection of RCOs under uncertainty in container terminals. The proposed approach can be applied to situations where qualitative and quantitative data have to be integrated and synthesised for evaluation processes during complex decision-making processes involving container port OSP.

The proposed AHP-FTOPSIS formulates a hybrid approach to assess the costs and benefits associated with operational safety strategies. The BER approach developed an integrated container port system risk analysis in order to evaluate the RR as a benefits criterion, such as risk reduction and probabilistic safety assessment simulations using ANNs that predict and evaluate the criticality of the hazardous events in a container terminal.

The new approach provides solutions and the most preferred safety control measures that are capable of addressing both operational efficiency and risk reduction in container terminals, such as automation solutions for the DMP. The proposed method can be tailored to other DMP (i.e., HEs) to ensure OSP.

Chapter 7 — Conclusion and Future Research Suggestions

Summary

This chapter briefly recaps all the developed models and techniques for the adequacy of operational safety performance (OSP) in container terminals and maritime ports. The developed models and techniques provide an effective risk management framework and an efficient safety prediction tool that can help maritime terminals' and ports' stakeholders, including risk managers, human resource managers, site control managers, safety officers, and port facility security to improve the safety and increase the reliability of their operations. Nevertheless, there are other risk concerns influencing container terminals and maritime ports safety that require further research, and these are outlined in this chapter.

7.1. Research contributions

Operational safety of container terminals and maritime ports is an essential link in ensuring supply chain resilience and sustainability that can affect the cost structures, industrial competitiveness, and living standards in any coastal state. Maritime container transportation occupies an increasingly important position in world trade, and is the fastest growing sector of the international shipping industry. The analysis of containerisation growth and optimum terminal operations are interrelated, in such that both concepts are developed side-by-side regarding operational complexity, transportation modes, terminal type and capacity, trade lanes and destinations, and technological aids including handling equipment, optimisations, and communications (See chapter 2, Sections 2.1 and 2.3).

There is an imperative need to establish a coherent risk-based methodology addressing the OSP in container terminals and maritime ports. The lack of an appropriate risk management framework and research upon which to base an effective safety measure for maritime terminals' and ports' complex operational activities that approximates the risk realities and solves the confusions over uncertainty terminology illustrates the necessity of conducting this study (see chapter 2, Sections 2.4 and 2.5).

As a result, an advanced risk management framework for the OSP in container terminals and maritime ports has been described through the development of several novel risk-based models in chapters 3, 4, 5 and 6. This includes the identification of the most significant HEs in maritime container terminals operation, risk assessment, risk models simulation, and decision making under uncertainty in which both qualitative and quantitative data can be used. The framework has been developed in a generic way that can be tailored for wider applications in other engineering and management systems, especially when instant risk ranking is required by the stakeholders to measure, predict, and improve their system safety and reliability performance.

The most significant HEs were identified through conducting an appropriate literature review, knowledge based on human expertise and case studies application for major risks that affect the container operation safety as the first phase of the Risk Assessment section. In the second phase, the proportion method is used to rationalise the DoB distribution in FMEA risk analysis that describes the relationship between risk parameters in the IF part and risk levels in the THEN part, taking into account the new risk parameter in the IF part, namely, the Impact (I) of a failure to the resilience of port operational systems introduced in this study. Consequently, a unique FRB was developed in order to assess the most significant HEs identified. The development of a generic risk-based model FRBN incorporating FRB and BN using *Hugin* software can help container terminals and maritime ports stakeholders to maintain efficient and safe operations and management by evaluating each HE individually and prioritising their specific risk estimations locally with a case study (see chapter 3).

The last phase in the Risk Assessment section is the development of a generic risk-based model incorporating FRB and Evidential Reasoning (FRBER) using the *IDS* software to evaluate all HEs aggregated collectively for their Risk Influence (RI) globally using a case study. Moreover, a new sensitivity analysis method is developed to rank the HEs taking into account their specific risk estimations locally and their RI globally (see chapter 4).

The Risk Assessment section provides an effective tool by developing two advanced risk assessment based models under high uncertainties for the OSP in container terminals and maritime ports using both quantitative and qualitative data. The first model (i.e., FRBN) evaluates each HE individually and prioritises their specific risk estimations locally, while the second model (i.e., FRBER) evaluates all HEs aggregated collectively for their risk influence globally. The risk assessment based methodologies introduced in this section enable the stakeholders to evaluate and improve the safety and reliability of the operational performance in their terminals' system. In addition, it will motivate them to take preventive and control measures confidently.

The Risk Models Simulations section commences with the construction of the BNANNs model that simulates the FRBN model in the first phase, followed by the second phase of the simulation model ERANNs, whose construction is based on FRBER model using a test case. The final phase in this section integrates the BNANNs and ERANNs models to develop the AnBnEvR model that is able to predict the risk magnitude for HEs and provide a panoramic view on the risk inference in both perspectives, locally and globally (see chapter 5).

The ANNs as a method-based uncertainty treatment theory is used to enhance the performance of FMEA by overcoming its incapability in tackling uncertainty in data and at the same time ease the evaluation process on the stakeholders from handling a complex large amount of data to measure, predict, and improve their system safety and reliability performance. The complexity of handling large amounts of data dealing with two different methodologies with reference to its software (i.e., FRBN and FRBER), would burden the stakeholders by going through copious nonuser-friendly calculations. It is noteworthy to mention that, due to the optimisation required for the five risk assessment attributes with their fuzzy parameters introduced in chapter 3 and chapter 4 (i.e., the inputs and outputs) with evaluations tasks, causes the amount of calculation to be tremendous for the interface of FRBN and FRBER, which can be avoided by applying the ANN concept.

The Risk Control Options section is the last link in the risk management based methodology cycle in this study. The Analytical Hierarchal Process (AHP) method was used for determining the relative weights of all criteria identified in the first phase. The last phase is the development of a risk control options model by incorporating Fuzzy logic and the Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS) that offers the best risk mitigation strategies with the most preferred safety control measures capable of addressing both operational efficiency and risk reduction in container terminals, such as automation solutions alternatives (see chapter 6).

The knowledge contribution of this research provides an effective risk management framework for OSP in container terminal and maritime ports by identifying, assessing, and controlling the most significant HEs in maritime container terminals operation. In addition, given the dynamic nature of the complex system and operation of maritime terminals and maritime ports, it provides an efficient safety prediction tool that can ease all the processes in the methods and techniques used with the risk management framework by applying ANN concept to simulate the risk models that provide a panoramic view of the risk associated with uncertainties from different perspectives, locally and globally.

All the proposed models have been developed in sequence. They provide an integrated approach to increase the safety and reliability of maritime engineering operations. Figure 7.1 depicts an overall framework diagram with a description illustrating the interrelationship of the developed models in a context of a risk management based methodology process.

