A RESILIENCE MODELLING APPROACH FOR OIL TERMINAL OPERATIONS UNDER HIGH UNCERTAINTIES

AMBISIRE YAHAYA USMAN

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Contents

Illustrations

List of Figures

List of Tables

Notation

The following notation and abbreviations are used in this thesis:

AH	Atmospheric Hazard
AHP	Analytical Hierarchy Process
ANP	Analytical Neural Process
BN	Bayesian Network
$_{+}BN - SAM$	Bayesian Networks Sensitivity Analysis Method
CHIRP	Confidential Reporting Programme for Aviation and Maritime
CMOs	Complex Marine Operations
CPT	Conditional Probability Table
DHE	Duty Holders Error
DAG	Directed Acyclic Graph
DAMATEL	Decision Making Trial and Evaluation of Laboratory
DMs	Decision Makers
EDS	Emergency Disconnect System
EF	Equipment Failure
ER	Evidential Reasoning
ETA	Event Tree Analysis
FEMA	Federal Emergency Management Agency
FMECA	Failure Mode Effect and Critical Analysis
FSA	Fault Safety Assessment
FTA	Fault Tree Analysis
FPSO	Floating Production Storage and Offloading
FSU	Floating Storage Unit
FST	Fuzzy Set Theory
HFs	Hazard Factors
HH	Hydrology Hazard
HAZID	Hazard Identification
HAZOPs	Hazard and Operability Studies
HAZMAT	Hazardous Material
HSE	Health Safety and Environmental Management
ICF	Indirect Contributing Factors
ICT	Information and Communication Technology

ID	Influence Diagram
IDS	Intelligent Decision Software
ISM	Integrated Safety Management System
IMDG	International Maritime Dangerous Goods Code
IMO	International Maritime Organisation
IOSH	Institute of Occupational Safety and Health
ISGOTT	International Safety Guide for Oil Tankers and Terminals
ISPS	International Ship and Port Facility Security Code
ITOPF	International Tankers Owners Pollution Federation Limited
JPD	Joint Probability Distribution
MADM	Multiple Attribute Decision Making
MAHs	Major Accident Hazards
MCDM	Multiple Criteria Decision Making
MCI	Maritime Critical Infrastructure
MCIT	Maritime Critical Infrastructure and Transportation
MEHs	Maintenance Event Hazards
MHIDAS	Major Hazard Incident Data Service
MODM	Multiple Objective Decision Making
MTS	Maritime Transport System
NASA	National Aeronautics and Space Administration
OCIMF	Oil Company International Marine Forum
OTOs	Oil Terminal Operations
PCM	Platform Communication Misinterpretation
PHA	Process Hazard Analysis
PI	Personnel Issues
PIMMs	Plan Inspect Monitor and Manage Resilience Strategy
PLEM	Pipeline End Manifold
PSA	Process Safety Analysis
PT	Prospect Theory
QRA	Quantitative Risk Analysis
RAGAGEP	Recognised and Generally Acceptable Good Engineering Practices
RE	Resilience Engineering
RM	Resilience Management
S	Sabotage
SA	Sensitivity Analysis
SChM	Swiss Cheese Model
SH	Seismic Hazard
SMC	Safety Management Chain
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solutions
UBL	Utility Belief Limit
UKOOA	United Kingdom Offshore Operators Association

UCC	Utility Context of Comparison
ULCC	Ultra Large Crude Carriers
UT	Utility Theory
$UtiSch_+$	Utility Swiss Cheese Model
VF	Value Function
VLCC	Very Large Crude Carriers
WCSF	Well Control System Failure
YOE	Years Of Experience

Preface

This thesis is primarily my own work. The sources of other materials are identifed.

Abstract

Oil terminals are complex infrastructures due to their diverse operational activities. They are exposed to diverse risks because they usually operate in a dynamic environment in which safety barriers are sometime overwhelmed, leading to the disruption of operations due to a high level of uncertainty. However, the ability of oil terminals to minimise vulnerability and maximise resilience depends on the availability of the correct anticipated information at the right time for a decision-making process.

An important finding from the reviewed literature revealed that uncertainties and the unpredictability of the convergent effect of several hazardous factors have the potential to cause major disruptions such as fire, explosion and transit accidents. The consequences of these disruptions can lead to infrastructure damage and loss of life. The common operational threats to oil terminal operations (OTOs) substantiates the need for a holistic resilience model for operations in offshore/onshore terminals such as berthing/unberthing, vessel manoeuvring, loading and offloading, storage, etc. Due to the uncertainties associated with these operations and the cases of reported incidents/accidents, this research focuses more on the aspect of loading and offloading operations at ship/terminal interface.

An emphasis on a resilience modelling approach provides a flexible yet robust model for OTOs to address disruption proactively, particularly with constantly evolving hazards and threats. This thesis introduces an innovative approach towards resilience modelling based on a developed novel framework. The key aspect of the framework was supported using three proposed models: (1) the integration of Utility Theory and Swiss Cheese Model ($UtiSch_{+}$), to evaluate the relative importance of the identified hazard factors (HFs), (2) a Bayesian network (BN), to calculate the overall probability that a specific hazard is present and, (3) an Analytical Hierarchical Process (AHP) - Prospect Theory (PT) approach, as an important model for a strategic decision selection method. An empirical study was conducted to test the validity the proposed models, using case studies and Sensitivity Analysis (SA). The result obtained demonstrated that the models are effective techniques to obtain the relative weight of the identified Hazard Factors (HFs) in order to prioritise them, for dynamic hazards probability evaluation and to prioritise suggested resilience strategies in order of importance to mitigate hazard/risk level. Evidently, the result revealed appears reasonable and appropriate for investment, in order to support a strategic decision for the selection of a resilience strategy for resilience improvement in OTOs.

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Chapter 1

INTRODUCTION

Summary

Seaport and offshore/onshore terminals play an important role in freight transport. Complex marine operational systems are exposed to diverse risks in their optimum standards due to the continual growth in system complexity. Ship/terminal interface and interaction collectively provide the functionality needed by a system to attain its goal, but they come under pressure due to the high level of uncertainty they encounter. This chapter intends to discuss the research background, motivation, aim, objectives and hypotheses, and the challenges of carrying out the research with a view to justifying the research area.

1.1 Background

Over the last few years, there have been a number of serious events relating to oil terminals, such as the Mumbai High North Platform disaster (2005) collision, which ruptured the flexible pipe system, causing 22 deaths; the Bunga Alpinia disaster (2012), which caused a severe explosion due to lightning during the loading/unloading operation leading to the deaths of three people; and the New York harbour oil terminal disaster (2012) caused by Hurricane Sandy, which damaged infrastructures and the environment and led to loss of life with high consequences. Other catastrophic accidents can be found in the 22nd and 23rd edition of MARSH (1974 - 2013) and the ITOPF (2014) statistical reports. These events resulted in economic losses for the terminal operators and the countries as a whole. The threats posed by the riskiness of such platforms are enormous, and as such require flexible yet robust risk analysis methods to tackle these unpredictable outcomes (Farquhar, 1984).

Terminals play an important role in freight transportation. When an accident occurs, a terminal cannot perform its desired functions, thus resulting in a failure (Baublys, 2007). A great number of factors such as man, machine, media, nature and management (Ding and Tseng, 2012) influence the operation of a terminal and may cause its malfunction. Safety in the design and operation of terminal platforms has become a prime concern for operating companies because hazards have a high potential financial impact in addition to causing shut-down and failures implications (Elsayed et al., 2009). The regular operations at oil terminal platforms will be discussed in this research, with more concentration on understanding terminal behaviour as well as considering unforeseen influences that may be internal or external in nature. For example, uncertainty concerning damage to property by fire, premature death caused by accidents or typical storms and wind, and the risks linked to terminal operations and management (Mokhtari et al., 2012). Risk assessment of Oil Terminal Operations (OTOs) and ship interface is an important process in maintaining the maritime industrys record for safe operations at terminal platforms (Hess and Hess, 2010).

When dealing with oil terminal and ship operations, there are a lot of uncertainties in such processes, thus to improve the standard of operation under high uncertainty is essential within operational research (Hess and Hess, 2010); such operations could be deterministic terminal behaviour, i.e. from ship navigation to the idle state, preparatory state, transhipment state, closing state, repair and maintenance state, or stochastic terminal behaviour, i.e. where the order of state and transition does not follow a logical workflow due to unforeseen influences on regular operations. Therefore, there is a need to investigate the uncertainties in OTOs, to improve the interface between terminals and ships, which has a direct influence on operational life.

An investigation into the existing problems in oil terminal platforms is required. This study will carry out a critical review on OTOs and the major hazards of Complex Marine Operations (CMOs). Moreover, the study will propose a research framework to present a preferred approach on oil terminal operations, and develop models to support the proposed research framework. This research will consider the assessment of risk, resilience models and regulatory guidelines in CMOs. Furthermore, it will investigate stakeholders' requirements in mitigating and controlling losses from operations. Finally, the research will use a real case study to justify the uniqueness of the proposed research framework and models in order to tackle uncertainties in real life.

1.1.1 Maritime Critical Infrastructure and Transportation (MCIT)

Ports have a design life of several decades that needs to accommodate todays needs as well as tomorrows. They also represent a major infrastructure investment. Their present volatility and complex and dynamic nature create new challenges for port planning and design. In order to cope with the many uncertainties, the traditional systems of engineering practices try to incorporate fundamental properties such as flexibility, versatility, and adaptability into their plans and designs (Taneja et al., 2012). Recent developments related to ports and shipping sectors, such as containerisation and trends in logistics and transport, are placing increasing demands on ports (Alderton, 1999; Meersman et al., 2008; Notteboom and Rodrigue, 2008). Congestion in existing ports and their hinterlands, insufficient water depth, changing environmental demands and increased economic activity call for the adaptation of existing ports or, alternatively, strategic investment into new infrastructure (Taneja et al., 2012; Madni and Sievers, 2014).

The development, expansion and modernisation of ports, as well as the roads, rail and inland waterway systems, which have often suffered from years of under-investment or total neglect, are the major challenges facing many ports today. Harm to people as a result of risky events in ports is usually reported in terms of number of casualties or number of injured people, but could be addressed in financial terms. Consequences are measured by economic loss; such consequences include loss of human life, material loss, loss of public image and environmental damage. The key to the smooth and dynamic operation of a system requires an added layer of complexity, for the system to exhibit resilience in the face of eventualities in the operational environment (Madni and Sievers, 2014). MCIT failure frequency is measured in terms of number of accidents per year or per operation (device or installation); therefore, todays systems have to satisfy a number of requirements such as affordability, reliability, adaptability, security and resilience.

1.1.2 Offshore/Onshore Terminal Platforms: Risk Management Perspective

Over the last few decades, both the frequency and consequences of accidents related to human activities have increased significantly due to the dramatic growth of industrialisation, which brought workers and the public in close contact with new technologies and materials. While modern industry expanded, a generalised concern for health, safety and environmental impacts began to spring up in most advanced countries. Archetypal disasters that have paved the way for a general awareness of the hazards of industrial activities, especially of those involving hazardous materials (often referred to as HazMat), have occurred in the nuclear industry: the Three Mile Island (1979) disaster and the enormous catastrophe of Chernobyl (1986). These raised public concerns about the risks entailed in industries and at the same time suddenly boosted the study of accident frequencies and facilities reliability (Taneja et al., 2012).

According to the International Safety Guide for Oil Tankers and Terminals (ISGOTT) (2006), an offshore/onshore terminal is a platform at the edge of an ocean, river or lake for receiving ships and transferring HazMat and other oil cargoes to and from them. These terminals have specially designed equipment to help in the loading/unloading activities. Cranes and storage tank farm facilities are often located very close by. Critical to the functioning of offshore/onshore terminal platforms is providing access to intermodal transportation, for instance, an intermodal node where goods are loaded/unloaded to/from vessels and sent to their destination, be it onshore or offshore. A terminal platforms system could be thought of as a complex, often huge environment, where several operations are carried out such as CMOs. Hydrocarbons are typically the major commodities being explored, stored or transhipped at offshore/onshore terminal platforms (ICS, 2006).

Risk management (RM) is an integral part of safety assessment. RM is a process where the adverse effects of risk are controlled or minimised to avoid any damage to which an organisation may be exposed (IOSH 2000, Shang and Tseng 2010). A risk may be conceptualised in terms of an event and consequence. For example, if A occurs, then it causes B. Organisations quantify risk with two parameters: the likelihood that a given event will occur and the impact of that event. For instance, NASA created two-dimensional risk charts that use the likelihood of an event and the impact of the event as either axis. Where high likelihood and high impact intersect, it denotes a serious problem, whereas low likelihood and low impact are less important. Various combinations in-between indicate serious, moderate and minor problems. Generally, risks may require risk mitigation plans to alleviate the risk or move it to an insignificant lesser level of importance (Madni and Sievers, 2014)

1.2 Research Motivation and Problems

Shipping/operational risk impacts associated with increased accidents can cause severe explosion, damage to infrastructure and environment and loss of life with devastating consequences. It has become apparent that the challenges of these risks/hazards are so enormous that flexible yet robust risk analysis methods are required in order to tackle such unpredictable events. This research study seeks to find a novel solution in the face of a major disruption where a system could adapt, sustain and recover from the uncertainties looming around oil terminal operational vulnerability. However, a systematic methodology to deal with such issues appears to be lacking. There is a need to move away from the current assessment techniques and focus on the proposed resilience framework and models.

Important questions to be considered and answered at the end of this research are:

- Will the proposed research framework and models affect the operations on oil terminals?
- What are the risks/hazards involved in oil terminal operations?
- What is the value of the proposed novel risk/hazard model(s) to OTOs?
- How do we implement the proposed research framework and models in case studies?
- Should operators attribute loss to normal errors in measuring risk/hazards, or rely on improved techniques to rectify measuring of errors?

1.3 Research Aim and Objectives

The primary aim of this research is to investigate the uncertainties for oil terminal operations in order to monitor, control and mitigate the operational risks. The proactive nature of this research will be beneficial in satisfying stakeholders requirements in controlling losses from operational hazards. One of the best ways in which to enhance oil terminal platform proactiveness is to meet the following:

1. Collect and review the literature and published material on the resilience modelling approach, oil terminal operations, risk assessments, maritime safety and regulatory guidelines.
2. Develop a research framework in order to integrate the necessary components to present a preferred approach for oil terminal operations.
3. Based on the proposed research framework, develop models to support the proposed framework using the Utility Theory and Swiss Cheese Model ($UtiSch_{+}$), Bayesian Network (BN) and Prospect Theory (PT) modelling techniques.
4. Conduct an empirical study to validate the research via data collection on oil terminal operations to support the proposed research framework and models.
5. Case study analysis to justify the proposed framework and models.

1.4 The Scope of the Research

The intent of this research is to provide stakeholders with recommendations on appropriate methodologies for assessing risks/hazards under uncertainty resulting from oil terminal operational systems, with the intent of satisfying stakeholders requirements for controlling losses from OTOs. The risk components covered in these methodologies are related to:

1. Oil terminals in the vicinity of highly active reputable ports; risks include the current and change in probability of ship navigation, (un)docking, pipe trestles, vapour handling, pumping, storage, loading and offloading.
2. Consequences resulting from oil operation-related accidents such as environmental consequences, consequences to the ship and port, and third-party consequences.
3. Other issues to be addressed in the study include effects on search and rescue operations, oil spill monitoring, surveillance and security and their risk-reduction measures.
4. All types of oil carrier vessels will be considered in this research, although the focus will be on commercial vessels.

1.5 Research Methodology

This research adopted a qualitative and quantitative research method. An empirical study was conducted and data were collected via questionnaire survey from experts, specialist, consultants and academicians with vast and relative experience of OTOs from specific crude oil-producing regions/countries and countries where large amounts of crude oil are being consumed/transported. The questionnaire was pilot tested and the results of the pilot study were used to reword the questions. The reviewed questionnaire was then used to undertake the empirical study via the internet. A link and a cover letter were e-mailed to targeted expert participants and then followed up. Expert participants such as; executive directors, senior managers, consultants, ship captains and academicians with industry experience are the most knowledgeable individuals within a firm who are able to answer all aspects of the survey. Data were collected through the same web-link as soon as the respondent completed the questions. This research adopted an e-mail questionnaire because it is easy to administer. Its advantage is that it reaches very busy experts/participant/respondents in the shortest period of time. The data collected was analysed using the Utility Theory and Swiss Cheese Model ($UtiSch_{+}$), Bayesian Network (BN) and Prospect Theory (PT) was used to determine the best alternative among different alternatives for strategic decisions for resilience improvements.

1.6 Research Challenges

Various challenges were faced in the identification of hazards, risk/hazard evaluation and reduction/mitigation of oil terminal operational hazards under high uncertainty in this PhD thesis. There were also difficulties encountered in the application of advanced computing models employed as a tool to address these challenges. The prominent challenges faced while conducting this research and how they can be addressed are described as follows:

- The task of conducting Hazard Identification (HAZID): it was clear from previous studies that there had been no comprehensive investigation of oil terminal operational hazards. The confidentiality of resources in the oil sector has made it even more difficult to conduct HAZID; thus, this research adopted a proactive approach. The use of a proactive approach can be justified in different studies (Ren et al., 2008; Mokhtari et al., 2012; Salleh et al., 2014; John et al., 2016).Therefore, a thorough critical appraisal of collected literature relevant to this research combined with experts judgements from a brainstorming session using an identified hazards checklist was used to reveal oil terminal operational hazards.

- Choosing the right methodology: to determine what kind of methodology and research design can best answer the research question posed a challenge. Since no similar investigation has been carried out on oil terminal platforms, an empirical approach based on a mixed research method (qualitative and quantitative) was adopted to deal with such challenges. Qualitative research aims to discover and understand meaning, interpretations, ideas, beliefs and values, as well as to describe and understand experience of a problem. The quantitative research method is characterised by collection of numerical data, demonstrating the relationship between theory and research.

- Development of a novel model for ranking hazard factors (HFs): understanding the assumption behind the Utility Theory and the Swiss Cheese Model to determine the relative weights of the HFs was a challenge. The Utility Theory was based on experts behaviour to elicit a response to a question while the Swiss Cheese Model incorporates several safety barriers for risk mitigation. This difficult task was tackled by integrating the theory and the model to develop a novel technique ($UtiSch_{+}$) to determine the relative weight for further risk/hazard evaluation.
- Estimation of the failure probabilities of HFs that can lead to an accident on OTOs: to estimate and facilitate the conversion of failure possibilities to their respective failure probabilities is a major challenge due to uncertainty. This problem is solved by adopting a dynamic model, the Bayesian Network (BN). The BN has been established as an ubiquitous tool for modelling and reasoning under uncertainty. The Netica (Netica, 2002) software is a robust BN software package. The software imposes no limitations for missing random data or the absence of an observation. The algorithms in the software can handle new evidence.
- The selection of the best strategy for resilience optimisation: on the other hand, the selection of the best strategy for resilience optimisation is addressed as a multi-attribute decision-making problem, and this was solved by adopting Prospect Theory (PT). PT is used to obtain overall prospect values (u(R)) from a number of different strategic decision alternatives; the greater the u(R) from the set of alternatives, the higher it will be classified in the list of best strategic resilience decision

1.7 Achievement of the Research

The achievement of this research will be in the proposed novel resilience framework, which is supported by the developed models. One of the model was implemented by the integration of behavioural and conceptual technique. Behavioural characteristics can play a key role in decision making during CMOs. The proposed framework can be used by oil industry, terminal stakeholders and in the marine domain. A detailed researched novel resilience framework was developed which presents a platform for techniques to be built on, to improve the resiliency of a system. The proposed framework will help in the assessment of the strengths and weaknesses of alternative strategies for collecting, analysing and interpreting data for OTOs. Another achievement this study will present is the development of a generic methodology that will provide a platform for a robust risk management model where hazards associated with a terminal's operations can be assessed and strategic resilience decisions can be made appropriately. Finally, the proposed novel resilience framework and models will demonstrate their effectiveness, flexibility and robustness to tackle unpredictable events, as well as provide solutions for real-life problems on OTOs.

1.8 PhD Thesis Structure

The thesis consists of seven chapters and follows a common writing structure: Chapter 1 is the introduction. It states the research background, aim, objectives and the generated research questions. Chapter 2 is a critical appraisal of the development of risk management from a resilience, operational and regulatory perspectives for OTOs. More so, the chapter provides an account of the uncertainties existing in oil terminal platforms, giving details of the identified possible operational hazards. Chapter 2 review resilience from an engineering perspective, as a strategy that could be used to improve a system's vulnerability to major disruption for OTOs. Chapter 3 discusses the proposed research methodologies, qualitative and quantitative research method adopted and also presents the proposed conceptual framework for this research. Chapter 3 also provides an account of how specific models' methodologies will be used to justify the conceptual framework for resilience optimisation. Chapter 4 is the first phase of the conceptual framework. It reports the survey by empirical study, where the data collected were analysed using the integration of Utility Theory and Swiss Cheese Model. This was carried out to determine the relative importance of the identified uncertainties that may lead to a system's failure. Chapter 4 will be the core step towards resilience that will lead to the design of a strategic optimisation model. Chapter 5 is the second phase of the conceptual framework. It provides a dynamic complementary analysis model which shows the relationship between researched variables that could cause a partial/total failure. A Bayesian Network (BN) model is used in this chapter. Chapter 6 is the third phase of the conceptual framework. Prospect Theory (PT) is used to provide the much-needed resilience strategy to reduce or mitigate risk/hazard. Chapter 7 discusses the results produced in Chapters 4, 5 and 6, and the merits and demerits of the model used in the chapters respectively. Chapter 7 also concludes the PhD thesis; it summarises the research results, limitations and the research's contribution to knowledge. The chapter ends with directions for further studies. Fig 1.1 shows the overall thesis structure.

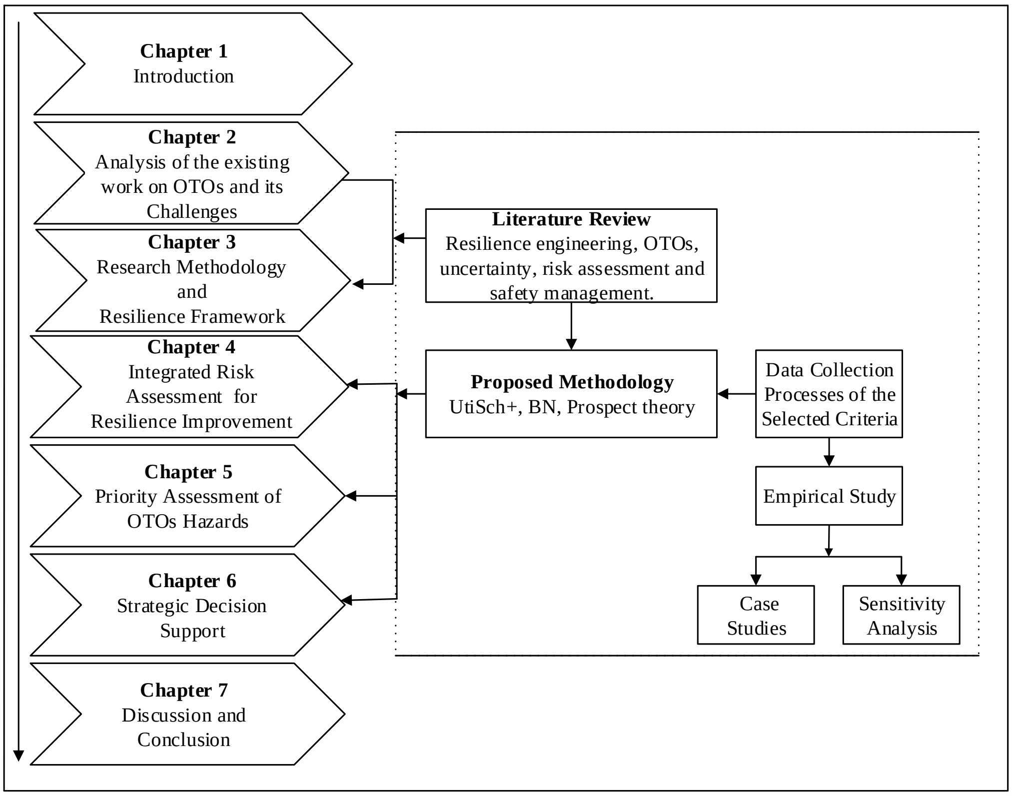


FIGURE 1.1: Thesis structure

Chapter 2

LITERATURE REVIEW

Summary

This chapter is an appraisal of the important literature that has influenced the current study. It discusses the operational overview of OTOs, risk assessment models, resilience engineering literature, safety management and the uncertainties in oil terminals. It also reviews the literature concerning the identified modelling techniques suited for this research.

2.1 Introduction

A seaport is an infrastructure system for receiving ships and transporting cargoes and people to and from its system. Basically, it is an inter-modal node where goods are loaded and offloaded to and from vessels and sent to their destination. Seaport systems are complex environment due to their diverse operations (Ronza et al., 2007), it aid in performing services in response to societal demand, providing infrastructure, operating procedures, management practices, and developing policies to accommodate and facilitate its dynamic services. Seaport terminals have always been volatile due to new demands placed on them. The growing volatility in maritime ports, stimulated by the global trends of liberalization, economic expansion of Europe, and changes in producer and consumer markets (China, India, Brazil, Eastern Europe) are adding to the uncertainty surrounding port operation, planning, and investment (Taneja et al., 2012). The requirements of vast vessels (requiring deeper drafts and longer berths) as well as the optimisation in operational scale and scope have led to the demand for port expansion, and this has been responsible for ports being built in close proximity to city centres (e.g. the ports of Antwerp, Rotterdam, Los Angeles), shifting operational activities towards land. The increasing recognition of uncertainty due to port expansion has re-invigorated researchers to explore other means and ways for seaports to display flexibility and more adaptive capabilities. A significant amount of research is required before development can get underway, i.e. the feasibility and consequences of planned changes relating to management, stakeholders and infrastructures. Projects in the maritime industry are seen as engineering projects, which require a firm system approach to dictate significant perception of problems, objectives, methods, criteria and solutions. In the maritime industry, performance measures are generally time, cost and quality. However, as seaports seek to strike a balance between social, ecological and business needs and objectives, it is being realised that soft issues are equally important. Stakeholders with multiple heterogeneous perceptions, values and interests are involved in safety, environmental impacts, legal acceptability, political and social impact issues and there is a need to address such an issues at the beginning of such seaport project.

The maritime industry, by nature, is very conventional and diversifying from the norm, and has often proven to be difficult. Offshore/onshore oil terminal platforms have continually been adapted to new requirements and regulations in design and operation. Modern technologies have been absorbed into the maritime industry and these technologies are being used to address a whole variety of issues, including operational efficiencies, environmental conditions and security. The impacts of such technologies such as bigger vessels, new equipment configurations, new logistic concepts, new cargo handling concepts, advancements in ICT leading to development of information systems such as GIS (Geographic Information Systems), dynamic real-time control of operations, efficient data collection and processing time, new camera systems, new gate processing systems, and the introduction of radiation detection monitoring systems leads to increased terminal productivity and efficiency, but new safety concerns on maritime infrastructures tend to emerge (Taneja et al., 2012).

Oil terminals play an important role in freight transportation. When an accident occurs, the terminal cannot perform its desired functions, which thus results in failure (Baublys, 2007). A great number of factors such as human error, technical failure, media, nature and management (Ding and Tseng, 2012) influence the operation of a terminal and may cause its malfunction. The safety in design and operation in oil terminals is a prime concern for operating companies because these hazards have a high potential for failures (Elsayed et al., 2009). In this research, the regular operations of oil terminals will be discussed, focusing on understanding terminal behaviour and considering unforeseen influences that may be internal or external in nature (Mokhtari et al., 2011). A risk assessment for oil terminal operations and ship interface (Hess and Hess, 2010) is an important process in safety management.

Requirements and Interface Definitions

The definitions of requirements and interfaces result from a flow down of users and customers needs through a process of refinement and allocation. Madni and Sievers (2013) defined requirements and interface as verifiable agreements that specify functionality and performance requirements within and between system components. Ship and terminal interface is the first activity carried out between port operators and vessel crew on arrival at any seaport before any major operation commences. Each requirement and interface is verified through a process that typically involves analysis, inspection and/or demonstration. Interfaces enable communication and interaction between elements within a system as well as between the system and its environment. More so, they are treated in the same way using common semantics because the two are intimately linked and quite often viewed as the same. They both represent binding contracts.

For a clearer understanding of terms, certain key words and phrases will be used regularly throughout this research. it is best to define them, such as:

- Risk is defined as a measure of the adverse effects of a hazard; The probability that something unwanted can happen from a hazard (Hoj and Kroger, 2002; Hollnagel, 2008).
- Safety is defined as the absence of risk (Hollnagel, 2008).
- Hazard is a physical condition or situation with the potential to cause harm to people, damage to properties, environment, plant, operation interruptions or increased liabilities (HSE, 2004; Trbojevic and Carr, 2000).
- Hazard Factors (HFs) are external or internal causes of major hazards under high uncertainty with unexpected consequences to people, properties, environment and operations.
- Uncertainty can be defined as an unexpected event (due to improper information concerning certain parameters) where there is the probability of a negative consequences to people or other risk targets e.g ships, terminals or OTOs (Hess and Hess, 2010; Taneja et al., 2012).
- An event is defined as an action or occurrence that take place at a determinable time and place, with or without the involvement of humans.
- An accident is an event that results in injury or ill health (HSE, 2004).
- Accident barriers are an effective means against known risk, which are used reactively or as a response to prevent the pathways of unwanted events from occurring and to protect against their consequences (Hollnagel, 2008). They absorb shocks and reduce system uncertainty.
- Incidents are near miss and/or undesired circumstances which have the potential to cause injury or ill health (HSE, 2004).
- Resilience is defined as a function of systems vulnerability against potential disruption with adaptive, avoidance and survival capabilities of recovering from the face of a major shock, enabling it to continue its activities within a reasonable time frame during and after a major accident(Wreathall, 2006; Mansouri et al., 2010).

2.2 Current Practices in Maritime Safety

Previous research on port terminal safety has dealt with the major trends in ports, such that, the identified driving force behind these trends are uncertainty (Taneja et al., 2012). The subsequent question asked on the current safety approaches for port operation evaluations is, if it can cope with these uncertainties. Different literatures have mentioned that the major limitations in the current safety practices are: (1) much focus is on port infrastructure facilities but not enough on port operation and maintenance, and (2) ignoring uncertainties while planning, and confusing risk and uncertainty with each other. Taneja et al. (2012) suggest the importance of reviewing how organisations currently plan and deal with safety issues in ports to see how they deal with uncertainties.

A safety case covers all standards of management health and safety, the control of major hazards identified within a system and it specifies how the risk involved are to be managed or minimised (Sii et al., 2002). Following the public inquiry into the Piper Alpha accident (1988) which claimed 167 lives, the response to the accepted findings of the Piper Alpha inquiry launched a review of all offshore safety legislation and implemented changes (Wang, 2002). In 1993, Formal Safety Assessment (FSA) adopted by the International Maritime Organisation (IMO) was the norm for a strategic oversight of safety and pollution prevention in the maritime sector. FSA processes involves hazards/risk identifying, hazard/risks evaluation and deciding on an appropriate course of action to manage these hazards/risks. This provided a good platform for safety management practices. Trbojevic and Carr (2000) developed an improved methodology for safety improvements in ports; the Integrated Safety Management System (ISM) which entails hazard identification and qualitative risk assessment. In the ISM, controls for managing hazards are developed and integrated into the Safety Management System, thus establishing barriers to prevent hazards occurrences. The Safety Management System (SMS) in the ISMs was further developed, through a quantified risk assessment that provides detailed assessment of risks/hazards and the identification /selection of the most appropriate management strategies. This conforms with the requirements of Port Marine Safety Code which applies to all UK ports, laid down by the department for transport and monitored by the Maritime and Coastguard Agency in consultation with the industry. The implementation of a SMS is the most proficient way of allocating resources towards safety. SMS implementation does not only improve working conditions, but also positively influences employees attitudes and behaviours with regards to safety, thus improving the safety climate considered as the basic component of a firm's safety culture in various models (Fernández-Muñiz et al., 2007). The purpose of SMS is to ensure that the organisation is achieving their goals safely, efficiently and without damaging the environment (Wang, 2002) therefore, high risk areas must be investigated in detail and the approach for risk prioritisation discussed by management. Wang (2002) proposed a proactive, risk-based goal setting regime introduced to the marine and offshore industries to increase the level of safety, yet noted that there can be significant uncertainties in the information and factors that are used in the decision-making process (Sii et al., 2002). Uncertainties could be on the availability of data, estimates of costs, time scales, risks/hazards, safety benefits, assessment of stakeholder views and perceptions. Wang suggested that common sense can be used to ensure any uncertainties are recognised and addressed but common sense is no longer acceptable in the 21^{st} Century due to new challenges such as technological advances, i.e. improvements in ship design and navigation aids which have reduced the frequency and severity of shipping incidents. The reduction of failures using technology has revealed the underlying level of the influence of human error in accident causation (Hetherington et al., 2006).

In the past decade, there was an insight that the reliability of complex systems to safely achieve operational goals depends on social structures as well as technical arrangements (Mearns et al., 2003). IMO has continuously dealt with safety problems in the context of operation, management, survey, ship navigation and the role of administration because there are enormous penalties for the lack of safety in an organisation; lives lost, damage to the environment, which the maritime industries want to avoid (Soares and Teixeira, 2001). Data on accidents at sea have primarily been generated and investigated by agencies affiliated with countries within which these accidents occurred or who flag the vessels. There have not been a standardised accident reporting systems for marine operations, thus possess a problem in trying to reveal causal themes from accident data (Hetherington et al., 2006). Fig 2.1 shows the main percentage of the principal causes of safety problems in maritime transportation and Fig 2.2 shows distribution of potential annual loss in Maritime Transport System (MTS).

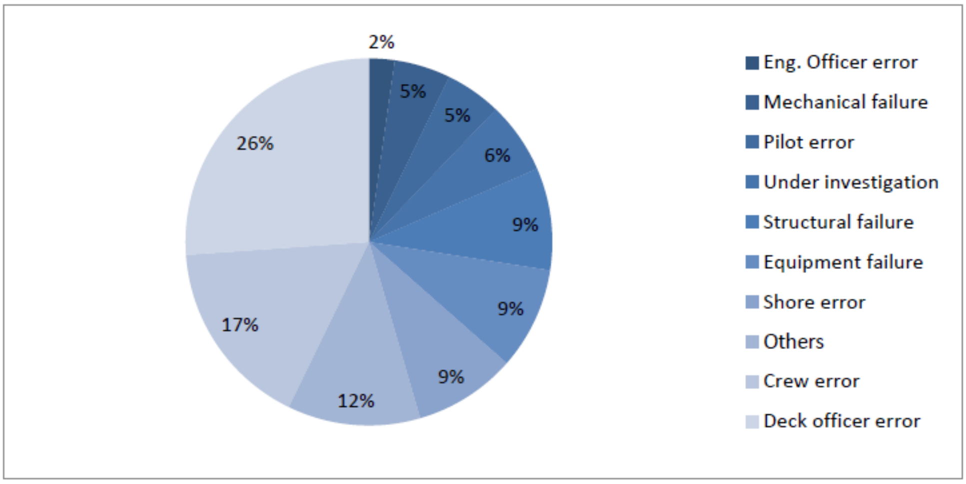


Figure 2.1: Percentage of the principal causes of safety problems (Soares and Teixeira, 2001)

In offshore safety analysis, safety-based design and operation decisions are expected to be made at the earliest stages in order to reduce unexpected costs and time delays (Wang, 2002). In hazardous environments such as onshore/offshore oil installations, it is essential to audit safety climate of the workforce and management practices. The

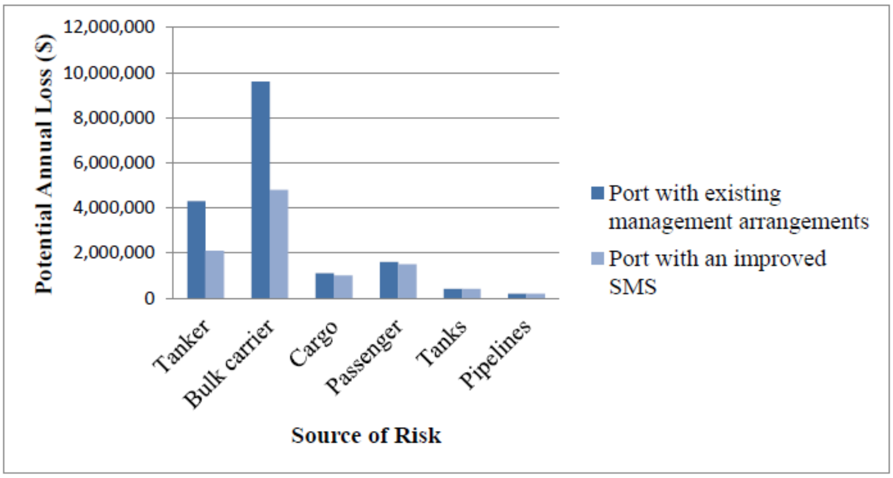


FIGURE 2.2: Comparison of potential annual loss in MTS (Trbojevic and Carr, 2000)

onshore/offshore oil and gas industry is distinctive because of the convergence of several hazardous factors; among these are the potential for fire, explosion, transit accidents and blowouts, work stress that can result from these threats, attendant priority of high reliability operation, and the relative isolation of installations. There is a continual risk of organisational shutdown or fatal accidents resulting from unanticipated actions of employees on offshore installations.

Poor standards, human error and management shortcomings on marine casualties motivated the introduction of the ISM which is directly related to the general operational aspect of shipping. Industries have to show an effective safety management system that addresses threats, and provide a proper control measure for dealing with these threats (Soares and Teixeira, 2001). A limited amount of research has identified that the best safety management practice are in the offshore industry (Mearns et al., 2003). However, the shipping industry has a fairly good safety record but in all, maritime incidents/accidents always have a high potential of catastrophes (Hetherington et al., 2006).