7.2. Implications for Future Research

Developing a risk management framework with uncertainty treatment based decision-making analysis methodology to identify, assess, and mitigate the risk factors affecting the OSP in container terminal and maritime ports has achieved the aim of this research. Although it is not claimed to be a decisive framework, it provides a comprehensive analysis using risk management based methodologies including many approaches and techniques to facilitate the quantitative and qualitative data in maritime engineering operations. Many important issues in each phase of each section are raised both at the beginning and throughout the research process, in which some are analysed, described, and consolidated into the study and due to its generality, the framework can be tailored for a wide range of applications in different safety and reliability engineering and management systems. Others, however, could not be incorporated due to scope, time constraints, and because the present research has prominently been exploratory, experimental and correlational. In this regard, the aspects that were not covered in detail are part of the suggestions that would be desirable for further investigations in future work as follows.

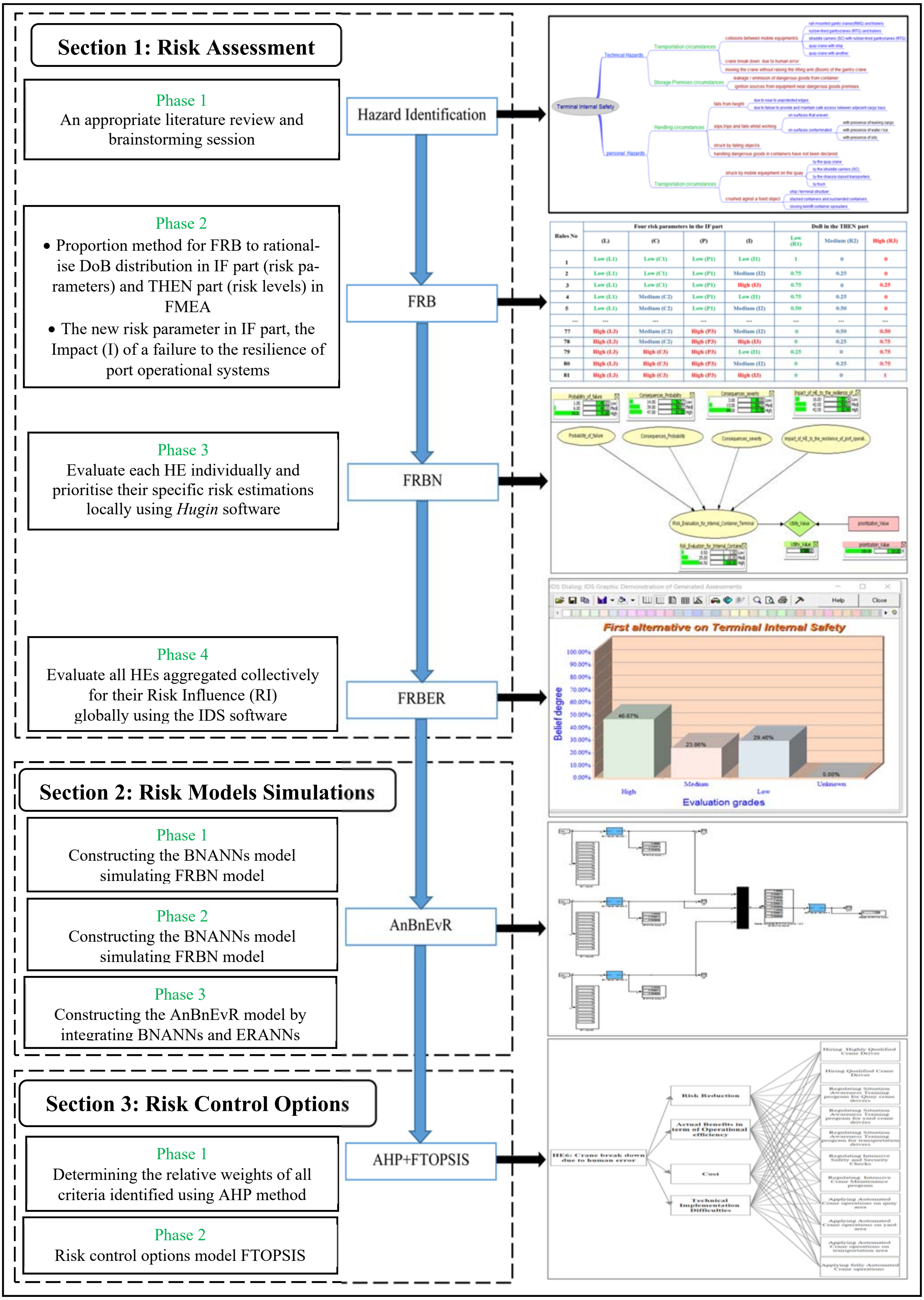

Figure 7.1: Overall framework diagram with description

Performing more data collection and test cases would be desirable for further validation of the developed risk management based methodology for container terminal and maritime port risk assessment taking into account the selection of the representative number of experts within the maritime industry to reduce the bias involved in the subjective judgements.

The BNANNs model can process and simulates each of the 24 HEs using the ANN concept since the evaluation is individually conducted, while the EvRANNs cannot because the hierarchical structure of the HEs has to be processed collectively due to the aggregation feature in the ER technique that requires a large amount of ED to be processed in the simulated model and creates a greater computational burden that is not possible to manage with existing technology and software. Therefore, it would be desirable to construct a model using an ANN approach simulating FRBER to include all HEs identified rather than the significant HEs only. However, it is a matter of advanced technology and software availability. In addition, the AnBnEvR model can be developed for windows-based software that can help container terminals and maritime ports stakeholders to maintain efficient and safe operations and management.

For extended research, it seems beneficial to include other risk concerns influencing container terminal and maritime port safety, such as managerial and policy implications, natural disasters, environmental, and political issues. Moreover, in the extended research, it would be useful to consider the sequence structure of the approaches and techniques in the three sections of the risk management framework with uncertainty treatment in this study for risk review, including the unique FRB that provide a rational distribution of the DoB as well as transparency and low complexity in the risk parameters.

The strategic management approach in maritime port industry is advancing towards systematic risk-based regulatory scheme to avoid overreaction to risks in regulatory systems by describing the tools for choosing the best of risk treatment strategies, including tolerating a risk, avoiding a risk, transferring a risk, and mitigating a risk. In this respect, container terminal and maritime port safety stakeholders, including risk managers, human resource managers, site control managers, safety officers, and port facility security officers would have more flexibility to use innovation for the most advanced risk management frameworks and MCDM tools. The FRB, BN, ER, AHP, FTOPSIS and ANN approaches and techniques used in this research may provide useful approaches that may be able to be utilised and implemented to facilitate other risk-based modelling and MADM systems. Therefore, the practical application of the aforementioned tools to the container terminal and maritime port industry can be highlighted for best practice and implementation strategies.

The proposed risk management framework in this study has potential to facilitate risk analysis of system design and operations in a wide context. The framework will need to be appropriately tailored to study other topics outside the maritime industry to offer practical guidance on the steps to be taken in implementing an action plan for best practice and in enhancing the risk management efficiency of the system as a whole.