2.2.1 Structured and Systematic Models in Maritime Safety: A Comparative Study

Different researchers have proposed different structured and systematic methodology aiming at enhancing maritime safety. The Formal safety assessment (FSA) has been gradually and broadly used in the shipping industry around the world since adopted by IMO at the 62nd meeting of Maritime Safety Committee (MSC) in 1993 (Hu et al., 2007). The FSA approach which is also an integral aspect of ISM, integrates quantitative risk assessment and a generic risk model especially frequency and severity as a criteria (Trbojevic and Carr, 2000). To maximise marine safety, there is a need to model hazards/risks in a logical way and safety-based decisions to be made confidently.

As such, ISM provides safety engineers in the maritime industry an overview of the offshore safety case approach and formal ship safety assessment (Wang, 2002). The FSA approach has been used on risk models in ship navigation, vessels, offshore/onshore terminals, tank farms, container terminals, naval architecture, pipeline transportation, and Maritime critical infrastructures and transportation (MCIT). The implementation of ISM improves working conditions and organisations safety climate (Fernández-Muñiz et al., 2007; Ren et al., 2008; Santos-Reyes and Beard, 2008).

Existing approaches to safety management represent a step forward in managing safety but may not be enough to address the changing safety issues effectively in the last few years (Santos-Reyes and Beard, 2008). A Systemic Safety Management System (SSMS) model was proposed as a sufficient structure, aimed at maintaining operational risk within an acceptable range in a coherent way (Santos-Reyes and Beard, 2008, 2009).The model has a fundamentally preventive potentiality and when adopted, it tends to make the probability of failure less than otherwise. The SSMS model intends to help provide a structural organisation that may facilitate the implementation and maintenance of safety culture as well as managing safety by treating an organisation as both vertically and horizontally interdependent. Vertical interdependence uses the concept of 'recursion', thus favours 'relative autonomy' which helps to maintain risk within an acceptable range at each level of recursion effectively. The horizontal interdependence deal with the interrelationships amongst the various subsystems that form part of system. SSMS can be applied in a reactive way, to examine a failed system or proactively, to examine a system which has not yet failed, i.e. as a 'template' to a past failed system or a 'laid on' for current un-failed system thereby leading to a more effective safety management for the oil and gas industry (Santos-Reyes and Beard, 2009).

In the shipping industry, enhancing maritime safety involves a set of decision makers focussing on the frequency and severity criteria in ship navigation. Models based on Relative Risk Assessment (MRRA) present a risk-assessment approach based on fuzzy functions and has already been used for the assessment of pilotage safety in Shanghai harbour, China. It is a useful method to solve problems in the risk assessment of safety system on ship operation in certain navigation areas such as oil terminals (Hu et al., 2007). A fuzzy AHP model was used to identify attributes mainly in the navigating services provided by port authorities in the context of regulators, maritime pilots, and tugboat drivers. Hsu, (2012) used Dissatisfaction Attitude (DA) to determine the attributes' priorities enhancing port authorities to create policies for the improvement of ship navigation safety within port terminals. The research recommended that operators' personal capabilities should be enhanced, such as professional skills, communication abilities, and work attitudes. A risk-based modelling approach was developed using fuzzy extended fault tree analysis (FFTA) that combines the effects of organisational faults and shipboard technical system failures under a unique risk assessment to enhance the execution process of accident investigation in maritime safety (Celik et al., 2010). This model was used to address the integration of FFTA into shipping accident investigation reports to ensure a consistent database and subsequent decision aid, to accident analysis and prevention efforts in the maritime transportation industry.

Structural equation model (SEM) was used to develop a measurement scale, operationalising the safety management system concept, and subsequently calculating its reliability and validity. This provided a tool for organisations to evaluate situation with regards to safety management, as well as guidance on areas that must be improved, to reduce occupational accidents (Fernández-Muñiz et al., 2007). SEM is more specific to each type of process. Introducing variables relating to operational control or management changes could make the model more specific to major risk installations. SEM was also used for the analysis of marine accidents, grounded on large empirical data; the Swedish Maritime Administration database containing marine accidents organized by ship and variable and the model has both theoretical and practical values (Mullai and Paulsson, 2011). SEM is proven to be complementary with the strength of multiple analysis techniques in explaining a structure, variance, and power of the identified leading indicators (safety factors) of adverse events in safety-critical settings. It also provides an orthogonal validation methods for the results (Grabowski et al., 2010).

Models such as the Swiss Cheese analogy model (Reason, 1997), the Bowtie model (Hollnagel, 2008), the FSA (IMO, 2002), Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) techniques (Ferdous et al., 2011), and other models (Leveson, 2004; Van Drop et al., 2001; Li et al., 2009; Larsson et al., 2010) have been introduced or proposed by experts in the fields with no reference to or systematic analysis of empirical data. Also, a lot of models are based on theories or concepts, e.g. systems theory concepts (Leveson, 2004; Laracy, 2006; Larsson et al., 2010), the Bayesian Belief Network concept (BBN) (Trucco et al., 2008; Merrick and Singh, 2003), Neural Networks (NN) concept (Hashemi et al., 1995; Le Blanc et al., 2001), fuzzy logic (Sii et al., 2001), risk-based approaches (Vanemand Skjong, 2006; Celik et al., 2010), simulation and expert judgement (Harrald et al., 1998).

According to Harrald et al. (1998), theoretical framework is of little use in an analysis unless there is relevant data to support it (Mullai and Paulsson, 2011). Analysts are confronted with incomplete and misleading data that makes it difficult to use theoretical frameworks and as a result, significant modelling assumptions have to be made in order to produce valid results. The data issues are common problems in maritime safety and that can be partly attributed to inadequate accident models (Huang et al., 2004; Celik et al., 2010).

In summary, no single model has the capability of serving all systems, issues, and needs in the maritime industry at all times. It is therefore relevant and important to develop a model grounded on empirical data that would primarily make use of data contained in the databases. As large-scale organisations and systems become more complex and difficult to understand. Thus, with notable failure on organisational practices to prevent disaster for safety critical systems, interest in identifying leading indicators of adverse events in safety-critical settings has increased (Grabowski et al., 2010). Various governments are focusing on safety chain as a concept for structuring options for risk mitigation. Efforts are made to control low probability disasters, such as floods, hurricanes and large-scale industrial accidents using safety chain concept consisting of proactive, preventive, preparation, repression and recovery. A similar approach is adopted in USA by the Federal Emergency Management Agency (FEMA) in 2003, to address safety and security issues (Jongejan et al., 2012). Fig 2.3 represents a safety chain for an effective safety management.

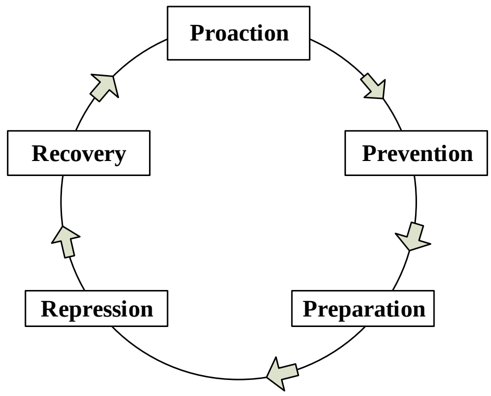


FIGURE 2.3: Representation of an effective Safety Management Chain (Jongejan et al., 2012)

Standard techniques from engineering such as resilience engineering and, risk analysis and reliability engineering can be adopted for the reduction of risks. This can be achieved by designing socio-technical systems in a way to ensure safe performance, although the probability of an accident, however remote, will always remain. Industries and organisations have long measured safety and organisational performance in safety-critical systems, tracking accidents, near misses, lost time, resources, and personnel providing early warning of impending failure to enhance safety (Grabowski et al., 2010; Jongejan et al., 2012).

2.2.2 Outline of the Offshore Safety Regulations

The UK Offshore Operators Association (UKOOA) with the assistance of the HSE have published industries guidelines on a framework for risk related decision support. The proposed guidelines could be beneficial for a wide range of applications under various conditions. The guidelines describe a generic framework which is able to help decision makers to identify a decision context for choosing an appropriate basis for decision making. The proposed framework provides a means to assess the relative importance of codes and standards, good practice, engineering judgement, risk analysis, cost benefit analysis, company and social values when making a decision. It is an appropriate basis to improve decision making which will result to a more transparent process to the wider public.

The guidelines were then transformed to regulation and were further refined into the Health and Safety at Work Act, 1974. In 1992 a draft of the offshore safety case regulations was produced (Skogdalen and Vinnem, 2011). It was later modified upon public consultation and opinion. The regulations came into force at the end of May 1993 and November 1993 for new and existing installations respectively (Wang and Foinikis, 2001). Offshore operators will have to submit operational safety cases for all existing and new offshore installations to the Offshore Safety Division of the HSE. The case must feature suitable use of quantitative risk assessment (QRA) as part of the demonstration of the adequacy of preventive and protective measures. Formal safety assessment (FSA) was then adopted for all member states of the IMO.

The subsequent years of application of the offshore safety case approach in the UK based on field experience lead to the amendment of the safety case regulations in 1996 to include the verification of safety-critical elements. In 1996, offshore installations and wells regulations (DCR 1996) (including design and construction, etc.) were introduced to tackle various stages of the life cycle of installation. The regulations place more emphases on inherent safe design, prevention, detection, control and mitigation measures to be implemented, maintained and verified throughout the life-cycle of such installations (Sii et al., 2002).

The main significance of the offshore safety regulations in the UK is the absence of a prescriptive regime, which defines specific duties of operators and adequate means. The regulations set forth high-level safety objectives, while leaving the selection of particular hazard arrangements in the hands of the operator. For reason being that the source of hazards of an installation are specific to its function and site conditions (Wang, 2002).

2.3 Oil Terminal Operations (OTOs) in Onshore and Offshore Terminals

In recent years, advanced computer technologies have been increasingly used to fulfil control tasks to reduce human error, and to provide operators with a better working environment. However, the utilisation of software in control system has introduced new failure modes and created problems in the development of safety-critical systems. A high level of uncertainty in failure data has been of major concern, which has been highlighted in the UKOOAs framework for risk related decision support. Novel decision-making models integrated in safety assessment are also required to make operation decisions effectively and efficiently (Trbojevic and Carr, 2000; Wang, 2002). Furthermore literatures reveal that operation is probably the main contributor of accidents in onshore/offshore terminals. Increasingly, more study should be prioritised on CMOs and a formalised risk assessment should gradually become more common in complex systems (Soares and Teixeira, 2001). The offshore/onshore facilities identified as marine platforms are as follows: (1) trans-shipment stations, (2) a maritime floating port terminal, (3) drilling platforms, (4) crude oil recovering platforms, (5) crude oil production platforms, (6) linking platforms, (7) water injection platforms, (8) pumping platforms, (9) shelter platforms, (10) telecommunication platforms, (11) crude oil measurement platforms, and (12) flaring platforms (Villasenor et al., 2003). Offshore/onshore installations and ships have constantly adopted new approaches, technology, and hazardous cargoes. Each element brings with it a new hazard in one form or the other, therefore the lack of reliable safety data as well as confidence in safety assessment in safety-critical operations has been the two major problems in the safety analysis of such complex systems. To solve such problems, further research is required to develop novel risk assessment model to tackle uncertainties and also to adopt decision-making techniques on a rational basis (Wang, 2002). In 2001, oil transportation rose to 12.8 trillion tonne kilometres (Ttkm) as compared to 6.5 Ttkm in 1985. When dealing with ship and OTOs, uncertainties are present in such processes, thus optimisation under high uncertainties is essential within operational research. Such operations could be deterministic or stochastic terminal behaviour, depending on the processes (Hess and Hess, 2010). Tankers, usually large ships are used for shipping oil cargoes in bulk. This has been the method of transporting large quantities of oil around the world. The classifications of tankers according to their capacity for transporting oil are as follows:

a) General Purpose (GP) tankers, with a loading capacity of under 38,000 tonnes,

b) Medium Range (MR) tankers, with a loading capacity of 38,000 to 50,000 tonnes,

c) Panamax tankers, which can access a Panama Canal and has a loading capacity of 50,000 to 79,000 tonnes,

d) Aframax tankers, with a loading capacity of 80,000 to 125,000 tonnes,

e) Suezmax tankers, with a loading capacity of 125,000 to 200,000 tonnes and also can access a Suez Canal,

f) Very Large Crude Carrier (VLCC) tankers, which has a loading capacity of over 200,000 tonnes, and

g) Ultra Large Crude Carrier (ULCC), generally considered as super tankers because they are ships capable of carrying above 250,000 tonnes.

When tankers, super tankers and liquid bulk carriers were first introduced, their sizes and draft (especially VLCC and ULCC) prevented them from docking at many existing docks. This required them to discharge their cargo into floating storage unit with the aid of a Single Point Mooring facility connected to a Pipeline End Manifold which then offloads visa-vis and termed a lightering operation. A typical super tank has a very poor manoeuvrability, and are vulnerable to grounding due to uncertainties while operating close to terminals and shorelines. Operations involving oil carriers include manoeuvring (with or without tugs), navigations, berthing, (off) loading, bunkering (vessel re-fuelling) and transhipment of oil generally performed with raiser pipes or hoses.

A number of novel techniques and innovative platform layouts have been tested and implemented in the last few decades, to make onshore and offshore infrastructures safer. Most important, loss prevention and risk assessment are now taken into account in complex marine operational systems and many conceptual techniques are available for risk identification, assessment, reduction and prevention during operation. HAZOP (Wang, 2002; Berenguer et al., 2011),FMECA (Wang, 2002),what-if analysis, preliminary hazard analysis had been used for operational hazard identification. FTA and ETA models (Ronza et al., 2006; Ferdous et al., 2011) were used to establish failure or, forecast the effects of anticipated failure and several of them have been implemented into computer programs. Other more structured methods used are the Quantitative Risk Analysis (QRA) and the inexpensive Qualitative Risk Analysis (QRA). Qualitative risk analysis is based on using a risk matrices (occurrence, consequences and severity ranges) while quantitative risk analysis adopts algorithms that allow the risk level associated with an operation be described by means of number or score (Ronza et al., 2007). More focus on conducting risk analysis that is specifically tailored to the operational phase of a selected infrastructure has become inevitable (Chen and Chen, 2010).Fig 2.4 shows a generic OTOs in an offshore/onshore terminal.

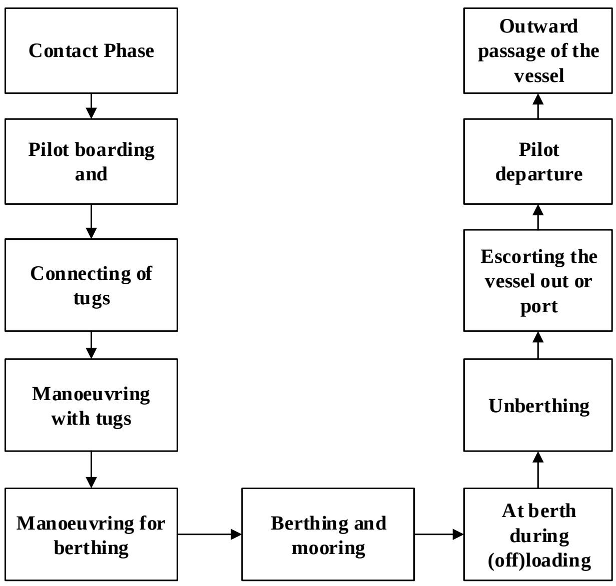


FIGURE 2.4: A Generic Oil Terminal Operation (Trbojevic and Carr, 2000)

Whilst tankers and bulk carriers are loaded with no more than two different hazardous materials at a time, they are complicated with highly dynamic interactions among several operating systems. The fact that there are situations in which information is incomplete or imprecise, as well as views that are subjective or endowed with linguistic characteristics, the presence of uncertainty is inevitable. Researchers have proposed fuzzy-based method to perform risk assessment at seaports and offshore terminal operations (Ren et al., 2005; Elsayed, 2009; Mokhtari et al., 2011; Tang et al., 2011; Ding and Tseng, 2012).

Most of the criteria used to assess the operations and technological processes of oil terminals are interlinked, and are called optimality criteria. The criteria of optimality should be considered as being random rather. Tang et al. (2011) proposed a multicriteria fuzzy optimisation model using fuzzy set theory to improve oil terminal operations and safety during berthing and mooring. The model considered vessel motion and line tensions and their non-uniformity coefficients as criteria. The analysed result shows that the proposed model is applicable in structural improvement in oil terminal layout. Offshore/onshore terminals are platforms where operations such as the Single Point Mooring(SPM) are employed. Accident while carrying out a complex operation between SPM equipments and a ship platform can cause serious losses. The possibility of reducing risk and increasing safety is of optimal importance and as such Paulauskas (2009) analysed dangerous situations with ships and SPM equipment at berth. Elsayed et al. (2009) proposed a probabilistic multi-attribute risk model, where multi-attribute Utility Theory is used to combine the effects of different consequences into a unified utility measure during loading and offloading operation of LNG ships at ship and terminal interface. The identified risks were assessed and ranked in terms of severity.

At an Offshore Technology Conference (OTC) presentation held in Houston, Texas, USA (2010), it was advocated that due to most practical risk analysis, problems are characterised by a large set of interrelated uncertain quantities and alternatives. Bayesian Network (BN) as a tool will further develop operational risk management system because it accounts for risks inherited or generated during the operational phase as well as epistemic uncertainties introduced from changes during the operational phase itself (Ren et al., 2008). Even though BN has not yet been proven to be effective in OTOs, other researchers have proposed the use of the bow-tie mode (Trbojevic and Carr, 2000; Hollnagel, 2008; Mokhtari et al., 2011; Shahriar et al., 2012) approach to assess risk in port terminals. An empirical study was conducted on the effects of safety climate on terminal operation, focusing on employees perception, and SEM was used for decision making purposes. The study identified that managing safety behaviours, safety training programmes and co-workers safety behaviour will help reduce injuries and accident (Shang and Lu, 2009).

2.4 Uncertainty Perspective in the context of Maritime Operations

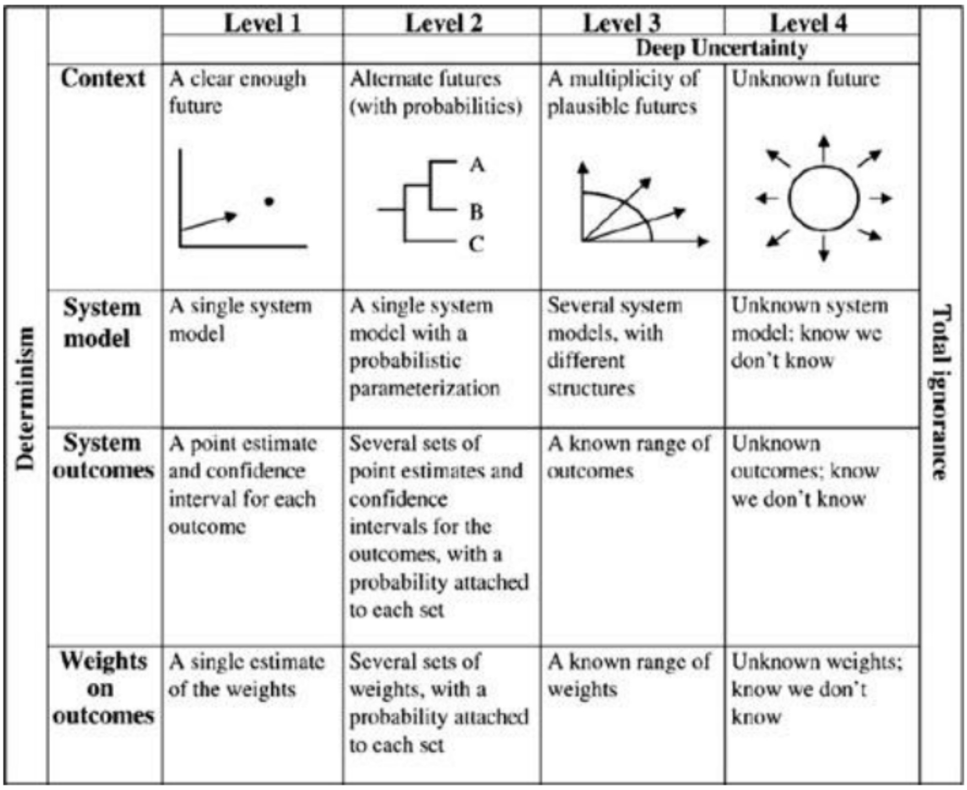
Incomplete information concerning relevant parameters may stem from a partial lack of data, either because these data are too expensive to collect or the data are impossible to collect. Thus, to confront uncertainty is a most challenging task. Over the past three decades, a number of uncertainty theories have emerged where pieces of information takes the form of fuzzy sets of possible values (Mauris, 2013). A significant amount of study has been directed towards terminal and port management problems, but there are still problems associated with ship and terminal interface where uncertainty due to natural disasters, human error, mechanical failure, communication and how the organisation conceptualise uncertainty during complex marine operations come into realisation (Hess and Hess, 2010). Future demand, vessel size, long-term space requirements for port expansion, and future operational requirements have been identified as the major uncertainties for port and terminals (Taneja et al., 2012).

Uncertainty can be looked at in two distinct perceptions in a decision-making context: first, uncertainty might be referred to as the parameters of uncertain probabilities associated with a particular outcome of a decision or set of outcomes, where the extent of this uncertainty is known or at least knowable; secondly, uncertainties arise under conditions where such probabilities and outcomes cannot be precisely specified or are unknown. However, such definitions provide little information. Therefore, for the purpose of this research, uncertainty will be assumed as situations where there is the probability of a negative consequences to individuals or other important risk targets (ships, terminal and OTOs). There is a fruitful relationship between possibility and the probability views of uncertainty representation. Possibility allows the systematisation of notions that already existed in the probability practice of statisticians under an incomplete developed form (Mauris, 2013). It is traditional to deal with uncertainty through the use of probability theory (Markowski et al., 2010).

Some of the most troubling risk and safety management challenges of our time are characterised by uncertainties (Cox, 2012). Where, when, and how to prepare for future effects of climate change to reduce risks/hazards of catastrophic failure, and trying to anticipate and defend against credible threats and other adversarial risks/hazards for robust and adaptive risk analysis methods are not yet as familiar to many risk analysts for confronting uncertainties on OTOs. Fig 2.5 describes different uncertainty levels in an operational environment.

2.4.1 Sources of Uncertainty in OTOs

According to a Process Safety Analysis (PSA) carried out during a chemical process, the prediction of future accident scenario of risk, related to unwanted release of dangerous substance were identified. Three main process components were observed; the first component comprises of a typical qualitative analysis while the second and third components are for quantitative analysis (Markowski et al., 2010). Models used in a PSA usually provide a single value of risk level as an output, whereas it is generally acknowledged that there are substantial uncertainties presented in every component of PSA. A single risk value represent only one possible output result, belonging to a risk distribution that reflect an uncertainty in an input data and models used in PSA. Therefore, uncertainty in a risk process can be described as an imperfect prediction of risk in a PSA.



Determinism		Level 1	Level 2	Level 3	Level 4	Total ignorance
				Deep Uncertainty		
	Context	A clear enough future	Alternate futures (with probabilities)	A multiplicity of plausible futures	Unknown future	
	System model	A single system model	A single system model with a probabilistic parameterization	Several system models, with different structures	Unknown system model; know we don't know	
	System outcomes	A point estimate and confidence interval for each outcome	Several sets of point estimates and confidence intervals for the outcomes, with a probability attached to each set	A known range of outcomes	Unknown outcomes; know we don't know	
	Weights on outcomes	A single estimate of the weights	Several sets of weights, with a probability attached to each set	A known range of weights	Unknown weights; know we don't know	

Figure 2.5: Suggested taxonomy of uncertainties (Walker WE, Marchau VAWJ and Swanson D, 2010)

Each component in a PSA has its own specific function, model and input data required, therefore there are different uncertainty sources related to the above-mentioned components in terms of PSA. It is convenient to distinguish the three main types of uncertainties:

1. Completeness uncertainty,
2. Modelling uncertainty, and
3. Parameter uncertainty.

The **Completeness uncertainty** refers to a question if all significant phenomena and relationships were considered. This type of uncertainty is difficult to quantify but it is considered a major contributor to qualitative hazard analysis. **Modelling uncertainty** refers to the inadequacies and deficiency in various models used to assess accident scenario probabilities and consequences (Merrick and Van Dorp, 2006). The availability and validity of these models may enable the assessment of different degrees of belief in each model, thus it is a major type of uncertainty for consequence assessment. **Parameter uncertainty** is a subjective type of uncertainty where knowledge is elicited from experts, which is often incomplete, imprecise and fragmentary. The imprecision and inaccuracies on the parameters which are used as an input for PSA models are inherent because the available data are usually unknown and inaccurate before an accident occur, and the inference process need to be based on the incomplete knowledge. However, there is an opinion that parameter uncertainty is easy to quantify.

There are different available approaches for uncertainty analysis: classical statistic, probabilistic, sensitivity analysis and possibility approach. One of the ways in analysing the different types of uncertainty is by using the fuzzy logic. Fuzzy logic is an ideal concept for representing vague issues in risk assessment. It presents a degree of membership function, indicating a possibility that certain phenomena will occur where there is no sufficient information to use other probabilistic methods. Another advantage of fuzzy logic is, the analysed uncertainties are not separated from the actual risk calculations but are built within the model calculations, depending on how the input parameters are defined. The use of fuzzy logic for risk assessment in various aspects of process and complex systems were undertaken in previous studies (Ren et al., 2005; Yuhua and Datao, 2005; Elsayed, 2009; Ren et al., 2009; Hejazi et al., 2011; Shahriar et al., 2012). Fig 2.6 shows a good example of uncertainty approach in process safety analysis (PSA).

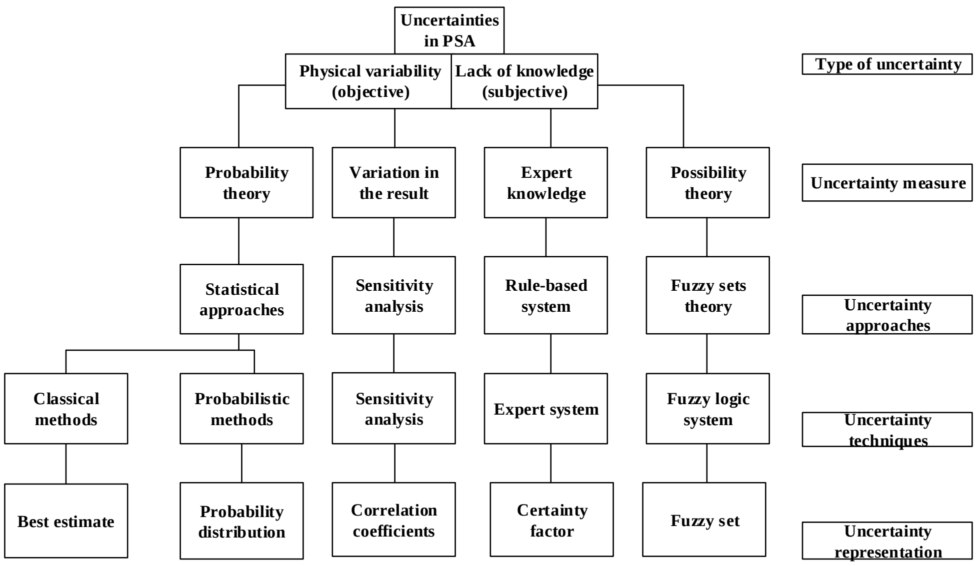


Figure 2.6: Uncertainty approaches in PSA (Markowski et al., 2010)

Complex dynamic systems require good understanding of the uncertainties surrounding them. The operations of offshore/onshore systems are often associated with high level of uncertainty due to operations under ever-changing environments leading to a range of possible accidents (Ren et al., 2009). The question of how to deal with unpredictable and uncertain events lingers within the research domain. Uncertainty is usually divided into epistemic and aleatory uncertainties within the offshore and onshore terminal operations: epistemic uncertainty is represented by insufficient data and lack of knowledge about the system, resulting to inadequate hazard identification whereas aleatory uncertainty stems from the variability of known quantities due to randomness of the system itself (Merrick and Van Dorp, 2006; Pasman et al., 2009). Addressing uncertainty on OTOs is critical towards dealing with unforeseen events within the offshore and onshore terminal platforms. Fig 2.7 shows OTOs having a similar type of uncertainty as PSA.

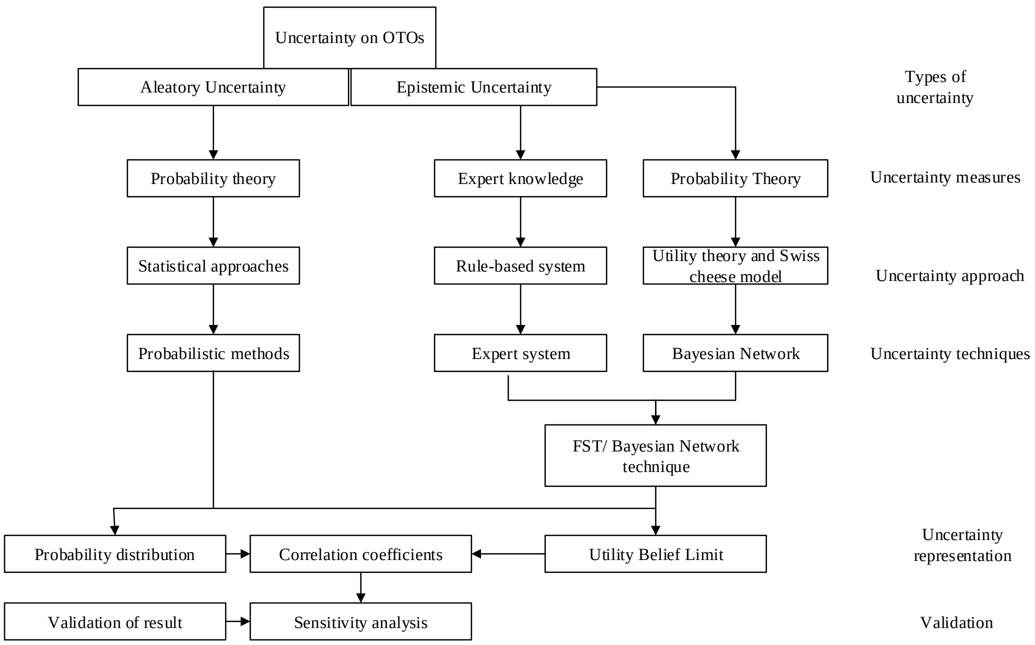


Figure 2.7: Uncertainty approaches for OTOs as adapted in Markowski et al. (2010)

ETA and FTA have been used to address Liquefied Petroleum Gas (LPG) release, petrol oil release, risk analysis of oil and gas pipelines, and runaway reaction in a reactor. Further research developed and proposed Fuzzy-based and evidence-theory-based formulations to address data and dependency uncertainties (Ferdous et al., 2011). It is important to propagate, characterise and represent uncertainty accurately to conduct a reliable analysis (Merrick and Van Dorp, 2006). The level of uncertainty associated with an operation in a terminal is proportional to its complexity, which is caused by vague known relationships among various entities, and the stochastic behaviours exhibited by these terminals. Complex dynamic systems in the maritime industry are characterised as environmental, engineering and economic systems. They involve human interaction and intervention; where majority of inputs and outputs are not captured analytically. A nonlinear behaviour with an uncertainty feature require methods that combine both expert judgement and human knowledge when developing a reliable model.

Researchers have demonstrated the use of a preventive or corrective action techniques such as the bow-tie approach. The bow-tie technique integrates the FTA and ETA in a common platform for decision making and risk management processes, but it is not able to characterise model uncertainty that arises due to vagueness and lack of data. Fuzzy logic was employed to further minimise uncertainty on maritime infrastructures (Shahriar et al., 2012). On oil terminal platforms, a thorough study on what can help a bit more to monitor, mitigate and control uncertainties is required and this study aim toward realising such further step.

2.5 Risk Management Perspective: Examining Current trends in Ports and Oil Terminals

Various parties (operators, shipyards, regulators and government) in their respective working contexts are very often involved in a sequence of events leading to an accident; this is the most critical issue in developing an effective risk or accident analysis. One good example of an error is an operator on-board ship operation, whom is presumed as the final act of a long and complex chain of organisational and systemic errors (Trucco et al., 2008). The IMOs suggested guidelines for safety management (see Subsection 2.2.2) has been effective, and the approach has supported the identification and evaluation of risk control option at the international panel of different European countries. However, the significant reduction of risk and safety concerns for OTOs come into context. Risk is present everywhere: nature itself is a cause of a disaster, thus, what is done, where it is done, with what technology, materials or facility, and in what safety conditions, are all integral in a risk assessment. Man, machine, media, nature and management have a greater influence in CMOs and may cause its malfunction (Ding and Tseng, 2012). Risk countermeasures can be taken proactively to reduce the possibility of a loss.

2.5.1 Risk Management: A Genuine Concept in Maritime Safety

In maritime operations, decision analyst faces having to make decisions at all time where an outcome is uncertain. Taking a corporate strategy perspective of Risk Management (RM), and understanding the risks involved will produce an enhanced performance, e.g. if A occurs, then it causes B, therefore RM is defined as the eradication or minimisation of the adverse effect of risks to which an organisation is exposed (IOSH, 2000). Researchers such as Eloff et al. (1993), British Bankers' Association (1999), Head and Hom (1988), Sung (2005) and Cheng (2005) defined risk management from a different perspective, but their definitions had the same purpose to develop a systems for controlling risk in advance, thereby establishing a set of efficient strategies to achieve an effective protection and control of risk. More so, to reduce the probability of the risk and avoid damage from the risk (Shang and Tseng, 2010). As systems continue to grow in scale and complexity, an added layer of complexity is introduced when the system has to exhibit resilience in the face of contingencies in an operational environment, thus risk management activities are an integral part in satisfying the various needs of stakeholders. The term "risk" may be conceptualised in terms of an event and impact, for example, some industries quantify risk with two parameters: the likelihood that a given event will occur and the impact of that event (Madni and Sievers, 2014). Risk management during marine operations subsumes operator's deployment, transition from existing system to new system, operations, maintenance, security and the environment. Mokhtari et al.

(2011, 2012) proposed a RM framework for seaport and offshore terminal operations and management. The proposed framework consists of three main phases, namely:

- Hazard identification
- Risk assessment
    - Risk analysis
    - Risk evaluation
- Risk mitigation

2.5.2 Hazard Identification (HAZID)

HAZID remains the first step taken to identify initiating failure events with the potential to cause harm to people, damages to properties and the environment. Empirical studies revealed that the techniques recommended in various research to conduct HAZID includes: (a) Hazard and operability studies (HAZOP), (b) Failure mode and effective critical analysis (FMECA), (c) What-if, (d) Preliminary hazard analysis (PHA) and, (e) Progressive loss of containment analysis-optimising prevention (PLANOP) (Wang, 2002; Pasman et al., 2009; Marhavilas et al., 2011; Groso et al., 2012). Most of the aforementioned techniques have their advantages and disadvantages; they can be exploited alone but according to Groso et al. (2012), the combination of two or more HAZID techniques gives a better result to identify a specific hazard in a complex dynamic system (Groso et al., 2012).

HAZID on offshore/onshore oil terminal facility is carried out in order to identify potential hazards which can result to failure of terminal infrastructures with high consequences. It is also implemented in an organisation to examine operational procedures. The process of conducting a HAZID can differ due to available resources and the system being evaluated.

In CMOs mainly OTOs, HAZOP is a significant technique in a hazard identification processes, and can be complemented by PHA or What-if techniques. HAZOP is an organised methodological technique for analysing hazards and operational concerns of a system. When there is a deviation from the normal operation, HAZOP helps to identify how unsafe the operation can become. HAZOP is a clearly structured technique which provides rigidity for focusing on system element and hazard. HAZOP can be used to scrutinise operations at ship and terminal interface, ensuring all potential hazardous situations have been noted and the resultant identified deviation in operational design are examined to find possible root causes and consequences. Generally, HAZOP assist in risk identification and consequences, root causes, and corrective measure.

Though HAZOP is time consuming and expensive, the What-if technique (a brainstorming approach in which a group of experienced participants familiar with the subject process raise the question what-if?), is used as an approach to complement a HAZOP process, thus, making it more convenient. PHA is a safety analysis tool for identifying hazards, causal factors and effects, which provides indication of system risk. It is easily and quickly performed, inexpensive and provides meaningful result. For an effective PHA to be carried out, a safety analyst requires information from the designed operation and a preliminary list of the identified hazards of previous operations.

2.5.3 Risk Assessment

Risk assessment is an essential and systematic process for assessing the impact, occurrence and consequences of human activities on systems with hazardous characteristics. It constitutes a needful tool in the safety policy of a company. Risk assessment helps to study how hazardous events or states develops and interact to cause an accident. It is aimed at assessing risks and the factors influencing the level of safety. For instance, shipping involves a sequence of distinctive phases between which the status of ship functions changes; the major phases include (a) design, construction, and commissioning, (b) entering port, berthing, unberthing, and leaving port, (c) loading and offloading, and (d) decommissioning and disposal. The failure of any of these system may cause disastrous consequences. Risk assessment can be carried out in respect to each maritime dynamic critical system. The probability of occurrence of any failure event and its possible consequences can be assessed using various risk assessment techniques such as (a) the qualitative, (b) the quantitative, and (c) the hybrid techniques (Marhavilas et al., 2011).The qualitative techniques are based on the safety managers engineering ability and his/her analytical estimation processes. The quantitative techniques are processes where risks are considered as quantities. They can be estimated and expressed by a mathematical relation, with the help of recorded accidents data of a work-site. The hybrid techniques present a great complexity due to their ad hoc character. Generic data or expert judgements can be used in risk assessment (Wang, 2002). The state of safety can only be known by analysing risks/hazards.