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LIST OF APPENDICES

Appendix I-1: FRB with Belief Structures for Chapter 3

Rules No	Four risk parameters in the IF part				DoB in the THEN part		
	Probability of failure (L)	Consequences/ Severity (C)	probability of failures being undetected (P)	Impact of a failure to the resilience of port operational systems (I)	Low (R1)	Medium (R2)	High (R3)
1.	Low	Low	Low	Low	1		
2.	Low	Low	Low	Medium	0.75	0.25	
3.	Low	Low	Low	High	0.75		0.25
4.	Low	Medium	Low	Low	0.75	0.25	
5.	Low	Medium	Low	Medium	0.50	0.50	
6.	Low	Medium	Low	High	0.50	0.25	0.25
7.	Low	High	Low	Low	0.75		0.25
8.	Low	High	Low	Medium	0.50	0.25	0.25
9.	Low	High	Low	High	0.50		0.50
10.	Low	Low	Medium	Low	0.75	0.25	
11.	Low	Low	Medium	Medium	0.50	0.50	
12.	Low	Low	Medium	High	0.50	0.25	0.25
13.	Low	Medium	Medium	Low	0.50	0.50	
14.	Low	Medium	Medium	Medium	0.25	0.75	
15.	Low	Medium	Medium	High	0.25	0.50	0.25
16.	Low	High	Medium	Low	0.50	0.25	0.25
17.	Low	High	Medium	Medium	0.25	0.50	0.25
18.	Low	High	Medium	High	0.25	0.25	0.50
19.	Low	Low	High	Low	0.75		0.25
20.	Low	Low	High	Medium	0.50	0.25	0.25
21.	Low	Low	High	High	0.50		0.50
22.	Low	Medium	High	Low	0.50	0.25	0.25
23.	Low	Medium	High	Medium	0.25	0.50	0.25
24.	Low	Medium	High	High	0.25	0.25	0.50
25.	Low	High	High	Low	0.50		0.50
26.	Low	High	High	Medium	0.25	0.25	0.50
27.	Low	High	High	High	0.25		0.75
28.	Medium	Low	Low	Low	0.75	0.25	
29.	Medium	Low	Low	Medium	0.50	0.50	
30.	Medium	Low	Low	High	0.50	0.25	0.25
31.	Medium	Medium	Low	Low	0.50	0.50	
32.	Medium	Medium	Low	Medium	0.25	0.75	
33.	Medium	Medium	Low	High	0.25	0.50	0.25
34.	Medium	High	Low	Low	0.50	0.25	0.25
35.	Medium	High	Low	Medium	0.25	0.50	0.25
36.	Medium	High	Low	High	0.25	0.25	0.50
37.	Medium	Low	Medium	Low	0.50	0.50	
38.	Medium	Low	Medium	Medium	0.25	0.75	
39.	Medium	Low	Medium	High	0.25	0.50	0.25
40.	Medium	Medium	Medium	Low	0.25	0.75	
41.	Medium	Medium	Medium	Medium		1	

Rules No	Four risk parameters in the IF part				DoB in the THEN part		
	Probability of failure (L)	Consequences/ Severity (C)	probability of failures being undetected (P)	Impact of a failure to the resilience of port operational systems (I)	Low (R1)	Medium (R2)	High (R3)
42.	Medium	Medium	Medium	High		0.75	0.25
43.	Medium	High	Medium	Low	0.25	0.50	0.25
44.	Medium	High	Medium	Medium		0.75	0.25
45.	Medium	High	Medium	High		0.50	0.50
46.	Medium	Low	High	Low	0.50	0.25	0.25
47.	Medium	Low	High	Medium	0.25	0.50	0.25
48.	Medium	Low	High	High	0.25	0.25	0.50
49.	Medium	Medium	High	Low	0.25	0.50	0.25
50.	Medium	Medium	High	Medium	0.75		0.25
51.	Medium	Medium	High	High		0.50	0.50
52.	Medium	High	High	Low	0.25	0.25	0.50
53.	Medium	High	High	Medium		0.50	0.50
54.	Medium	High	High	High		0.25	0.75
55.	High	Low	Low	Low	0.75		0.25
56.	High	Low	Low	Medium	0.50	0.25	0.25
57.	High	Low	Low	High	0.50		0.50
58.	High	Medium	Low	Low	0.50	0.25	0.25
59.	High	Medium	Low	Medium	0.25	0.50	0.25
60.	High	Medium	Low	High	0.25	0.25	0.50
61.	High	High	Low	Low	0.50		0.50
62.	High	High	Low	Medium	0.25	0.25	0.50
63.	High	High	Low	High	0.25		0.75
64.	High	Low	Medium	Low	0.50	0.25	0.25
65.	High	Low	Medium	Medium	0.25	0.50	0.25
66.	High	Low	Medium	High	0.25	0.25	0.50
67.	High	Medium	Medium	Low	0.25	0.50	0.25
68.	High	Medium	Medium	Medium		0.75	0.25
69.	High	Medium	Medium	High		0.50	0.50
70.	High	High	Medium	Low	0.25	0.25	0.50
71.	High	High	Medium	Medium		0.50	0.50
72.	High	High	Medium	High		0.25	0.75
73.	High	Low	High	Low	0.50		0.50
74.	High	Low	High	Medium	0.25	0.25	0.50
75.	High	Low	High	High	0.25		0.75
76.	High	Medium	High	Low	0.25	0.25	0.50
77.	High	Medium	High	Medium		0.50	0.50
78.	High	Medium	High	High		0.25	0.75
79.	High	High	High	Low	0.25		0.75
80.	High	High	High	Medium		0.25	0.75
81.	High	High	High	High			1

Appendix I-2: The Conditional Probability Table for The Risk Estimate (N_R)

L	L1																										
D	D1									D2									D3								
C	C1			C2			C3			C1			C2			C3			C1			C2			C3		
R RE	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
RE1	1	0.75	0.75	0.75	0.50	0.50	0.75	0.50	0.50	0.75	0.50	0.50	0.50	0.25	0.25	0.50	0.25	0.25	0.75	0.50	0.50	0.50	0.25	0.25	0.50	0.25	0.25
RE2	0	0.25	0	0.25	0.50	0.50	0	0.25	0	0.25	0.50	0.25	0	0	0.50	0.25	0.50	0.25	0	0.25	0	0.25	0.50	0.25	0	0.25	0
RE3	0	0	0.25	0	0	0.25	0.25	0.25	0.50	0	0	0.25	0.50	0.75	0.25	0.25	0.25	0.50	0.25	0.25	0.50	0.25	0.25	0.50	0.50	0.50	0.75

L	L2																										
D	D1									D2									D3								
C	C1			C2			C3			C1			C2			C3			C1			C2			C3		
R RE	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
RE1	0.75	0.50	0.50	0.50	0.25	0.25	0.50	0.25	0.25	0.50	0.25	0.25	0.25	0	0	0.25	0	0	0.50	0.25	0.25	0.25	0.75	0	0.25	0	0.75
RE2	0.25	0.50	0.25	0.50	0.75	0.50	0.25	0.50	0.25	0.50	0.75	0.50	0.75	1	0.75	0.50	0.75	0.50	0.25	0.50	0.25	0.50	0	0.50	0.25	0.50	0.25
RE3	0	0	0.25	0	0	0.25	0.25	0.25	0.50	0	0	0.25	0	0	0.25	0.25	0.25	0.50	0.25	0.25	0.50	0.25	0.25	0.50	0.50	0.50	0

L	L3																										
D	D1									D2									D3								
C	C1			C2			C3			C1			C2			C3			C1			C2			C3		
R / RE	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
RE1	0.75	0.50	0.50	0.50	0.25	0.25	0.50	0.25	0.25	0.50	0.25	0.25	0.25	0	0	0.25	0	0	0.50	0.25	0.25	0.25	0	0	0.25	0	0
RE2	0	0.25	0	0.25	0.50	0.25	0	0.25	0	0.25	0.50	0.25	0.50	0.75	0.50	0.25	0.50	0.25	0	0.25	0	0.25	0.50	0.25	0	0.25	0
RE3	0.25	0.25	0.50	0.25	0.25	0.50	0.50	0.50	0.75	0.25	0.25	0.50	0.25	0.25	0.50	0.50	0.50	0.75	0.50	0.50	0.75	0.50	0.50	0.75	0.75	0.75	1

Appendix I-3: Questionnaire Used for HEs Evaluation in Chapter 3

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11 November 2011

To: **WHOM IT MAY CONCERN**

A research project at Liverpool John Moores University is currently being carried out with regard to the container terminal safety and it is specific on the container shipping sector. This subject would become a critical topic in the maritime community internationally due to the fast expansion in containerisation and the global economic recession over the past decade.

The aim of this study is to investigate and examine the current safety level of container terminals operations. Furthermore, evaluate the most significant failure events and its consequences on the safety management of a desired container terminal. At the end of this research, a conceptual methodology and an advanced model would be generated that can be used by container terminal management to investigate and mitigate the risk affecting the operations of the terminal and to obtain a cost effective strategy. To achieve the above aim, the research objectives are as follows:

1. To investigate the high significant failure events influencing the safety level of the terminal by using a *proportion technique*.
2. Analyse the uncertain conditions in the terminal industry by using a *rule-based technique.*

A number of evaluation criteria have been determined in this research. All the evaluation criteria need to be measured by using the two techniques that have been mentioned above. This process is required to provide reliable data by identifying an expert opinion of each evaluation parameter. A set of questionnaires is compiled in this letter.

I should be most grateful if you could kindly spend your valuable time to complete the accompanying questionnaire and email it at the address shown above. Your vital feedback will greatly benefit and contribute to the formulation of an industry wide opinion. I can assure you that the confidentiality of your response will be honoured and respected.

Yours faithfully,

Hani M.A. Alyami
PhD researcher, School of Engineering, Technology and Maritime Operations
Liverpool Logistics Offshore and Marine Research Institute
Room 2.23, LOOM Research Institute

The procedures and guidelines for answering this set of questionnaires are explained as follows:

The linguistic meaning

To proceed with the proportion technique, an expert has to understand the ratio scale measurement used in this study. The table below describe the numerical assessment together with the linguistic meaning of each number.

Numerical Assessment	Linguistic meaning
$0 \leq L \leq 100$	Low (L)
$0 \leq M \leq 100$	Medium (M)
$0 \leq H \leq 100$	High (H)

An expert is required to give a possible judgement to all questions based on his/her expertise and experience in the shipping industry. The judgment process has to be focussed on how to achieve the goal. The total assessment for each parameter must not be over 100%. For instance, you have two types of Roads and two types of cars as shown.


 

The Goal *is to evaluate the risk of driving deferent types of cars on deferent types of roads with 30 mph speed.*

Attributes / Failure Event	Probability Risk Assessment Scale			Consequences Risk Assessment Scale		
	H	**M**	**L**	**H**	**M**	**L**
How likely to drive a formula 1 on rugged road?	**100%**	**0%**	**0%**	**100%**	**0%**	**0%**
How likely to drive a formula 1 on gravel road?	**90%**	**10%**	**0%**	**95%**	**5%**	**0%**
How likely to drive a four-wheel vehicle on rugged road?	**40%**	**20%**	**40%**	**45%**	**15%**	**40%**
How likely to drive a four-wheel vehicle on gravel road?	**0%**	**0%**	**100%**	**0%**	**0%**	**100%**

Explanation of the above example,

i) The probability of driving a formula 1 on rugged road is 100% High risk because it cannot be driven on this type of roads and the consequences of driving it, is 100% High risk because it will be instantly severely damaged. That means the risk assessment of driving a formula 1 on a rugged road is 100% High risk, and recommended not to drive.

ii) The probability of driving a formula 1 on gravel road is 90% High and 10% Medium risks because it can be driven but not for long time and the consequences of driving it, is 95% High and 5% Medium risks because the damage will increase as it runs on the road. That means the risk assessment of driving a formula 1 on a gravel road is reasonably High risk, and recommended not to drive.

iii) The probability of driving a four-wheel vehicle on rugged road is 40% High, 20% Medium, 40% Low risks, and the consequences of driving it, is 45% High, 15% Medium, 40% Low risks because the speed limit. That means the risk assessment of driving a four-wheel vehicle on rugged road is reasonably Medium risk, and recommended to drive with extreme caution.

iv) The probability of driving a four-wheel vehicle on gravel road is 100% Low risk and the consequences of driving it, is 100% Low risk. That means the risk assessment of driving a four-wheel vehicle on a gravel road is 100% Low risk, and recommended to drive.

The Attributes description

L describes the failure occurrence probability. It means the rate of failure occurring in a designated period, which directly represents the number of failure frequencies during the design life span of a particular system.

C describes the consequences/ severity. It represents the magnitude of possible loss when risk happens, which is ranked according to the severity of failure effects.

P defines the probability of failures being undetected (P). It refers to the probability that possible failure can be detected before occurrence.

R defines the chance of container terminal operations being disrupted due to a failure. It refers to the probability that possible disruption happens given the occurrence of a failure event.

RE is the Risk Evaluation. It is the only output used to produce safety evaluation for a particular cause to technical failure.

Note: The Probability of the failure mode should be given on an annual basis.

Parameters

The degree of the parameters estimated for each hazard may be based on knowledge of the results of similar past events and can be defined as follows.

High (H): loss of ability to accomplish the operations or operation failure; death or permanent total disability accident risk; loss of major facility damage; severe environmental damage.

Medium (M): degraded operations capability or readiness; minor injury accident risk that disrupted operations over 3 hours a day; minor capability to equipment or system, facility or the environment; minor damage to facility or environment.