2.5.4 Risk Analysis

Over the past three decades, research on an improved and effective seaport and offshore/onshore risk analysis has constantly been undertaken. The main issues on these risk analysis were how to deal with unpredictable and uncertain events (Ren et al., 2009). The transportation of large quantities of hazardous materials can explode, burn or be released into the environment, with a potential to cause harm to the life and health of people, damages to structures and environment, therefore, risk analysis can be improved and adopted to minimise risk to people, operators and management. A risk analysis is necessary because it reveal the areas where unacceptable high risks are present in a system, so that additional protective or proactive measures can be taken. According to previous researches, risk analysis is performed in various degrees of detail (Mullai and Paulsson, 2011), three methods come into context: (a) the qualitative (b) the quantified and (c) semi- quantitative risk analysis methods. The qualitative risk analysis remains the lightest form of analysis (Pasman et al., 2009) where subjective estimates are made (risk ranking) and the results estimated in a risk matrix. Bragatto and Pirone (2011) used a bowtie approach for the assessment of the personnel risk at an Italian industrial port.

On the other hand, the quantitative risk analysis requires technique and expertise to analyse possible events with potential harmful impact. With the emergence of probabilistic approaches for risk analysis in offshore/onshore terminals and maritime transportation (Clark and Besterfield-Sacre, 2009), uncertainties are taken into context to further improve maritime safety. The quantitative techniques adopted for maritime risk analysis includes FTA/ ETA, BN and Fuzzy Set Theory (FST).

Fault Tree Aanalysis and Event Tree Aanalysis

Fault tree analysis (FTA) and Event tree analysis (ETA) are two distinct methods that develop a logical relationship among events leading to an accident and also they estimate the risk associated with such accident (Trbojevic and Carr, 2000; Marhavilas et al., 2011). ETA is a technique used to describe the consequences of an event (initiating event) thereby estimating the likelihood (frequency) of possible outcomes of an event. FTA estimates the likelihood (probability) of the basic occurrence of an unwanted event as well as the contribution of different causes leading to the unwanted top event.

FTA helps to conduct a QRA on two major assumptions (a) the likelihood of basic events is assumed to be exact and precisely known, which is not often true due to inherent uncertainties such as vagueness of critical complex system, variant failure mode, poor understanding of failure mechanisms, and defining the relationships of basic events (b) the interdependencies of basic events in fault tree are independent (Ferdous et al., 2011). In offshore and onshore terminals, FTA is a technique used for conducting a quantitative risk analysis to predict the probability of hazardous incidents and to identify the most important risk contributors. A typical fault tree consists of a top event, basic events, and the logic gates to determine the causes of failure (Mokhtari et al., 2011). Performing a QRA using FTA requires applying logic gates on a combination of failures and their occurrence probability (OR gates, AND gates). An event occurs when a gate output changes state. Input such as good knowledge in design, systems, personnel training and accident history are required to conduct a FTA, and its output consists of a fault diagram, which exhibits the root causes of an accident. If the fault tree is evaluated, the identified system failure is defined as the top event (Fernàndez-Garcia et al., 2012). FTA has been combined with other probabilistic risk analysis methods to produce a better result. FTA is suitable for investigation and management of multiple cases of failures, reliability, and maintainability (Yuhua and Datao, 2005).

On the other hand, ETA uses an inductive approach to determine the consequences of an undesirable event. The consequence of event follows a series of paths to which probabilities are given. The outputs of ETA are accident outcomes, risk probabilities, causal sources and safety requirements. The main disadvantage of ETA is that it cannot be used to study multiple failures on the same initiating event (Groso et al., 2012). The integration of FTA with ETA is possible. Ferdous et al. (2011) used both techniques to assess uncertainty in a QRA framework of a process system. Fig 2.8 and Fig 2.9 are examples of a typical FTA and ETA

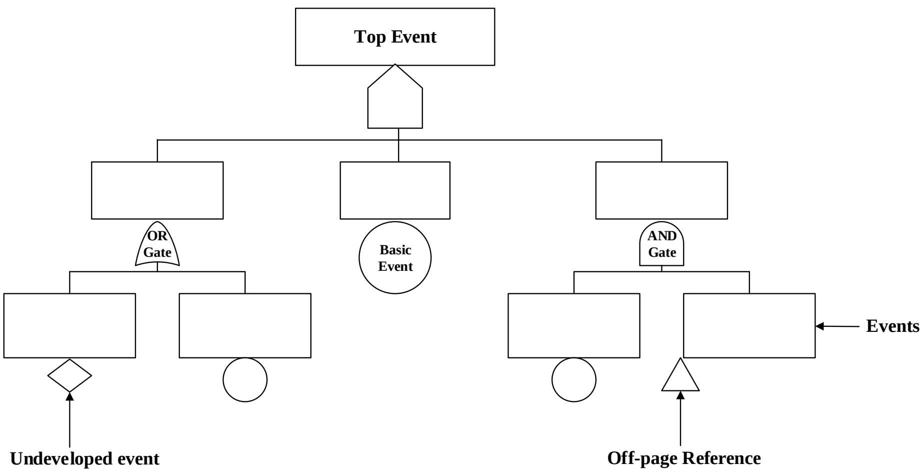


FIGURE 2.8: A standard fault tree symbol (Wang, 2002; Ferdous et al., 2011)

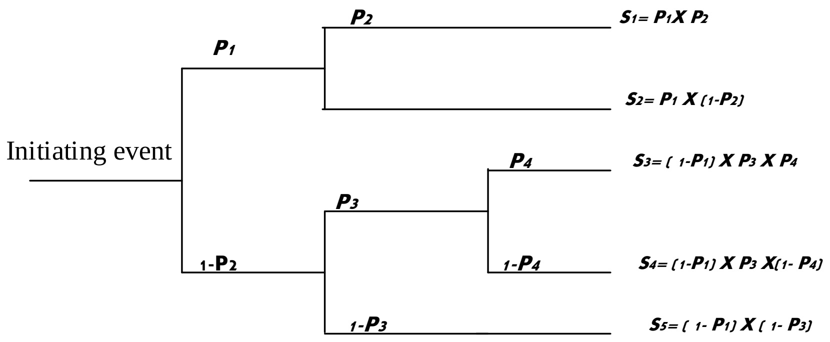


FIGURE 2.9: Sample of a conventional event tree (Ferdous et al., 2011; Jongejan et al., 2012)

Fuzzy Set Theory (FST)

Fuzzy-based methods have been employed to perform risk assessment in many research domains (Ballı and Korukoğlu, 2009; Celik et al., 2010; Hejazi et al., 2011; Ding and Tseng, 2012; Shahriar et al., 2012). It is a powerful mathematical tool for modelling industrial systems, nature and humanity under uncertainty (Ballı and Korukoğlu, 2009).

Extensive research has been performed using FST and the basic advantage of a fuzziness-based method is its ability to deal with vagueness in a fuzzy environment and its tolerability to linguistic or imprecise data (Elsayed et al., 2009). Fuzzy set is a class of objects with a range of grades of membership. FST is developed on a fundamental concept of set which is either a member or non-member. A crisp, sharp and definite distinction exists between a member and non-member for any well-defined set of entities in this theory and there is a very precise and clear boundary to indicate if an entity belongs to the set (Ballı and Korukoğlu, 2009; Celik et al., 2010). Such a set is characterised by a membership (characteristic) function, in which each object is assigned with a grade of membership ranging between 0 and 1 (Ren et al., 2005). The theory allows operators, navigators and programmers to apply FST in a fuzzy domain.

Balli and Korukoglu (2009) used Fuzzy Analytic Hierarchy Process (FAHP) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methods in developing a fuzzy decision model to select an appropriate operating system for a computer system of an organisation. Ding and Tseng (2012) proposed a systematic fuzzy risk analysis steps to evaluate safety operations, using the linguistic value of FST as well as conducting an empirical study at Kaohsiung port container terminals in Taiwan. Yuhua and Datao (2005) analysed the failure of oil and gas transmission pipelines by combining fuzzy set theory with fault tree analysis (FFTA). More so, Celik et al. (2010) developed a risk-based modelling approach using FFTA to enhance the execution process of shipping accident investigation (SAI). Elsayed et al. (2009) used fuzzy set rule base and a fuzzy inference for the risk assessment of liquefied natural gas carriers during loading/offloading operation at terminals where FIS is an alternative approach to the qualitative risk matrix techniques. Hejazi et al. (2011) assessed new factors such as probability of failure detection and economic disbenefits of failure occurrence using some set of generalised fuzzy numbers. Shahriar et al. (2012) combined the bow-tie approach with fuzzy logic to develop a model to deal with uncertainty for oil and gas pipelines. The combination of fuzzy logic and Process Hazard Analysis (PHA) was used to determine uncertainties of input data as well as simulating models, used for process safety analysis (Markowski et al., 2010). Hu et al. (2007) developed a risk assessment approach based on fuzzy function to solve a problem of ship navigation safety practice in Shanghai harbour, China. At seaport and offshore terminals, FST has been combined with the bow-tie approach and evidential reasoning for risk analysis and decision support (fuzzy logic incorporating the Dempster-Shafer approach) respectively for safety management systems (Sii et al., 2002; Ren et al., 2005; Mokhtari et al., 2011, 2012).

Utility Theory (UT)

Theories of decision making under uncertainty in particular, sometime relies on the subjects behaviours or appetite towards risk. Psychological research presented that Decision Makers (DMs) hold domain-specific risk attitudes that often vary between individuals.

One approach for analysing probabilistic choice outcome under uncertainty to aid a Decision Maker (DM) is to use a risk-based Utility Theory. The term Utility is defined as the measure of satisfaction of a choice or result (Keeney and Raiffa, 1993). In order words, Utility assessment is the psychology of assessing and judging risk. Utility Theory can be used to support decision-making process by providing quantitative backing to gut feeling in real-time decision support system. Farquhar (1984) presented a comparative study of the process involved for utility assessment in decision analysis as well as methods for assessing expected utility function. Van Bossuyt et al. (2012) used Utility Theory and the Engineering Domain Specific Risk Taking (E-DOSPERT) risk appetite research to determine the true value of risk decision using utility function. Finnell et al. (2012) compared the influences of standard gamble and time trade-off utility assessment based on Von Neumann and Morgenstern (1979) to determine the value of health care measurement for parents risk attitude. Huang et al. (2013) proposed a multi-attribute Utility Theory for assessing and ranking alternatives in a decision group.

A DMs risk attitude can be classified into a risk tolerant, risk-averse and risk-neutral, depending on how skewed the intrinsic value for the risk decision is, based on the utility function. Pratt (1964) provided a classical definition of utility functions as a function that specifies the utility of a DM for all the combinations made qualitatively or quantitatively (Miyamoto, 2003; Van Bossuyt et al., 2012). Thus, a risk-tolerant decision makers utility function outcome is skewed more heavily towards a higher intrinsic value for riskier decisions. A risk-averse decision makers utility function will shift towards a lower-value outcome while a risk-neutral decision makers utility distribution is not skewed towards either direction along the utility axis.

There are different methods used for utility assessment (Farquhar, 1984), but a more robust assessment technique to tackle uncertainty is the hybrid assessment method. To design and produce a hybrid assessment method, other methods are required to be merged, methods such as the Certainty Equivalent (CE), preference comparison and the probability equivalence. In order to find the equivalent value of a specific risk, Certainty Equivalent Value (CEV) based on Utility Theory gamble comparison is developed and found in conjunction with the probability of an outcome. The interpretation of the CE is given, by assessing the context in which judgement are made. For example, the status quo of four situation is used to regulate the context of choice comparison, and the CE depends upon the context given as the status quo. Farquhar (1984) presented a good example of how to assess the CE among two alternative choices $(s + c, 0)$ (s, p), which he is indifferent between. The certainty effect in the utility assessment specifies that the utility of an outcome seems greater when it is certain than when it is not certain. Preference comparison is used to investigate the risk attitude for a preliminary analysis, and probability equivalence specifies an indifference probability for which two alternative choices are in-between (Hauser and Urban, 1979; Novick et al., 1980; Farquhar, 1984; Miyamoto, 2003).

The psychology on risk decision making describes how decision analysts may unavoidably (1) formulate the decision problem, the alternatives, the measurement scales, and other structural features; and (2) control the response mode and perspectives of the DM. In as much as there are many possible sources of bias in making preference judgements, evaluating and analysing individual risk attitude as well as other factors affecting individuals preferences provides a reasonable basis for making a decisive assessment among alternative choices for investigating risk.

Swiss Cheese Model (SChM)

Reasons Swiss Cheese Model is classified among the dominant paradigms for analysing the occurrence of system failures in different fields. The model is frequently referred to and widely accepted by safety professionals in process industries, maritime domain, transportation systems, high reliability organisations, management and health service research (Reason, 2000, 2004; Sklet, 2004; Perneger, 2005; Broadribb et al., 2009; Wu et al., 2009; Xue et al., 2013; Underwood and Waterson, 2014). The SChM is a heuristic explanatory device for communicating the interactions and sequences that occur when a complex secured system undergoes a catastrophic breakdown. The SChM involves an unlikely and often unforeseeable conjunction of several contributing factors arising from different levels of the system. It also acts as a framework for accident investigation. The SChM is used for three different purposes (1) as a heuristic explanatory device (communication) (2) as a framework for accident investigation (analysis) and (3) as a basis for measurement (Reason, 2000; Ren et al., 2008; Sheridan, 2008; Broadribb et al., 2009; Xue et al., 2013; Fan et al., 2013). As pointed out earlier, SChM has been used as the basis for analysis by promoting the view of accidents, as a combination of specific events and the failure of barriers. Weaknesses on the barriers may exist when events in the sequence are described as near-misses, incidents or failures, and this occurs at different operational levels, going from senior management to unsafe acts. Thus, failures caused by either human or technical factors are not sufficient to cause an accident. The SChM uses broad practical experience towards system functions but it is often associated with the occurrence of incidents and accidents when safety defences or barrier(s) fails. Fig 2.10 and Fig 2.11 shows the SChM and a safety defence barrier function.

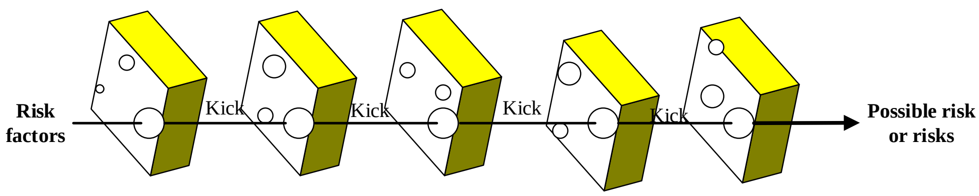


FIGURE 2.10: Reasons Swiss Cheese Model

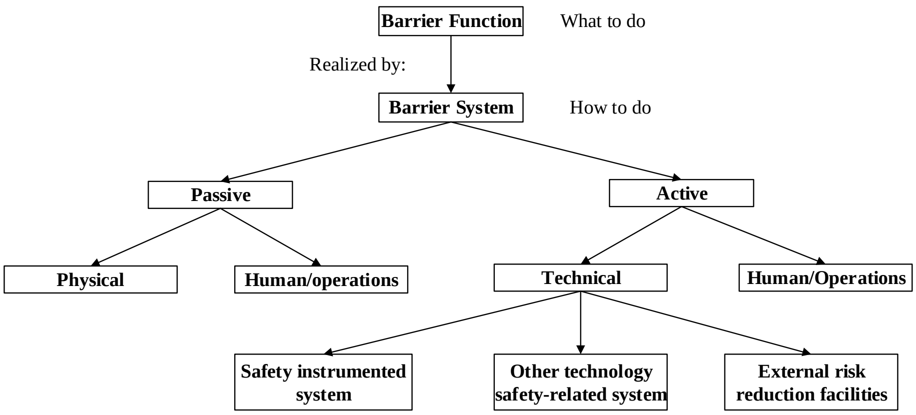


FIGURE 2.11: Classification of safety barriers (Sklet, 2006)

In an ideal world, the safety barriers are intact, designed to serve a specific purpose within the system. In reality, they are full of holes that represent weakness/failures. When the holes in a systems defence align, an accident trajectory cuts through the defence layers and thus result to a hazard, causing harm to people, assets and the environment. According to Reason (2004), there are two major reasons for barrier failure in the SChM, namely:

- Active failure: these are errors or unsafe act from those in direct contact with the system. This creates gaps or absence in or among the safety defence barriers, and the more sequences of gaps created on the defence barriers build up to cause a major disruption.

- Latent conditions: these are weakness created as a result of decisions made during system designs, wrong decision taken by managements, regulators, managers or the person on duty. This weakness occurs in most complex hazardous system as such due to the complexity within the system, decision makers hardly foresee all the possible accident scenarios. The effects of latent conditions are such that they are long-lasting weakness and are present within the system prior to an unsafe event occurrence. They are the primary source of safety barrier failure but can be detected and repaired before they can cause a major disruption.

The failures of safety defence barriers in most complex hazardous system can be detected proactively or reactively using ETA/FTA (Sheridan, 2008; Xue et al., 2013). Undoubtedly, the SChM remains a viable model that provides a system thinking approach and a deeper understanding of how event sequences within complex dynamic system results in an accident.

The SChM has been severally criticised by quite a number of researchers. Dekker (2006) described the SChM as a model which oversimplifies accident causes by not taking into context the complex interaction of a system components. Others criticised its application, focusing on the lack of specificity of the aligned holes and their effects as well as its prescriptive attributes; suggesting that its application could be misleading or entirely incorrect (Hollnagel, 2012; Shappell and Wiegmann, 2012; Le Coze, 2013; Underwood and Waterson, 2014).

2.5.5 Risk Evaluation

Risk evaluation is a process where results from risk analysis are considered against judgements, standards or criteria. Criteria are useful for defining parameters used for decision making (Mokhtari et al., 2012). It defines the metric and the level of risks that are acceptable, as well as the level of investment in the reduction of risk that are considered to be non-negligible. An evaluation process study the level of risk/hazard factors within a platform and a risk criteria will be formulated as a maximum level of risk that should not be exceeded (Mokhtari et al., 2011). As Low As Reasonable Practicable (ALARP) is widely used to determine criteria for acceptable risks principle (Wang, 2002). The risk evaluation process can use any combination of the basic, detailed, comparative or absolute assessments and this can be repeated severally, provided that the analysts believe that such combination of techniques will support a conclusion (Skjong et al., 2005).

ABS (2003) expressed that in the past, managers experiences were a basic factor for risk evaluation. The manager evaluating the possible options for dealing with issue on risk factors needs to consider the following:

- Is the risk assessment good enough to be relied upon?
- What criteria are used in the risk ranking of each option to model uncertainties?
- What are the benefits associated with each risk management option?
- Are residual risks aligned with a chosen risk management option?
- How effective will it be to execute the risk management option?