Low (L): little or no adverse impact on operations capability; minor medical treatment in accident risk; slight equipment or system damage but fully functional and serviceable; little or no facility or environment damage.

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
collision between a rail-mounted gantry crane (RMG) and a trailer.												
collision between a rubber-tired gantry crane (RTG) and a trailer.												
collision between straddle carriers (SC) and a rubber-tired gantry crane (RTG).												
collision between the quay crane and the ship.												

Failure Event \ Attributes	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
collision between two quay cranes.												
crane break down due to human error.												
moving the crane without raising the Boom (lifting arm) of the gantry crane.												
leakage/ emission of dangerous goods from a container.												
ignition sources from equipment near dangerous goods premises.												
person falls from height due to being too near to unprotected edges.												
person falls from height due to non-provision / maintenance of safe access between adjacent cargo bays.												
person slips, trips and falls whilst working on surfaces that are not even.												
person slips, trips and falls whilst working on surfaces with presence of leaking cargo.												

Failure Event \ Attributes	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
slips, trips and falls whilst working on surfaces with presence of water / ice.												
person slips, trips and falls whilst working on surfaces with presence of oils.												
person struck by falling object/s.												
person handling dangerous goods in containers that have not been declared.												
person struck by quay crane.												
person struck by straddle carriers (SC).												
person struck by chassis-based transporters.												
person struck by trucks.												
person crushed against a fixed object and ship / terminal structure.												
person crushed against a fixed object and stacked containers and suspended containers.												
person crushed against a fixed object and closing the twin lift container spreaders.												

Appendix I-4: ALL Experts Evaluations Table in Chapter 3

Attributes / Failure Event		Probability of failure/ Likelihood			probability of failures being undetected			Consequences / severity			Chance of terminal operation being Disrupted due to failure		
	Experts	H	M	L	H	M	L	H	M	L	H	M	L
(CRMGT)	A	0	20	80	5	15	80	70	20	10	80	20	0
	B	10	10	80	15	15	70	70	20	10	90	5	5
	C	10	30	60	10	25	65	85	15	0	30	20	50
	Prior Probability	6.7	20	73.3	10	18.3	71.7	75	18.3	6.7	66.7	15	18.3
CRTGT	A	40	30	30	50	30	20	50	30	20	20	40	40
	B	60	15	25	60	30	10	70	15	15	10	20	70
	C	50	20	30	60	30	10	40	30	30	15	45	40
	Prior Probability	50	21.7	28.3	56.7	30	13.3	53.3	25	21.7	15	35	50
CRTGSC	A	40	40	20	40	40	20	30	40	30	20	20	60
	B	30	30	40	40	30	30	30	40	30	10	10	80
	C	45	45	10	50	30	20	20	50	30	25	25	50
	Prior Probability	35	41.7	23.3	40	36.7	23.3	23.3	36.7	40	26.7	16.7	56.7
CQCS	A	80	10	10	80	15	5	90	10	0	90	10	0
	B	90	10	0	80	20	0	70	15	15	85	10	5
	C	80	15	5	70	20	10	90	5	5	90	10	0
	Prior Probability	83.3	11.6	5	76.7	18.3	5	83.3	10	6.7	88.3	10	1.7
CQC's	A	0	10	90	0	10	90	0	20	80	60	20	20
	B	10	20	70	50	20	30	70	10	20	80	10	10
	C	10	10	80	20	10	70	30	25	45	45	25	30
	Prior Probability	6.7	13.3	80	23.3	13.3	63.3	33.3	18.3	48.3	61.7	18.3	20
CBD	A	90	10	0	90	10	0	90	10	0	90	10	0
	B	80	15	5	70	15	15	90	10	0	80	10	10
	C	85	15	0	85	15	0	80	20	0	40	40	20
	Prior Probability	85	13.3	1.6	81.7	13.3	5	86.7	13.3	0	70	20	10
MCWRLAGC	A	20	20	60	20	20	60	50	30	20	50	30	20
	B	70	20	10	80	10	10	60	30	10	60	20	20
	C	50	10	40	15	15	70	60	25	15	40	25	35
	Prior Probability	46.7	16.7	36.7	38.3	15	46.7	56.7	28.3	15	50	25	25
	A	40	40	20	40	40	20	30	30	40	20	20	60

leakage/ emission of dangerous goods from a container.	B	80	15	5	70	20	10	50	30	20	40	30	30
	C	50	45	5	45	45	10	30	30	40	25	25	50
	Prior Probability	56.7	33.3	10	51.7	35	13.3	36.7	30	33.3	28.3	25	46.7
ignition sources from equipment near dangerous goods premises.	A	10	20	70	10	20	70	50	30	20	50	30	20
	B	10	10	80	70	20	10	60	30	10	60	40	0
	C	15	25	60	10	20	70	60	30	10	60	30	10
	Prior Probability	11.7	18.3	70	30	20	50	56.7	30	13.3	56.7	33.3	10
person falls from height due to being too near to unprotected edges.	A	10	20	70	10	20	70	20	20	60	10	20	70
	B	10	20	70	70	30	0	50	30	20	30	30	40
	C	30	25	45	50	30	20	40	30	30	10	30	60
	Prior Probability	16.7	21.7	61.7	43.3	26.7	30	36.7	26.7	36.7	16.7	26.7	56.7
person falls from height due to non-provision / maintenance of safe access between adjacent cargo bays.	A	30	30	40	30	30	40	40	40	20	30	30	40
	B	10	20	70	60	30	10	45	45	10	40	20	40
	C	15	35	50	30	40	30	45	45	10	20	20	60
	Prior Probability	18.3	28.3	53.3	40	33.3	26.7	43.3	43.3	13.3	30	23.3	46.7
working on surfaces that are not even.	A	60	30	10	60	30	10	70	20	10	30	30	40
	B	50	10	40	60	30	10	50	30	20	40	30	30
	C	60	35	5	60	35	5	70	15	15	25	35	40
	Prior Probability	56.7	25	18.3	60	31.7	8.3	63.3	21.7	15	31.7	31.7	36.7
person slips, trips and falls whilst working on surfaces with presence of leaking cargo.	A	60	30	10	60	30	10	70	20	10	40	40	20
	B	50	30	20	70	30	0	60	30	10	40	40	20
	C	50	25	25	70	20	10	70	20	10	45	45	10
	Prior Probability	53.3	28.3	18.3	66.7	26.7	6.7	66.7	23.3	10	41.7	41.7	16.7
presence of water / ice.	A	70	20	10	70	20	10	60	30	10	50	25	25
	B	70	30	0	60	30	10	60	30	10	50	30	20
	C	10	40	50	70	20	10	60	30	10	25	25	50
	Prior Probability	50	30	20	66.7	23.3	10	60	30	10	41.7	26.7	31.7