To answer the above questions, Mokhtari et al. (2012) proposed a generic risk evaluation model, considered to be a key part in the RM framework. The proposed model was used to provide continued risk control assurance within ports, terminals and management. Yuhua and Datao (2005) evaluated the risk factors for the failure of oil and gas transmission pipelines under uncertainty. Ren et al. (2005) proposed a risk evaluation method for the operation of tandem (off) loading between floating production, storage and offloading unit (FPSO) and a shuttle tanker. Shang and Tseng (2010) evaluated the risk factors of stevedoring operation in Kaohsiung harbour container terminal using risk matrix chart. Evaluation metrics could have qualitative and/or quantitative parameters which have a characteristic to evaluate a proposed design or operation in terms of its level of safety (Wang, 2002; Shang and Tseng, 2010; Mokhtari et al., 2011, 2012; Groso et al., 2012).The qualitative risk evaluation techniques include

FMEA, risk matrix chart, cause-consequences analysis (CCA) whereas the quantitative evaluation techniques used mostly under uncertainty includes FFTA, FETA, and FST. Mokhtari et al (2012) proposed a risk evaluation process methodology for ports and terminals operations and management (PTOM). In the most generic case, the major activities in an evaluation process are as follows:

- Define the objectives of the evaluation,
- Conduct a basic risk assessment (comparative or absolute).

Bayesian Network (BN)

A Bayesian network (BN) have been established as a suitable tool for modelling and reasoning under uncertainty (Ren et al., 2008; Trucco et al., 2008; Clark and Besterfield-Sacre, 2009; Ren et al., 2009; Lu et al., 2011; Fernàndez-Garcia et al., 2012; Li et al., 2014; Alyami et al., 2014). A BN is a versatile modelling framework, which provide a systematic and localised method for structuring probabilistic information of a situation into a coherent whole, such as graphically representing the relationships among a set of variables, and for dealing with uncertainties in such variables (Ren et al., 2009), supported by a suite of inference algorithms. BN has been used in many different domains; many applications can be reduced to a BN inference, allowing one to capitalise on BN algorithms instead of having to invent specialised algorithms for each new application. A BN has two components; a structure called a Directed Acyclic Graph (DAG) (Kjaerulff and Madsen, 2008; Verma and Pearl, 2013) and a set of computed conditional probability table(s) (CPT)(Fenton et al., 2007; Trucco et al., 2008; Yang et al., 2008; Ren et al., 2009; Li et al., 2012; Alyami et al., 2014; Salleh et al., 2014; John et al., 2016)

A BN consists of qualitative and quantitative parts (Cai et al., 2013). The qualitative part of a BN are graphical directed acyclic graphs (DAGs) as shown in Fig 2.12, where the nodes represent prepositional variables of interest (Pearl, 2011). The arcs in a BN specify direct causal relationships between the linked nodes. The quantitative part of a BN is the Conditional Probability Tables (CPTs) and they are assigned to the nodes. Nodes could be a parent node or a child node. The former is called root node and the later are called a leaf node. Root nodes have prior probability distribution while leaf nodes have conditional probability distributions (CPD). Based on the assumption of conditional independence, the conditional probability distribution for a random variable associated to a node, is specified by considering the probability of each of its state, conditioned on the combination of the states of its parent nodes (Zhou et al., 2011). A BN must include a CPT for each variable; this quantifies the relationship between a child node and its parent node. The nodes of a structure correspond to the variables of interest, and the edges have a formal interpretation in terms of probabilistic independence.

A BN is often used for causal representation of the phenomena involved in a complex system or process, where information is based on expert knowledge. BN has numerous advantages because of its distinct features in maritime safety, but also has some inherent

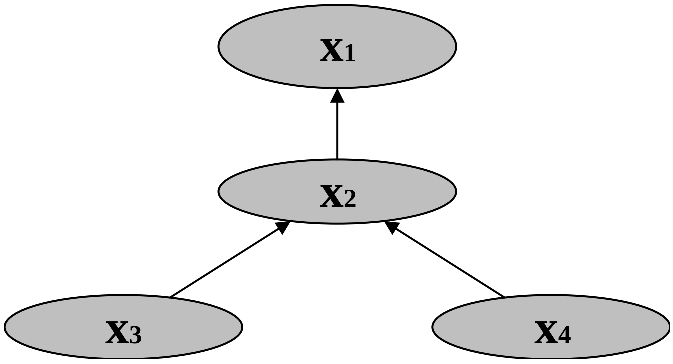


FIGURE 2.12: A graphical representation of BN

limitations (Eleye-Datubo et al., 2006; Ren et al., 2008; Trucco et al., 2008; Eleye-Datubo et al., 2008; Ren et al., 2009; Li et al., 2014; Dabrowski and De Villiers, 2015). Prior to the occurrences of certain events, it is possible to investigate other factors influencing or being influenced by an event in the overall risk analysis, and this requires too much data in the form of prior probabilities, such that these data are often difficult, if not impossible, to obtain in the risk assessment (Yang et al., 2008). A simple understanding of a BN is to imagine how to model a situation where causality play a role but our understanding of what is actually going on as incomplete, thus requiring to describe things probabilistically. A BN has been extensively used in risk analysis based on probabilistic and uncertain knowledge (Nordgård and Sand, 2010; Gran et al., 2012; Cai et al., 2013; Wang et al., 2013). A representation of a typical BN is shown in Fig 2.13.

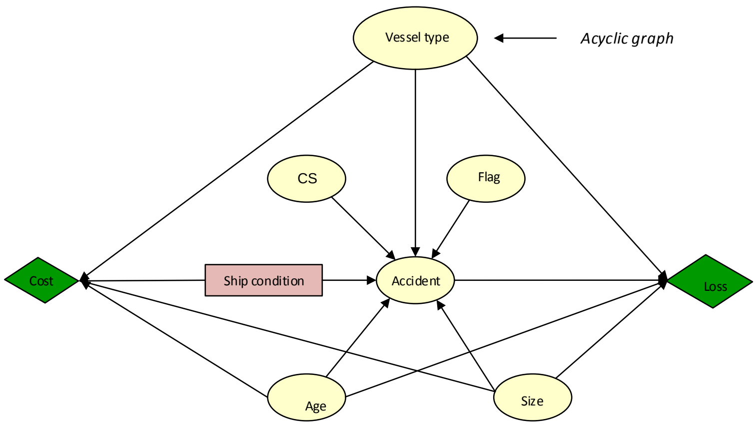


FIGURE 2.13: An example of a vessel accident model using BN (Li et al. 2014)

Comprehensive Review of Bayesian Network

The BN has been applied in different domains for diagnostics (Heckerman 1990), fault diagnosis in complex nuclear power systems (Kang and Golay, 1999), prediction and machine learning, e.g. finance, robotics, forecasting, google, medicine, control and modelling for human understanding, ecological risk assessment (Hayes, 1998), map learning and story understanding. BNs are often known by other names and different authors often mean slightly different things when they use these terms. Lauritzen (1995), Cheng et al. (1997), Darwiche (2002), Jensen et al. (1990b), Heckerman (2007) and Shachter (1986a) represent BN as recursive graphical models, Bayesian belief networks, belief networks, causal probabilistic networks, causal networks, influence diagrams respectively (Daly et al., 2011). Van der Gaag (1996) in his work presented a review of the historical development of BNs and extended further by introducing their formalism and use. Jensen (2001) introduced BNs and their decision support extensions.

The Bayesian approach requires information in the form of prior probabilities (Li et al., 2014). This offers a compact representation of the interactions in a system (stochastic or deterministic) by visualising system variables and their dependencies (Nordgård and Sand, 2010). The BN corresponds to nodes which in turn correspond to events (random variables), and these nodes are linked by arcs, which suggests that the child of an arc is influenced by its parent; in a deterministic and probabilistic way. As such, a BN is a complex representation of distribution over a large joint probability distribution of random variables. Once the BN is specified, it tends to observe variables and compute probabilities of the parent nodes. A node (variable) may be of various types. It may represent a continuous variable, or a discrete states. The discrete states may be in the form of Boolean, interval based, numbered or labelled states (Heckerman and Wellman, 1995; Gran et al., 2012). According to the d-separation concept from Pearl (1988) based on the conditional independence, certain independence assumptions holds for all CPTs (Charniak, 1991). A BN represent the joint probability distribution of variables $P(R)$ where $R = A_i \ldots, A_n$, included in the network as:

$$P(R) = \prod_{i=1}^{n} P(A_i|P_a(A_i) \tag{2.1}$$

Where $P_a(A_i)$ is the parent set of A_i (Jensen and Nielsen, 2007)

A BN also takes advantage of Bayes theorem to update failure probability of events (propagation) given new information, called evidence E, thus yielding the posterior probability. This new information usually becomes available during operation processes, where there is an occurrence/non-occurrence of primary event(s)/accident(s):

$$P(R|E) = \frac{P(E|R).P(R)}{P(E)} = \frac{P(E|R).P(R)}{\sum_U P(E|R)} \tag{2.2}$$

The evidence E ranges from subjective judgements through to more objective data, and in some situations, an extensive historical data could be used.

Other approaches based on logical algorithms such as FST have been integrated to further improve the scope and ubiquity of a BN (Yang et al., 2008). A key factor of a BN is it compactness which leads to a representation that scales significantly better to large network, than becoming the trail approach which goes to all combination of various variables. Recently, Weber et al. (2010) compared a BN with other methods, as well as reviewed BN application in dependability, maintenance and risk analysis; making it a well-suited technique for dynamic risk and safety analysis.

In an uncertain environment where there is little or no data, making a decision based on gut feel and having to justify it could lead to a disaster in the event of subsequent safety incidents. BN provides a useful framework for modelling complex systems, identifying gaps associated with uncertainties in an explicit manner for decision makers.

The advances of BNs in the 21st Century

Over the last few years, a method of reasoning using probabilities, variously called belief networks, Bayesian networks, knowledge maps, probabilistic causal networks etc., has become popular within the artificial intelligence (AI) probability and uncertainty community. Probabilistic models based on DAGs began in the early 19th century with the geneticist Sewall Wright in 1921. The long and rich tradition of DAGs modifications has appeared within cognitive and artificial intelligence (AI), and such models are BN. Initial modifications of BN in the late 1970s were motivated by the need to model the top-down (semantic) and bottom- up (perceptual) combination of evidence reading (Pearl, 2011). According to Pearl (1998), Shafer and Pearl (1990), Heckerman et al. (1995) and Jensen (1996), the rapid emergence of BNs as a method of choice for uncertainty reasoning was dependant on the proficiency for bidirectional inferences, combined with rigorous probabilistic foundation. The BN replaces the earlier ad-hoc rule-based schemes in AI and expert systems (Pearl, 2011).

Subsequent algorithm have been developed, that first builds an undirected graph from a BN (Howard and Matheson,1979, 1981; Olmsted, 1983, 1984; Pearl,1986; Lauritzen and Spiegelhalter, 1988; Shachter, 1986a, 1986b, 1988; Smith,1989; D Ambrosio, 1991) as cited in (Heckerman and Wellman, 1995). Ramamurthi and Agogino (1988), Jensen and Anderson (1990), Shachter, Andersen and Poh, (1990), Suermondt, H.J and Cooper (1991), and Heckerman (1993) suggested that a typical BN is constructed using notions of cause and effect, thereby drawing arcs from cause variables to their immediate effects. Researchers are developing customized techniques, tailored for a particular network topologies or inference queries, for impracticable inference methods applications (Smith, 1989; Heckerman and Wellman, 1995).

A BN that incorporates decision nodes (nodes indicating actions that can be performed) and value nodes (nodes indicating the values of various outcomes) is called an *influence diagram*, a concept invented by Howard and Matheson (1979,1981). According to Oliver (1986), Barlow et al., (1986) and Smith (1988), influence diagrams are also a very natural representation of useful Bayesian models (Smith, 1989; Eleye-Datubo et al., 2006; Zhou et al., 2013). They make the graphs somewhat more helpful for exploring the consequences of a DM stated beliefs in the form of dependency knowledge (Howard and

Matheson, 1981; Pearl, 1982, 1985, 1986, 1988; Shachter, 1985, 1988; Smith, 1987; Pearl and Venna, 1987). The validity of graphical manipulations such as arc reversal and node removal can now be affirmed on solid theoretical foundations. A stratified protocol of a dependency knowledge model is well explained in (Verma and Pearl, 2013).

The use of Bayesian networks and decision theory has proven to be better than the Dempster-Shafer theory of belief (Shafer 1976). A BN offer a convenient way to compute multitude of problem so as to arrive at a conclusion that is not warranted logically but probabilistically. Furthermore, a BN allow the computation of these problems without the traditional hurdles of specifying a set of numbers that grows exponentially with the complexity of the model. The major drawback a BN is the time of evaluation (exponential time for the general case). However, because a large number of people are now using BN, there is a great deal of research on efficient exact solution methods as well as a variety of approximation schemes (Daly et al., 2011).

Owing to various risk factors of uncertainty in CMOs, a BN support causal inference in situations where data for analysis has a high level of uncertainty. A BN has the capacity of integrating prior knowledge and sample data, capable of replicating the essential features of plausible reasoning in a consistent, efficient and mathematically sound way under a dynamic environments. In recent years, relatively few researchers have adopted a BN approach for risk management in large engineering projects (Ordonez, 2007). The emergence of new algorithms for BN have attracted increasing attention (Eleye-Datubo et al,. 2006; Lauritzen and Spiegelhalter, 1988; Zhang et al., 2004), making it more effective and essential guarantee in the plausibility for application (Zhang et al., 2013). BN has several advantages:

- It has the ability to incorporate new observations in the network and to predict the influence of possible future observations onto the results obtained (Heckerman and Breese, 1996).
- It can let users observe the relationships among variables easily and also give an understandable semantic interpretation to all the parameters in a BN (Myllymaki, 2005). This allows users to construct a BN directly using domain expert knowledge.
- It has both causal and probabilistic semantics, and thus it provides an ideal representation scheme for combining prior knowledge (which often comes in causal form) and data.
- It can handle missing and/or incomplete data. This is because the model has the ability to learn the relationships among its nodes and encodes dependencies among all variables (Heckerman, 1997).
- It can conduct inference inversely.
- According to Bobbio et al. (2001), it can perform a forward or predictive investigative analysis as well as backward or diagnostic analysis of factors being influenced, given a certain event in an overall risk analysis (Cai et al., 2013)

Maritime accidents in offshore oil industries can lead to devastating consequences, and this can be analysed using a BN to identify the most important indicators, and to determine the relationships among these indicators (Li et al., 2014). The application of a BN for offshore risk assessment have its difficulties (Ren et al., 2008) e.g. how to deal with incomplete and vague information that largely exists both at the early system design stage and during normal operations. However, this weakness can be overcome by the quantitative calculation with a BN where the hierarchy of nodes and states are defined (Wang, 2002; Sii et al., 2002; Ren et al., 2005, 2008; Wang et al., 2013).

More recent studies have focused on the integration of BNs with other proven risk assessment techniques. It has proven to be a powerful formalism to express complex dependencies among random variables and has been applied to a variety of real-world problems. A BN has been combined with Reasons Swiss cheese Model, ET and FT, Bow-ties (BT), Logistic regression, Human Factors Analysis and Classification System (HFACS), FST, Dynamic Event Tree (DET), pseudo-fault tree (Uusitalo, 2007; Eleye-Datubo et al., 2008; Kjaerulff and Madsen, 2008; Ren et al., 2008; Wang et al., 2011; Gran et al., 2012; Cai et al., 2013; Feng et al., 2014). The combination of a BN and other risk assessment techniques has provided a dynamic systems and a promising technique in knowledge fusion, but yet remains a challenging research topic. Kuikka et al. (1999), Bobbio et al. (2001), Vinnem et al. (2006, 2012), Montani et al. (2008), Badreddine and Ben Amor. (2010), Wang et al. (2011), Zhou et al. (2011), Gran et al. (2012), and Khakzad et al. (2013) demonstrated the effectiveness of combining a BN with other techniques. According to Feng et al. (2014), an effective method for combining BNs should meet three important criteria; (a) avoiding cycles (b) preserving conditional independences and (c) preserving the characteristics of the individual BN parameters (Feng et al., 2014).

A BN is also a good tool for expert elicitation (Uusitalo, 2007). Unlike the traditional rule based approach to expert systems, expert knowledge can be combined with the unique intuitive visual representation of BN to replicate the essential features of reasoning under conditions of uncertainty. This provides a consistent, efficient, and mathematical basis in Bayesian probability. Expert elicitation combined with uncertain knowledge can add substantial insight to many real-life problems, communicating theories and results to decision makers (Uusitalo, 2007). While the development of BN methodology is still ongoing, not all algorithm that has been proposed is likely to establish a standard method for analysing problems dominated by uncertainty (Gran et al., 2012).

The reason for focusing on operational resilience is, the trends of hazards on existing operational installations in the oil industries, in the last few years has been constantly increasing. Thus a robust initiative is needed to upturn these trends. Perhaps the greatest testament of a simple BN provides new developments in computational probability and decision theory. A good reference work for the computational method underlying the implementation are described in Jensen et al. (1994), Kadie et al. (2001), and Netica, (2002) perceived to address BN shortcomings. Building models forces us to think clearly about the subject, and articulate that thinking in the form of the model. Since most real-life problems involve inherently uncertain relationships, BN is a technology with huge potential and applicable for building resilient models for marine and offshore operations.

Bayesian Inference Mechanism

Bayesian inference provides the basic tool for both Bayesian belief updating and for treating probability as logic i.e. the concept of conditional independence, d-separation and the pattern of inference (Wellman and Henrion, 1993; Lauritzen and Spiegelhalter, 1988; Pearl, 1988) . It is a process where an observable real-world situations are used to update the random uncertainty about one or more variables and thus defines the manner in which uncertainties ought to change in light of newly made observations. Bayesian inference depends on the use of *Bayess theorem* (Bayes, 1763) as its rule of inference. Bayes Theorem also referred to as Bayes rule is the fundamental rule of probability computations (Zhou et al., 2011). According to Zhou et al. (2011), computation using Bayes rule can be achieved using Eq (2.3)

$$P(R|E) = \frac{P(E|R).P(R)}{P(B)} \tag{2.3}$$

Where:

$P(R)$ = is the prior probability of (A)

$P(B)$ = is the prior or marginal (total)probability of B

$P(R|E)$ = is the posterior probability of A, given B, and

$P(E|R)$ = is likelihood function for A, for a specific value of B

The Eq (2.3) can be paraphrased as:

$$\text{Posterior } = \frac{likelihood \times prior}{evidence} \rightarrow P(R|E) \tag{2.4}$$

The process of Bayess theorem develops into a recurrent concept when an additional information or events become available. Therefore, the posterior probability of R for an event E with states $\{e_1, \ldots, e_m\}$ in the same universe, can be computed from the Bayess rule as;

$$P(R|e_1, \ldots, e_m) = \frac{P(e_1, \ldots, e_m).P(R)}{P(e_1, \ldots, e_m)} \tag{2.5}$$

According to Lindley (1970) *"today's posterior probability is tomorrow's prior"*. Thus, an increase in the number of evidence result to a prior decrease on the original estimated dependence of the posterior probability (Eleye-Datubo et al., 2006).