person slips, trips and falls whilst working on surfaces with presence of oils.	A	60	30	10	60	30	10	70	20	10	40	40	20
	B	60	30	10	70	20	10	70	25	5	30	30	40
	C	65	35	0	60	30	10	70	25	5	30	40	30
	Prior Probability	61.7	31.7	6.7	63.3	26.7	10	70	23.3	6.7	33.3	36.7	30
person struck by falling object/s.	A	55	35	10	50	30	20	20	30	50	20	30	50
	B	50	30	20	40	30	30	60	30	10	30	30	40
	C	55	35	10	55	20	25	40	40	20	20	30	50
	Prior Probability	53.3	33.3	13.3	48.3	26.7	25	40	33.3	26.7	23.3	30	46.7
dangerous goods in containers that have not been declared.	A	10	10	80	10	10	80	80	20	0	80	20	0
	B	50	40	10	60	30	10	80	20	0	80	20	0
	C	80	10	10	70	20	10	80	20	0	10	40	50
	Prior Probability	46.7	20	33.3	46.7	20	33.3	80	20	0	56.7	26.7	16.7
person struck by quay crane.	A	30	40	30	30	40	30	20	40	40	10	20	70
	B	20	40	40	30	30	40	40	20	40	30	30	40
	C	20	40	40	30	45	25	30	40	30	5	15	80
	Prior Probability	23.3	40	36.7	30	38.3	31.7	30	33.3	36.7	15	21.7	63.3
person struck by straddle carriers (SC).	A	40	40	20	40	40	20	20	40	40	10	20	70
	B	30	30	40	30	30	40	40	30	30	20	30	50
	C	10	30	60	25	25	50	50	20	30	20	15	65
	Prior Probability	26.7	33.3	40	31.7	31.7	36.7	36.7	30	33.3	16.7	21.7	61.7
person struck by chassis-based transporters.	A	40	40	20	40	40	20	20	40	40	10	20	70
	B	30	30	40	30	30	40	20	60	20	10	20	70
	C	30	30	40	40	30	30	60	10	30	10	20	70
	Prior Probability	33.3	33.3	33.3	36.7	33.3	30	33.3	36.7	30	10	20	70
person struck by trucks.	A	40	40	20	40	40	20	20	40	40	10	20	70
	B	40	30	30	40	30	30	60	30	10	10	20	70
	C	40	40	20	40	40	20	50	40	10	10	20	70
	Prior Probability	40	36.7	23.3	40	36.7	23.3	43.3	36.7	20	10	20	70

person crushed against a fixed object and ship / terminal structure.	A	20	20	60	20	20	60	20	40	40	10	20	70
	B	10	10	80	60	30	10	70	10	20	30	30	40
	C	15	15	70	15	15	70	40	30	30	10	20	70
	Prior Probability	15	15	70	31.7	21.7	46.7	43.3	26.7	30	16.7	23.3	60
person crushed against a fixed object and stacked containers	A	40	40	20	40	40	20	20	40	40	10	20	70
	B	50	30	20	50	30	20	50	30	20	20	30	50
	C	40	40	20	40	40	20	80	10	10	5	15	80
	Prior Probability	43.3	36.7	20	43.3	36.7	20	50	26.7	23.3	11.7	21.7	66.7
closing the twin lift container spreaders.	A	20	20	60	20	20	60	20	40	40	10	20	70
	B	10	10	80	20	20	60	20	40	40	10	20	70
	C	15	15	70	20	20	60	20	40	40	5	15	80
	Prior Probability	15	15	70	20	20	60	20	40	40	8.3	18.3	73.3

Appendix II-1: The Questionnaire used for AHP Technique in Chapter 6

School of Engineering, Technology and Maritime Operations
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Byrom Street
L3 3AF UK
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13 Jun 2015

To: **WHOM IT MAY CONCERN**

A research project at Liverpool John Moores University is currently being carried out with regard to the container terminal safety and it is specific on the risk management for container terminal safety. This subject would become a critical topic in the maritime community internationally due to the fast expansion in containerisation and the global economic recession over the past decade.

The aim of this study is to investigate and examine the significant Hazard Events (HEs) that affecting the container terminal safety in order to optimise the terminal operations efficiency. Furthermore, the current risk assessment of the container terminal industry will be explored in order to conduct analysis on how risk factors influencing other parameters in the container terminal sector. At the end of this research, a conceptual methodology and an advanced model would be generated that can be used by container terminals stakeholders to investigate, mitigate and control the HEs in order to maintain the efficient functionality of the terminal operations and to obtain a cost effective strategy. To achieve the above aim, the research objectives are as follows:

3. To investigate the most important factor/s influencing the efficient functionality of the terminal operations by using a *pair-wise comparison technique*.

A number of evaluation criteria have been determined in this research. All the evaluation criteria need to be measured by using the technique that have been mentioned above. This process is required to provide reliable data by identifying an expert opinion of each evaluation parameter. A set of questionnaires is compiled in this letter.

I should be most grateful if you could kindly spend your valuable time to complete the accompanying questionnaire and email it at the address shown above. Your vital feedback will greatly benefit and contribute to the formulation of an industry wide opinion. I can assure you that the confidentiality of your response will be honoured and respected.

Yours faithfully,

Hani M.A. Alyami
PhD researcher, School of Engineering, Technology and Maritime Operations
Liverpool Logistics Offshore and Marine Research Institute
Room 2.23, LOOM Research Institute

The procedures and guidelines for answering it are explained as follows:

PAIR-WISE COMPARISONS TECHNIQUE

To proceed with the "*Pair-wise Comparisons*" technique, an expert has to understand the ratio scale measurement used in this study. The table below contains two parts which describe the numerical assessment together with the linguistic meaning of each number. The first part is on the left hand side which explains "IMPORTANT", while the right hand 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 important

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 unimportant

An expert is required to give a possible judgement to all questions based on his/her expertise and experience in the shipping industry. The judgment process has to be focussed on how to achieve the goal for each part. For instance:

***Goal**: To select the most important component of computer*

1) Monitor Screen

	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 Screen compare to the mouse?															/		
To achieve the above goal, how important is the Monitor Screen compare to the Keyboard?											/						
To achieve the above goal, how important is the Monitor Screen compare to the CPU?	/																

Explanation of the above example,

i) The monitor screen is 7 times more "Important" than the mouse. It is because we can still use our computer even without the mouse. If the mouse is broken, then we can use the short cut system to access any file or document in the computer by using a keyboard, for instance: to print (Ctrl+P), to save document (Ctrl+S), etc.

ii) The monitor screen is 3 times more "Important" than the keyboard. It is because we can still explore a computer even without the keyboard, for example, to search file in My Document by using a mouse. Additionally, we can read any journal or article papers on the monitor screen even without the keyboard. The only thing we cannot do without the keyboard is typing.

iii) The monitor screen is 1/9 times less "Unimportant" than the CPU. The monitor is useless without the CPU.

PAIR-WISE COMPARISONS TECHNIQUE

Goal: *To select the most important factor influencing the container terminal.*

1) Risk reduction

	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 *Risk reduction* compare to the *Handling capacity (TEU/H)?*																	
To achieve the above goal, how important is the *Risk reduction* compare to the *Cost (£)*?																	
To achieve the above goal, how important is the *Risk reduction* compare *Terminal Resilience (% of fully operational terminal after HE occurred)?*																	

2) Handling capacity (TEU/H)

	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 *Handling capacity (TEU/H)* compare to the *Cost (£)*?																	
To achieve the above goal, how important is the *Handling capacity (TEU/H)* compare to *Terminal Resilience (% of fully operational terminal after HE occurred)?*																	

3) Cost (£)

	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 *Cost (£)* compare to *Terminal Resilience (% of fully operational terminal after HE occurred)?*?																	

Appendix II-2: Experts Evaluation On Risk Reduction (RR) in Chapter 6

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20 August 2015

To: **WHOM IT MAY CONCERN**

A research project at Liverpool John Moores University is currently being carried out with regard to the container terminal safety and it is specific on the container-shipping sector. This subject would become a critical topic in the maritime community internationally due to the fast expansion in containerisation and the global economic recession over the past decade.

At the end of this research, a conceptual methodology and an advanced model would be generated that can be used by container terminal management to investigate and mitigate the risk affecting the operations of the terminal in order to obtain a cost effective strategy. To achieve the above aim, the research objective is as follows:

- Support the decision-making system by evaluating the risk of HE6 after applying alternatives to mitigate the risk affecting the operations of the terminal.

Your vital feedback will greatly benefit and contribute to the formulation of an industry wide opinion. I can assure you that the confidentiality of your response will be honoured and respected. Any refusal or incomplete questionnaire will be excluded without any responsibility on the participant. Completion of the questionnaire will indicate your willingness to participate in this study. If you require additional information or have questions, please contact me at the addresses listed below.

If you are not satisfied with the manner in which this study is being conducted, you may report any complaints to the LJMU-LOOM research centre.
(https://www.ljmu.ac.uk/research/centres-and-institutes/faculty-of-engineering-and-technology-research-institute/loom/get-in-touch-page)

Hani M.A. Alyami
PhD researcher, School of Engineering, Technology and Maritime Operations

Liverpool Logistics Offshore and Marine Research Institute
H.M.Al-Yami@2010.ljmu.ac.uk

Introduction

The most significant hazardous events (HEs) and its consequences on the RSGT container terminal safety level operations were investigated and examined for each HE locally and globally (i.e., for individual HE and all HEs aggregated collectively). As a result, the most significant HE that has a great impact on the RSGT container terminal operations locally and globally is HE6: Crane break down due to human error which was chosen for further analysis. The aim of this study is to support decision-making system in order to re-evaluate the risk of HE6 after applying alternatives to mitigate the risk affecting the operations of the terminal in order to select the appropriate container port safety plan to optimise the operational efficiency.

A number of Risk Control Options (RCOs) have been determined in this research. All the RCOs criteria need to be measured by using TOPSIS technique. This process is required to provide reliable data by identifying an expert opinion of each evaluation parameter.

The procedures and guidelines for answering this set of questionnaires are explained as follows:

The linguistic meaning

To proceed with the proportion technique, an expert has to understand the ratio scale measurement used in this study. The table below describe the numerical assessment together with the linguistic meaning of each number.

Numerical Assessment	Linguistic meaning
$0 \leq L \leq 100$	Low (L)
$0 \leq M \leq 100$	Medium (M)
$0 \leq H \leq 100$	High (H)

An expert is required to give a possible judgement to all questions based on his/her expertise and experience in the shipping industry. The judgment process has to be focussed on how to achieve the goal. The total assessment for each parameter must not be over 100%. For instance, you have two types of Roads and two types of cars as shown.




The Goal *is to evaluate the risk of driving deferent types of cars on deferent types of roads with 30 mph speed.*

Attributes / Failure Event	Probability Risk Assessment Scale			Consequences Risk Assessment Scale		
	H	**M**	**L**	**H**	**M**	**L**
How likely to drive a formula 1 on rugged road?	**100%**	**0%**	**0%**	**100%**	**0%**	**0%**
How likely to drive a formula 1 on gravel road?	**90%**	**10%**	**0%**	**95%**	**5%**	**0%**
How likely to drive a four-wheel vehicle on rugged road?	**40%**	**20%**	**40%**	**45%**	**15%**	**40%**
How likely to drive a four-wheel vehicle on gravel road?	**0%**	**0%**	**100%**	**0%**	**0%**	**100%**

Explanation of the above example,

i) The probability of driving a formula 1 on rugged road is 100% High risk because it cannot be driven on this type of roads and the consequences of driving it, is 100%

High risk because it will be instantly severely damaged. That means the risk assessment of driving a formula 1 on a rugged road is 100% High risk, and recommended not to drive.

ii) The probability of driving a formula 1 on gravel road is 90% High and 10% Medium risks because it can be driven but not for long time and the consequences of driving it, is 95% High and 5% Medium risks because the damage will increase as it runs on the road. That means the risk assessment of driving a formula 1 on a gravel road is reasonably High risk, and recommended not to drive.

iii) The probability of driving a four-wheel vehicle on rugged road is 40% High, 20% Medium, 40% Low risks, and the consequences of driving it, is 45% High, 15% Medium, 40% Low risks because the speed limit. That means the risk assessment of driving a four-wheel vehicle on rugged road is reasonably Medium risk, and recommended to drive with extreme caution.

iv) The probability of driving a four-wheel vehicle on gravel road is 100% Low risk and the consequences of driving it, is 100% Low risk. That means the risk assessment of driving a four-wheel vehicle on a gravel road is 100% Low risk, and recommended to drive.

The Attributes description

L describes the failure occurrence probability. It means the rate of failure occurring in a designated period, which directly represents the number of failure frequencies during the design life span of a particular system.

C describes the consequences/ severity. It represents the magnitude of possible loss when risk happens, which is ranked according to the severity of failure effects.

P defines the probability of failures being undetected (P). It refers to the probability that possible failure can be detected before occurrence..

R defines the chance of container terminal operations being disrupted due to a failure. It refers to the probability that possible disruption happens given the occurrence of a failure event.

RE is the Risk Evaluation. It is the only output used to produce safety evaluation for a particular cause to technical failure.

Note: The Probability of the failure mode should be given on an annual basis.

Parameters

The degree of the parameters estimated for each hazard may be based on knowledge of the results of similar past events and can be defined as follows.

High (H): loss of ability to accomplish the operations or operation failure; death or permanent total disability accident risk; loss of major facility damage; severe environmental damage.

Medium (M): degraded operations capability or readiness; minor injury accident risk that disrupted operations over 3 hours a day; minor capability to equipment or system, facility or the environment; minor damage to facility or environment.

Low (L): little or no adverse impact on operations capability; minor medical treatment in accident risk; slight equipment or system damage but fully functional and serviceable; little or no facility or environment damage.