Flow of Information in Causal Networks: Serial Connections, Diverging Connections and Converging Connections

A causal network, intuitively speaking is a BN with the added property that the parents of each node are its direct causes. A BN represent causal information, with the arcs representing direct causal influences. According to recent work put forward on the generalisations of BNs by Richardson and Spirtes (2002) and Zhang (2008), it is worth noting that, a BNs is seen by many as the best way to represent uncertain causal knowledge (Pearl, 2011). For example, fire → smoke is a causal network whereas smoke → fire is not, even though both variables are equally capable of representing any joint distribution on the two variables.

There has been much debate over the use of causal networks and their application (Druzdzel and Simon, 1993). Many studies such as Acid and de Campos (1995) and Acid et al. (2001) have assumed wrongly that BNs and causal Bayesian networks are equivalent. Literature review on learning causal networks has focused on constraint-based algorithms, building on work from Glymour et al. (1986), Spirtes et al. (1989, 1990), Geiger et al. (1990), Pearl and Verma (1991), Spirtes and Glymour (1990a, 1991) and Verma and Pearl (1991, 1992). Heckerman (1995a, 2007) however focused on learning causal structures from a score and search perspective, particularly within a Bayesian framework. The two most relevant studies on learning causal networks are probably those by Spirtes et al. (2000) and Pearl (2000) who expound their views on the possibilities of BNs having the ability to capture causal information. There are three different kinds of causal networks in a DAG, as shown in 2.14;

Serial Connections: Information may flow through a serial connection (X → Y → Z) with or without hard evidence on the middle variable (Y). Evidence may be transmitted through a serial connection if we do not know the state of Y for sure, but when there is a hard evidence on Y, the flow of information between X and Z are independent. Soft evidence (unreliable information) on the middle variable is not enough to block the flow of information over a serial connection.

Diverging Connections: Information may flow through a diverging connection (X ← Y → Z) when the state of the middle variable (Y) is known or unknown. For the later, provided that the information about X will influence our belief about Y, then Y is a possible explanation for X. The updated belief about the state of Y will make us update our belief about Z. For the former, provided that the state of Y is known for sure, the information about the state of either X or Z is not going to change our belief about the state of Y.

Converging Connections: Information may flow through a converging connection X → Y ← Z if evidence about the middle variable (Y) and one of its descendants is available. Information will not be transmitted via a converging connection if there is no

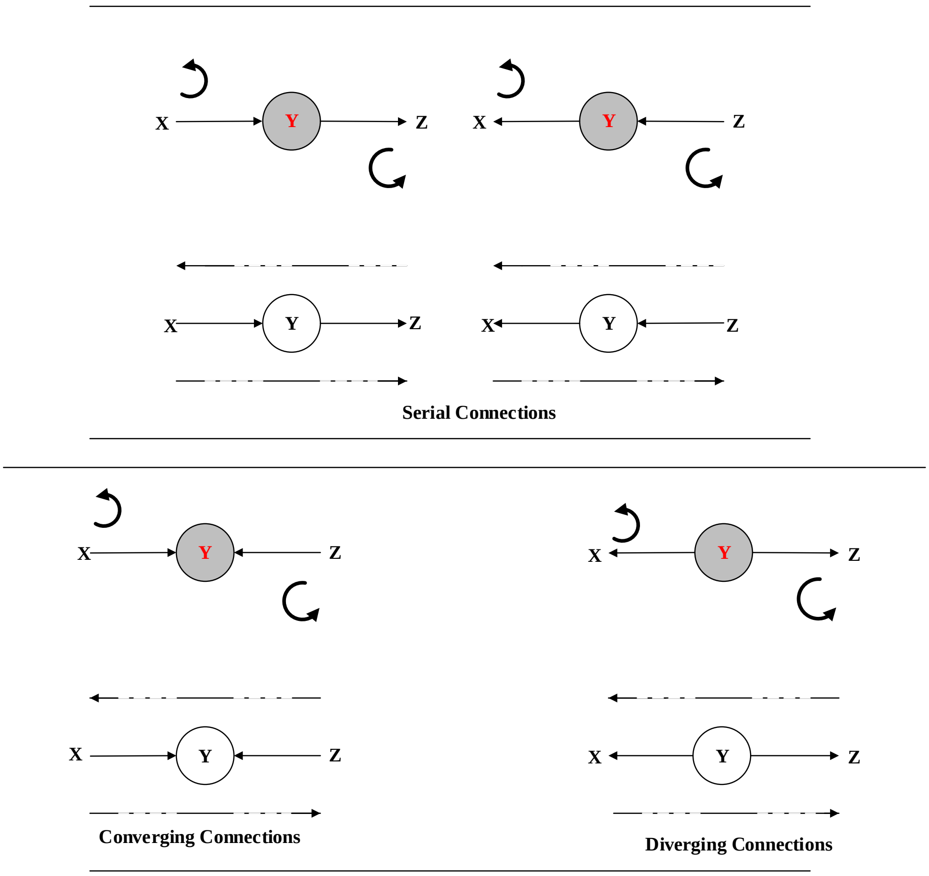


FIGURE 2.14: A diagram explaining the concepts of D-separation

evidence available for Y (Kjaerulff and Madsen, 2008).

Inter-causal Inference (Explaining Away): Explaining away is a property of a converging connections, where the information about the state of X or Z provides an explanation for an observed effect on Y, and hence confirms or dismisses X and Z (Kjaerulff and Madsen, 2008).

Constructing a BN for Risk Analysis: Application and Challenges

The objective of using a BN is to make the right decision depending on the corresponding marginal probabilities. In the context of risk assessment, logical reasoning of marginal probabilities could either be for risk prediction or diagnosis. For diagnosis, prior probabilities must be appropriately distributed, and the task of analysing the constructed network to obtain the marginal probabilities of the interested nodes will be calculated. For prediction, a risk variable in the same universe at random can present itself as a query or a piece of evidence, thereby permitting forward inferences. The query variable posterior probabilities provide the estimates of the casual effects of the evidence. The dissemination of the whole process yields a pre-posterior analysis (marginal distribution). The state of variable for a risk evidence is assumed to be known with certainty and is called an instantiation of the variable (Yang, 2006). According to Zaili (2006), in risk assessment, information variables are usually defined as risk causes. An effective way to identify these risk causes is to simulate an operational chain in the domain developed. Additionally, techniques such as HAZID, HAZOP, FMECA etc., also have great potential in addressing this kind of requirement. A BN has designated that random risk variables or nodes representing an uncertain quantity necessitate a finite number of possible states. The most popular states used to define the corresponding risk variables are developed based on the rate of event occurrence. Under the BN formalism and in order for them to be admissible, the variable states must satisfy the two criteria (1) the completeness of states, and (2) the mutually exclusivity of such states (Yang, 2006). States can be assigned to various variables according to their individual characteristics. A proposed BN for the assessment of hazards variables for OTOs can be described using safety degrees to facilitate the simplification and application of OTOs risk assessment. Consequently, two exclusive states, ”Yes” and ”No” uniformly define a risk-based nodes in a hazard-related BN . ”No denotes the probability of being safe and Yes” represents the probability of being unsafe. A criterion for computing the states of variables is by using the basic concept in Bayesian computation under uncertainty, the conditional probability distributions. The number of probability distribution required to populate a CPT in a BN grows exponentially with the number of parent nodes associated with the table. Some well-known methods on approaches to populate a CPT have been based on available data/information or using subjective expert judgements(Das et al., 2002; Wellman 1999; Druzdzel and Gaag, 1995; Takikawa and DAmbrosio, 1999; Pearl, 1988; Diez, 1993; Lemmer and Gossink, 2000; Riahi et al., 2012; Salleh et al., 2014). Normally to compute a CPT using a simple averaging scheme, some inconsistencies can arise when attempt to do so especially when its states consist of many sub-parameters which increases exponentially with the number of variables, and tends to make the results computationally intensive.

However, according to Heckerman (1995) and Kontkanen et al. (1997a), Dong and Agogino, (1997), Kahn et al. (1997) and Garbolino and Taroni (2002), the emergence of some software products from artificial intelligence research have been developed and applied to deal with the computational problems. A BN software provide a natural way to handle missing data. They syndicate data with domain knowledge, enable learning on causal relationships amongst variables, and provide a method to evade overfitting of data. According to Andersen et al. (1990) software's such as *Hugin* (Jensen, 1993), *Netica*, *SamIam*, *B-Course* , *Bayesian network toolkit by Microsoft*, *Ergo* and *GeNIe* can perform these computations.

The *Netica* (Netica, 2002) software is a widely used BN software package that provides an applicable programmer's interface (API) (Riahi et al., 2012, 2014; Salleh et al., 2014). The user has to define the model structure but the software provides

Expectation-Maximisation (EM) algorithm to support the execution of probability calculations (CPT). Heckerman (1995) and Wooldridge and Done (2004) further reveal the advantages of the EM algorithms. Netica software calculates the maximum likelihood estimates for all variables given the data and the model structure when inference is drawn. The general strategy of using Netica software for a BN model must be obeyed and can be given as follows:

- Initially, the nodes of BNs must be mapped out (enter evidence for some variables),
- Secondly, the states of the nodes must be defined (observe the effect of the evidence on other variables), and
- Thirdly, the probabilities of each state must be determined (explain the new probabilities).

According to Neil and Cabaliero (2007), the challenges in the use of BN are in three fundamental criteria; the discretisation of continuous variables (Uusitalo, 2007), collecting and structuring expert knowledge (Morgan and Henrion, 1990; Keith, 1996; Neil and Cabaliero, 2007), and having no support for feedback loops. Moreso, uncertainty and a superficial knowledge about a methodology may also lead to distrust towards a BNs, which easily leads to a reluctance for providing an estimate when structuring expert knowledge in large BNs."Estimating probabilities may also result in a biased outcomes" (Morgan and Henrion, 1990, pp. 130-131 as cited in (Uusitalo, 2007)).

Although BN has challenges as any other technique, the advantages of BNs cannot be ignored. In more realistic cases, the networks would consist of hundreds or thousands of nodes, and they might be evaluated many times as new information comes in, thus, changing the conditional probability of the nodes given the changing evidence. The complete distribution is specified by $2_n - 1$ joint probabilities, showing built-in independence assumption which relates to the causal interpretation of arcs (Uusitalo, 2007; Kjaerulff and Madsen, 2008).

A BN Modelling Concept and Hypothesis

The use of a BN model tailored for the resilience improvement of OTOs presents a more advanced technique to evaluate complex operational hazards or risk. This in turn optimises stochastic behaviours of subsequent operations on oil terminals, even after a major disruption.

The BN established for the purpose of resilience improvement is based on a presented modelling approach. It is composed of critical variables, categorised into four different groups by their function: (a) Decision nodes (b) Starting nodes (c) Intermediate nodes and (d) Target/goal nodes (Bayraktar and Hastak, 2009; Riahi et al., 2014). Decision nodes are nodes without parents. They are nodes that define the problem under consideration, and are dependent on the other nodes in the network. Meanwhile, starting nodes are input nodes; they are nodes with no parents and cannot be easily modified when modelling, although they are reflected in the child nodes through conditional probabilities. The intermediate nodes are the nodes that convey conditional probabilities, from the starting nodes to the target nodes. They have both parent and child nodes. Finally, the target nodes represent performance indicators, and they have parents and child nodes.

In the proposed BN, the developed hypotheses will ease computational complexities as well as create flexibility in the modelling process.

BN Processes

To assess the influence of each critical variable on accidents scenarios in OTOs under high uncertainty for resiliency, the use of BN as a model is proposed. The processes involved in the development of the BN model for decision support consist of two major steps; identification of critical variables and their causal network, and the quantification of the significant interrelationship among critical variables.

Section 4.3 highlighted preliminary questions and problems on how a holistic approach can be used to enhance the ability to process large volumes of data in real-time situations. The dependency of critical variables were not considered in the hierarchical relationship as referred to Tables 4.1, 4.2, 4.3, 4.4, and 4.5. To overcome this difficulty, Bayesian Network Sensitivity Analysis Method ($_{+}BN - SAM$) is presented using a bayesian reasoning mechanism to conduct the analysis. Transforming experts' opinions into subjective conditional probabilities in the BN model remains the prerequisite of this approach.

When considering a group of variables for evaluation, judgements on the relative importance of these variables should be considered to permit a quantitative interpretation among them. Based on this compromise, the methodology follows four major steps:

- Establish potential hazards of relative importance,
- Establish the BN model,
- Analyse the model,
- Model Validation.

Step 1: The formulation of the problem to capture what can go wrong and why this is a potential hazard with relative importance to OTOs and their potential consequences will provide inputs to what should be investigated and included in the model. A mapping process was adopted; transforming data from $UtiSch_{+}$ to establish the graphical representation of the BN.

Mapping algorithm : Bobbio et al. (2001), presented a method to map FT to BN and also show how inference can be later used to obtain the probability of the top event. Toledano et al. (2003) presented a method to map Reliability

Block Diagrams (RBD) to BNs such as Bobbio et al. (2001) method. Riahi et al. (2012) presented a novel approach to monitor the performance of seafarers; a mapping process was adopted in the evaluation of seafarers reliability. Zhou et al. (2011) provided a method to map a dynamic event tree to BN by utilising various exact and approximate inference algorithms. Mapping processes have provided a powerful formalism to express causal relationships among random variables in BNs, and have been applied to a variety of real-world problems as above mentioned.

Step 2: A directed acyclic graph comprising of nodes and arcs is established based on the identified hazard factors. In the presence of evidence, a conditional independence for a random variable associated to a node is specified but may not be complete and well represented. The representation of Joint Probability Distribution (JPD) of child node combination to its parent nodes will also be established. Ren et al. (2008) presented a functional component focusing on exploring and establishing a BN model on offshore safety assessment. Li et al. (2012) focused on establishing a BN model for maritime risk analysis where influence diagram was augmented with decision and utility nodes. Nordgard and Sands (2010) approach was in the engineering domain, where their focus was on risk analysis of MV air-insulated switch operation for electricity distribution companies. Alyami et al. (2014) prioritised establishing a BN model for container port risk evaluation. John et al. (2016) established a BN model for resilience improvement of a seaport systems.

Step 3: The Joint Probability Distribution (JPD) will be calculated in the CPT, it comprises of a conditional and unconditional probabilities. Calculating JPD is necessary in a BN because it is used to estimate and analyse how the probability of each node are affected by both prior and posterior knowledge. Different researchers have presented diverse techniques in analysing JPD over a set of random variable, which are uniquely defined by the product of the individual distributions of each random variable. Pearl (1988) and Diez (1993) established the Noisy-OR and Noisy-MAX model for JPD analysis. Ren et al. (2009) approach used a domain experts-dependant, where judgement was based on fuzzy probabilities and then refined by fuzzy membership function on offshore risk assessment. Riahi et al. (2012) synthesised the weight assigned to each parent node using Analytical Hierarchical process (AHP) with the symmetric model for seafarers reliability. Salleh et al. (2014) further justified this method when assessing operational reliability for linear shipping operator but then measured the unconditional probability using the if-then rule. Yang et al. (2008) presented the if-then rule-base Bayesian reasoning, which was used to estimate the conditional probabilities of failures in FMEA. Alyami et al. (2014) combined the if-then rule with expert judgement for

JPD analysis for container port safety evaluation. Li et al. (2012) used the binary logistic regression method to determine the JPD for maritime risk analysis. Fenton et al. (2007) used ranked variables (nodes) as mirror image for prior probabilities. John et al. (2016) combined the symmetric model and rule-base assessment based on linguistic terms to determine the JPD for seaport system resilience improvement. Each approach is either an expert opinion distributed by likelihood or relative importance of each parent nodes associated with their aligned child nodes.

Step 4: Sensitivity Analysis (SA) as a means of partial model validation provides a reasonable level of confidence on the result obtained. It allows changes in input variation of uncertainty updates in order to provide tested logical output of the model. Sensitivity on the other hand refers to the sensitive nature a model's performance on minor changes of input parameters. In the maritime domain, SA has been used for model validation to ensure consistency in tackling inaccuracies or incompleteness of parameters. Ren et al. (2008, 2009) used SA to validate safety assessment and FBN output result on offshore platforms. Salleh et al. (2014) used SA to calculate liner shipping operators reliability. Wang et al. (2011) demonstrated how a minor change on the BN output of Human and Organisational Factors (HOFs) could behave. Li et al. (2012) developed a SA for the BN result of maritime risk analysis with quantitative input. Cai et al. (2013) used SA for DBN modelling to provide a reasonable representation of an actual system for offshore blowout. Yang et al. (2008) established a SA of failure priority values between a shuttle tanker and a Floating, Production, Storage and Offloading (FPSO) system. Ugurlu et al. (2015) carried out a SA to minimise margin of error in the possibility values of event sets prominent in collision and grounding accidents of oil tankers. Alyami et al. (2014) analysed the reliability of the developed container port safety evaluation model using SA. Riahi et al. (2014) used SA to test the degree of belief associated with the reliability value of a seafarer. John et al. (2014a, 2014b, 2016) conducted a SA study of seaport operations, resilience strategies for seaport operations and BN approach to improve the resilience of seaport system, by increasing the weight of each criterion for the results.

2.5.6 Risk mitigation

After performing a risk assessment, it is required to reduce the risks associated with significant hazards that deserve attention (Wang, 2001; Wang and Foinikis, 2001; Wang, 2002). Risk mitigation or risk reduction can be defined as the systematic reduction on the extent of exposure to a risk and/or the likelihood of its occurrence. It involves a range of methods, e.g. Prospect Theory (PT), which may be used to reduce high-probability, high-impact type risks or both (Wang and Foinikis, 2001). To reduce risks to an ALARP level, risk control measures (RCMs) are evaluated (Wang, 2001). The hierarchical structures of RCMs according to Wang (2002) are:

- Elimination and minimization of hazards using safer design,
- Prevention,
- Detection,
- Control,
- Mitigation of consequences.

Reduction strategies are used for any level of risk where the remaining risk has high probability of impact and the strategies for risk reduction are (a) management (b) engineering and (c) operational. Managerial solutions involve development of a safety culture, while the key factor for their success is elective communication. Engineering solutions involve the design and/or construction to address hazards in the early stages of PHA (e.g. introduction of double hull in oil carriers). Operational solutions involve the development and introduction of appropriate procedures for carrying out 'risk-critical tasks, by establishing safety procedures, safe working practices, contingency plans and safety drills. This addresses human error risk factors and ensuring the existence of uniformity of the adopted safety standards (Wang and Foinikis, 2001). The lack of historical data on designs and the inability to carry-out a full-scale experimentation/replacement of a system/equipment during an operation poses the only limitation of an engineering solution.

Prospect Theory (PT); A Multiple Attribute Decision Making perspective for risk mitigation

Over the past few years, numerous studies attempting to handle multiple attribute assessment problems under uncertainty have been conducted to a considerable effect. Following the growing need to develop sound method and tools in this line of research, different approaches with rational, repeatable, reliable, and transparent characteristics have been developed. Multiple criteria decision making (MCDM) involves to structure and solve decision problems based on multiple criteria. Typically, solving these problems can be interpreted in different ways; it could correspond to the most preferred alternative of a decision maker involving different attributes (MADM) or choosing the best alternative from a set of conflicting gaols with the use of advanced computational techniques with objective functions (MODM)(Lai et al., 1994). Furthermore, Multiple Attribute Decision Making (MADM) techniques as a tool evaluate and select the preferred alternative from a predetermined number of alternatives, characterised by multiple attributes.