Alternative 1:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Hiring Highly Qualified Crane Drivers alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 2:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Hiring Qualified Crane Driver alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 3:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Regulating Situation Awareness Training programme for Quay crane drivers alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 4:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Regulating Situation Awareness Training programme for yard crane drivers alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 5:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Regulating Situation Awareness Training programme for transportation drivers alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 6:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Regulating Intensive Safety and Security Checks alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 7:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Regulating Intensive Crane Maintenance Programme Drivers alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 8:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Appling Automated Crane operations on quay area alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 9:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Appling Automated Crane operations on yard area alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 10:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Appling Automated Crane operations on transportation area alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Alternative 11:

Based on your experience on RSGT, could you please evaluate the HE crane break down due to human error, if the Appling fully Automated Crane operations alternative applied using the linguistic rating variables (H, M, and L).

Attributes / Failure Event	Probability of failure/ Likelihood			probability of failures being undetected			Consequences/ severity			Chance of terminal operation being Disrupted due to failure		
	H	M	L	H	M	L	H	M	L	H	M	L
crane break down due to human error.												

Appendix II-3: Questionnaire Used for Alternatives Rating in Chapter 6

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15 October 2015

To: **WHOM IT MAY CONCERN**

A research project at Liverpool John Moores University is currently being carried out with regard to the container terminal safety and it is specific on the container-shipping sector. This subject would become a critical topic in the maritime community internationally due to the fast expansion in containerisation and the global economic recession over the past decade.

At the end of this research, a conceptual methodology and an advanced model would be generated that can be used by container terminal management to investigate and mitigate the risk affecting the operations of the terminal in order to obtain a cost effective strategy. To achieve the above aim, the research objective is as follows:

- Support the decision-making system by selecting the optimal measure/s to mitigate the risk affecting the operations of the terminal.

Your vital feedback will greatly benefit and contribute to the formulation of an industry wide opinion. I can assure you that the confidentiality of your response will be honoured and respected. Any refusal or incomplete questionnaire will be excluded without any responsibility on the participant. Completion of the questionnaire will indicate your willingness to participate in this study. If you require additional information or have questions, please contact me at the addresses listed below.

If you are not satisfied with the manner in which this study is being conducted, you may report any complaints to the LJMU-LOOM research centre. (https://www.ljmu.ac.uk/research/centres-and-institutes/faculty-of-engineering-and-technology-research-institute/loom/get-in-touch-page)

Hani M.A. Alyami
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Liverpool Logistics Offshore and Marine Research Institute
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Introduction

The aim of this study is to support decision-making system in order to select the appropriate container port safety plan to optimise the operational efficiency. The most significant hazardous events (HEs) and its consequences on the RSGT container terminal safety level operations were investigated and examined for each HE locally and globally (i.e. for individual HE and all HEs aggregated collectively). As a result, the most significant HE that has a great impact on the RSGT container terminal operations locally and globally is: Crane break down due to human error which was chosen for further analysis.

A number of Risk Control Options (RCOs) have been determined in this research. All the RCOs criteria need to be measured by using TOPSIS technique. This process is required to provide reliable data by identifying an expert opinion of each evaluation parameter.

The procedures and guidelines for answering this set of questionnaires are explained as follows:

<u>The linguistic meaning</u>

The following questions are based on pairwise comparison technique. An expert is required to give a possible judgement to all questions based on his/her expertise and experience in the shipping industry.

The following linguistic rating variables could be used to express your judgments for each alternative with respect to each criterion under uncertainty, vagueness, and/or incomplete data.

Very High	**(VH)**
High	**(H)**
Medium	**(M)**
Low	**(L)**
Very Low	**(VL)**

Based on your experience on RSGT, could you please evaluate each Alternative against each Decision Criteria in order to eliminate and/or mitigate the Crane break down due to human error using the linguistic rating variables (VH, H, M, L and VL).

<u>The objective:</u> selecting the best alternative in order to eliminate and/or mitigate the Crane break down due to human error.

- What would be the impact on the TEU movement/H, if applying A_1, A_2, A_3, A_4 and A_5.

Decision Criteria / Alternatives		**C_1 Actual Benefits in term of Operational efficiency**	**C_2 Cost (£)**	**C_3 Technical Difficulties**
A1	Hiring Highly Qualified Crane Driver			
A2	Hiring Qualified Crane Driver			
A3	Regulating Situation Awareness Training programme for Quay crane drivers			
A4	Regulating Situation Awareness Training programme for yard crane drivers			
A5	Regulating Situation Awareness Training programme for transportation drivers			
A6	Regulating Intensive Safety and Security Checks			
A7	Regulating Intensive Crane Maintenance programme			
A8	Appling Automated Crane operations on quay area			
A9	Appling Automated Crane operations on yard area			
A10	Appling Automated Crane operations on transportation area			

A11	Appling fully Automated Crane operations			

- How much would be the Cost to apply A_1, A_2, A_3, A_4 and A_5?
- what would be the Technical Difficulties to apply A_1, A_2, A_3, A_4 and A_5?

The Definition of each Criteria:

Criteria	Description of criteria	Type of Assessment	Definition	Category
C2	Additional Benefits	Linguistic Assessment	Improvement on operational efficiency (i.e. TEU movements, crane turning journey, etc.)	B
C3	Cost (£)	Real Data	Capital required to apply the alternative.	C
C4	Technical Difficulties	Linguistic Assessment	The ability of applying the required alternative accurately and dependably.	C

The Source of each Alternative:

Alternatives	Type of Reference
Hiring Qualified Crane Drivers	Literature and Experts
Regulating Situation Awareness Training programme.	Literature and Experts
Regulating Intensive Safety and Security Checks	Experts
Regulating Intensive Crane Maintenance programme	Experts
Appling Automated Crane operations on quay cranes area	Literature
Appling Automated Crane operations on yard cranes area	Literature
Appling Automated Crane operations on transportation area	Literature
Appling fully Automated Crane operations in	Literature

The Key Concepts of Container Terminal Efficiency:

Objective	Eliminate and/or mitigate the Crane break down due to human error
Perspective	Decision maker: the shipper
	Key stakeholder: the consignee
RCOs	Hiring Qualified Crane Drivers
	Regulating Situation Awareness Training programme.
	Regulating Intensive Safety and Security Checks
	Regulating Intensive Crane Maintenance programme
	Appling Automated Crane operations
Decision attributes	Risk Reduction
	Handling Productivity (TEU movement/H)
	Cost (£)
	Technical Difficulties
Constraints	Required time and waiting time
Risk factors (not controlled by decision makers)	Nominal journey time, nominal postponement and adjusted journey time

Appendix II-4: Chapter 3 publications

Publisher URL http://www.tandfonline.com/doi/abs/10.1080/03088839.2014.960498

Appendix II-4: Chapter 4 publications

Publisher URL: http://dx.doi.org/10.1016/j.aap.2016.08.007