A survey on MCDM was conducted to identify its approaches and application. The survey suggested which MCDM techniques are most robustly and effectively usable to identify the best alternative (Aruldoss et al., 2013). The application of various decision making techniques to solve MCDM problems have been published in professional and academic journals of diversified discipline; including economics, airline performance evaluation, behavioural decision theory and software development and information systems (Jiang et al., 2011; Yang et al., 2011; Behzadian et al., 2012; Aruldoss et al., 2013).

To determining the best optimal solution for a decision making problem, an appropriate MADM method among numerous MADM/MCDM methods developed to solve real-world decision problems have to be considered. Each of the MADM has it uniqueness in determining a unique optimal alternative which clearly lead to more informed and better decisions. TOPSIS, VIKOR, AHP, ANP, ELECTRE, Grey theory, SMART, ER, DEA, AIRM and DAMATEL have all been employed to solve various decision problems based on the problem uniqueness (Belton, 1986; Watson and Bued, 1987; Saaty, 1987, 1990; Lai et al., 1994; Yoon and Hwang, 1995; Edward and Barron, 1994; Barron and Barrett, 1996; Triantaphyllou, 2000; Bolton and Stewart, 2002; Goodwin and Wright, 2004 as cited in (Yang and Xu, 2002; Chen and Chen, 2010; Yang et al., 2011; Behzadian et al., 2012; Büyüközkan and Çifçi, 2012; Aruldoss et al., 2013; John et al., 2014b; Tadić et al., 2014). Although these methods have their pros and cons, each method has partial or full involvement of the decision maker. Other MCDM techniques have been combined to tackle decision problems in different domain such as HSE, safety and risk management, energy management, resilience improvements, berth allocation, vessel selection, engineering design selection, operational planning and business/marketing management. The distribution by combined methods span across journals, year of publication, country and authors nationality. Recent trend of papers have moved towards applying a combined MCDM techniques rather than a stand-alone method. These tends to give a more representative and workable platform when dealing with real life and theoretical problems. According to Behzadian et al 2012, TOPSIS have been the most widely combined MCDM/MADM tool in recent time. The common techniques used to extend:

- TOPSIS technique are AHP, FST, ANP and Delphi methods,
- VIKOR method are AHP, ANP and ELECTRE,
- ER method are AHP, FST, ANP and DAMATEL and ,
- Grey theory is ELECTRE.

The combination of different MCDM/MADM tool also known as a hybrid approach assumes that problems with imprecise information can be handled more effectively. The identity of the hybrid approach clearly tackles the weaknesses in judgements taken away from the DM and MCDM/MADM methods.

Prospect Theory (PT)

Prospect theory is one of the famous element of behavioural economic, it was invented by two psychologist, Kahneman and Tversky (1979). PT describes how people form decisions about a prospect and a prospect is a gamble; people decision under uncertainty.

The theory states that people make decisions based on the potential value of losses and gains rather than the perspective of outcome, thus people evaluate these losses and gains using certain heuristics. Ongoing research by scholars have begun to focus on risks and uncertainties decision-making methods under a conditions in which the rational choice model is a standardised model (i.e. to solve a problem when management face the risk of selecting what decision is to be implemented), and applied it in a more convenient way. MADM method based on PT to solve decision making problem is becoming an aspiring idea in the maritime domain.

Von Neumann and Morgenstern (1953) developed a wealth Expected Utility Theory (EUT). The theory provided a mathematical axioms, however it encountered a lot of problems. The theory could not explain many of its visions and also, have a few basic axioms contrary to the experimental data. The resulting questions to the problems stimulated a number of other attempts to explain the risks under uncertain individual behavioural theories of development. PT was among the more outstanding one. Where a DM no longer consider decision-making issues from the perspective of final assets, but from a view point of winning or losing, caring much about gains and losses.

PT was based on the combination of a large number of empirical research in psychology, demonstrating a person's decision-making behaviour complexity to urgent needs, thereby analysing and guiding people behavioural decision. Peoples risk preference and decisions under risk and uncertainty are task independent, thus they present that PT is an alternative descriptive theory for DMs actual decision behaviour in making decisions under risk. They viewed decision making under risk as a choice between prospects or gambles. A prospect $(x_1, p_1; \ldots, ; x_n, p_n)$ is a pact that yields an outcome x_i with probability $p_i($ where $p_1 + p_2 + \ldots, p_n = 1)$ (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992; Kusev et al., 2009; Fan et al., 2013; Levy and Wiener, 2013). The application of prospect theory, particularly in applied research is still insufficient, yet the values are very large, and has a wide range of applications. PT has been applied in financial markets, insurance, industrial organisations, endowment effect and consumption-saving decision (Barberis, 2013) but the application scope is yet to be expanded. When people make decisions, they tend not to measure the true value of an item but to some it is relatively easy to evaluate clues to judge. However, there is some reason to believe that peoples choices about monetary gambles may not correspond with their preponderance for risk i.e. in situations where decisions regarding other kind of risks are considered.

Empirical evidence have shown that DMs treat probabilities non-linearly. Specifically, when DMs is making a risky decision, they tend to overweight small probabilities and underweight large probabilities (Gonzalez and Wu, 1999; Kusev et al., 2009). This results in risk seeking and risk aversion for both low probability gains and losses respectively, and however show a contrasting risk aversion for high probability gains and risk seeking for high probability losses. Given that there may be differences in DMs decision behaviour as a function of the type of risk they may be contemplating, there is a need to be sensitive to the different possible psychological types of risky decisions (Kusev et al., 2009).

Components of PT

To set the stage for the present development, four basic conclusions must be met for PT to provide a unified treatment of both risk and uncertainty (Gurevich et al., 2009; Barberis, 2013). A number of experiments have confirmed these findings (Kusev et al., 2009). In the face of risk and uncertainty, adopting PT for decision making needs to reflect the following components: 1) Reference dependence, 2) Loss aversion, 3) Diminishing sensitivity and, 4) Probability weighting.

1. *Reference dependence*: risk analysts derive outcomes from either gains or losses, measured relative to a reference point. In other words, rather than representing the status quo point from absolute wealth levels for gains and losses, risk analysts are more attuned to changes in current wealth from a reference point. Thus, it serves as an argument for the value function (VF) and, as such, is divided into two parts: the gain and loss domains, based on the reference point.

2. *Loss aversion*: refers to the tendency that risk analyst are much more sensitive to small losses than to gains of corresponding value when moving away from the reference point. Hence, the value function is steeper in the region of loss than in the gain domain. Some studies suggest that losses are as much as twice as psychologically powerful as gains.

3. *Diminishing sensitivity*: risk analysts have deferent psychological mirrors for gains and losses. They exhibit a risk-averse tendency over moderate probability gains and a risk-seeking tendency over losses. This element of PT is in accordance with diminishing sensitivity, where the value function is concave down in the region of gain and concave up (convex) in the loss domain. The impact of diminishing sensitivity creates a decrease in size of the marginal value for both gains and losses with changes in the reference point.

4. *Probability weighting*: risk analysts do not weight outcomes by their objective probabilities, but rather by transformed probabilities or decision weights. The decision weight are computed with the help of a weighting function, they are actual weight deemed fit for either gain or loss. Thus *"Probability weighting function"* (PWF) has an inverse-S-shaped: concave up for low probability and concave down for high probability. The principle of diminishing sensitivity also applies to PWF as well. It entails that the impact of a given change in probability diminishes with its distance from the boundary; two natural boundaries 1) certainty and 2) impossibility and this correspond to the endpoints of the certainty scale. For example, an increase of 0.1 in the probability of a positive prospect has more impact when it changes the probability of gain from 0.9 to 1.0 or 0 to 0.1, than to

when it changes in probability from 0.2 to 0.3 or 0.6 to 0.7. Therefore, diminishing sensitivity gives rise to a weighting function that is concave near 0 and convex near 1. Thus, this principle yields sub-additivity for very unlikely events and super-additivity near certainty for prospects under uncertainties.

The meaning of the first three components can be described by an asymmetric S-shaped PT value function as shown in Fig 2.15(a). For the purpose of understanding PWF proposed by Tversky and Kahneman (1992), Fig 2.15(b) shows a graph for gain or loss which corresponds to risk analyst transformed decision weight. Weighting function overweight low probabilities and underweight high probabilities. Fig 2.15 shows the graphical representation Of the VF and PWF.

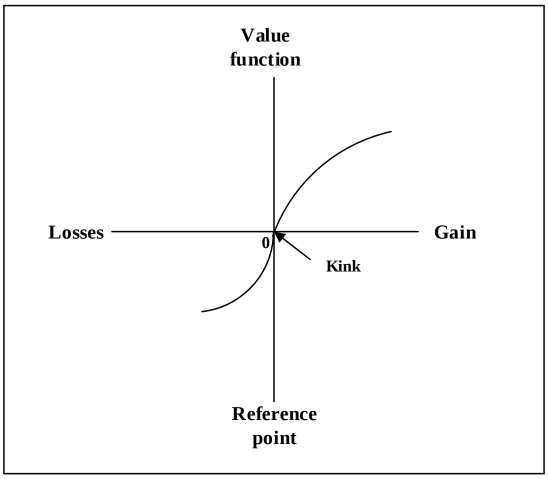
Features of PT

Framing effect: according to Kahneman and Tversky (1992), it is a rational theory of choice such that a risk analyst can give the same prospect to decision makers, but worded in different ways. That suggest a different reference point option, which often yield to systematically different preferences thus, eventually changes the DMs behaviour.

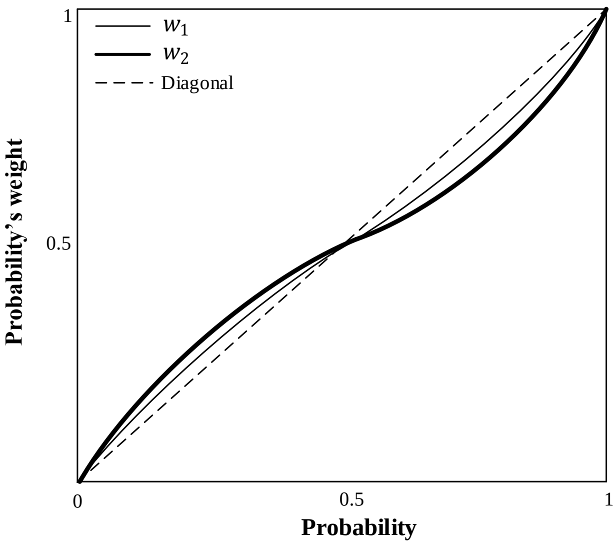
Reflection Effect: Kahneman and Tversky (1979) found in the reflection effect that, when a promising positive prospects for the same absolute value is reversed to be replaced by a negative, the selection between the positive prospects is a mirror relationship of the preference between negative prospects.

Isolation Effect: when risk analysts choose to simplify the choice between prospects, they tend to ignore all the common parts the prospects share, and focus on the components that distinguish them. This behavioural approach to choice problems may yield inconsistent preferences, because a pair of prospect can be interpreted in more than one way, and the different decomposition (i.e. common and distinctive components) sometimes leads to different preferences.

Prospect theory editing Heuristics: according to Kahneman and Tversky (1979) it consists of the preliminary analysis of the offered prospects. The function of editing is to organise and reformulate prospect options, which often produces a simpler representation of prospects, for subsequent evaluation and choice. The several operations applied to transform the outcomes and probabilities associated with the offered prospects are described as follows: (1) Coding: to identify outcomes as gains and losses depends on the reference point, however the location of the reference point can be affected by the originated offered prospects and the expectation of the risk analyst, (2) Combination: combining probabilities associated with identical outcomes, e.g. Prospect = (100,0.2;100,0.1;0,0.7) will be reduced to Prospect=(100,0.3;0,0.7), (3) Segregation: some prospects contain a riskless and risky components. Thus, separating out guaranteed outcome components, e.g.



(a)



(b)

Figure 2.15: Fig A represent the reference point curve of a prospect value and Fig B shows the probability weighting function (Kahneman and Tversky 1979)

Prospect = (100,0.2;200,0.8) will be reduced to a guaranteed gain of 100 and a risky prospect of (100, 0.8) or Prospect = 100 + (0,0.2;100,0.8), (4) Cancellation: discarding of components that are shared by the offered prospect. Thus, ignoring the common constituents to of both options and focusing on the difference, e.g. the choice between prospects (100,0.2; 50,0.5; 25,0.3) and (100,0.2; 40,0.4; 30,0.4) can be reduced by cancellation to prospects (50,0.5; 25,0.3) and (40,0.4; 30,0.4), (5) Simplification: discarding extremely unlikely outcomes by rounding the probabilities or outcomes, e.g. the prospect (100,0.49999; 201,0.2) is likely to be recorded as (100,0.5; 200,0.2), which can also be interpreted differently by risk analysts, and (6) Determination of dominance: to detect the dominated alternatives of the offered prospect, and then rejecting the dominated options with no further evaluation, e.g. between prospects (100,0.6; 50,0.4) and (60,0.6; 20,0.4), the final prospect will be (100,0.6; 50,0.4) with no further evaluation of the dominant prospect. Furthermore, there is no specific way of applying these editing heuristics, no insight on what order it has been applied. It depend on a scenario as long as it gets into the framing effects and the steps seems in line with what decision makers actually do.

Loss Effect: losses looms larger than gains (loss aversion) under both risk and uncertainty, thus risk-seeking choice often prefer a small probability of gains over the expected value of that prospect (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992). The observed asymmetry between gains and losses can be established when a risk analyst must make a choice between a prospect of a sure loss and a significant probability of a larger loss. It is far too extreme to be explained by certainty effects or by decreasing risk aversion.

Application of prospect theory

According to Barberis (2013), PT as a model for decision making under risk and uncertainty has been successfully applied in the areas of economics, decision making under risk, accident analysis and prevention, banking and finance, and transport research. Finance and insurance are the most areas where prospect theory has been actively applied in economics. In the field of finance, three main context are considered (1) a cross section of financial assets average returns, (2) aggregate stock market, and (3) trading of financial assets over time. Whereas in insurance, it has been most extensively applied on (1) property and casualty insurance, (2) morality insurance with the main product in life and annuities, and (3) health insurance.

In transportation research, a pricing model was proposed and PT was adopted for the determination of travellers reference point, to capture travellers response to pricing signals under risk (Xu et al., 2011). Zhou et al. (2014) applied PT to describe routes choice behaviour based on the travel time distribution of alternative routes and route choice shown on variable message signs (VMS). Gao et al. (2010) presented a model based on the cumulative prospect theory (CPT) to tackle travellers strategic behaviours when adapting to revealed traffic conditions en-route in a stochastic network, viewed as a choice problem under risk. Gurevich et al. (2009) presented a research to test CPT in the financial market; focusing on investors preferences using the conventional option analysis from US stock option data. Fan et al. (2013) proposed a method based on PT to solve MADM problem by calculating the three format attribute aspirations, to obtain overall prospect values in order to determine ranking of alternatives. Kusev et al. (2009) compared risks taken for precautionary decisions with those taken for equivalent monetary gambles using PT in five experiments.

The applications of CPT/PT discussed above are based on decision-making under risk, however, the insight of PT can be used in a more predictive way to nudge decision makers towards making choices that are viewed as more desirable. CPT/PT provide a quantitative meaning to DMs observed behaviours. The fundamental difficulty in applying PT for decision making is that, even if we accept that the carriers of utility are gains and losses, it is often unclear what a gain or loss represents in any given situation. Thus, this challenge provided a hypothesis (Kőszegi and Rabin, 2006). Additionally, further testing of the hypothesis is necessary for to the fact that it was based on finance rather than the gains and losses in risky decisions under high uncertainties. Otherwise it is unlikely to be completely true.

Critique of PT

The key difference between PT and CPT is where the subject decision weight are assigned to cumulative probabilities rather than the raw probabilities, otherwise CPT upholds the core values of PT. CPT was developed to improve on the lapses within PT, and it applies to both risky and uncertain prospect. Assuming that the PT value function is an S-shaped function with a convex segment steeper than its concave counterpart; provided a prospect does not violate first degree stochastic dominance (FSD) such that if prospect A dominates B by FSD, such dominance will be found also in the CPT framework. Thus, PT and CPT are not differentiated, we simply refer to PT as long as the transformation of initial probability to cumulative probability does not violate FSD. Wakker (2010) in his book "Prospect theory: for risk and ambiguity" pointed out a feature of PT largely discredited through its inbuilt violation of dominance, although clearly stated that this deficiency was rectified by CPT in Tversky and Kahneman in 1992 (Hey, 2011).

According to Nwogugu (2006), PT/CPT models are inaccurate and were derived from improper methodology and calculation. PT/CPT do not incorporate the many psychological, legal, biological, knowledge and situational price-dynamic factors inherent in decision making. Furthermore, prior work by Nwogugu (Nwogugu, 2005*a*,*b*) suggested that PT/CPT and Expected Utility Theory (EUT) are similar in concept, both based on probability-weighted or factor-weighted summations of possible outcomes. Thus, showing inherent flaws and invalidity due to weak theory, incorrectness in real-life conception and perception and/or being derived from a questionable method. For this reasons, PT/CPT and EUT do not explain many aspect of decision making and risk (Nwogugu, 2006).

First of all, as a somewhat popular and a descriptive model, PT/CPT has its advantages and disadvantage. It can deal with decision making under both risk and uncertainty, it has a scientific basis for several major effects in decision making and choice as well as allows for rank-dependant probability distortion to rely on prospective gains or losses. The major disadvantage is how does PT/CPT tackles a prospect choice where in a realistic case both positive and negative outcomes are possible. Second, the application of prospect theory, particularly in applied research is still insufficient, therefore PT and its value is very large, with a wide range of applications. So the application scope has yet to be expanded. Lastly, even after more than 30 years of its existence as a decision model for both risk and uncertainty, PT is still widely considered as the best available description of how subjects evaluate risk. The authors Kahneman and Tversky (1979, 1992) have contributed immensely, and this decisively awarded their efforts with a Nobel Prize in economic science (2002).

2.5.7 Existing Hazards in oil terminals and OTOs

In the past decades, researches has been undertaken in the maritime industry ranging from dry dock, sea ports and offshore terminals, maritime transportation, oil and gas pipelines, maritime critical infrastructures, ship safety assessment, ship navigation, tank farms, exclusive container terminal, onshore platforms, maritime security etc. but there is a common threat which has been a stigma in such different research areas. This stigma termed "hazard" has cut across all aspect of the maritime industry, and researchers are still examining the RM model that will best reduce risk to ALARP for specific critical systems.

A literature review on oil terminals and OTOs has been conducted and some major hazards in such terminals and operations were discussed. A generic oil terminal and OTOs hazards can be categorised into (a) Man related hazard (b) Machine related hazard (c) Communication and Correspondence related hazards (d) Management related hazards and (e) Nature related hazards. Fig 2.16 represents a generic environment of operators in an oil terminal.

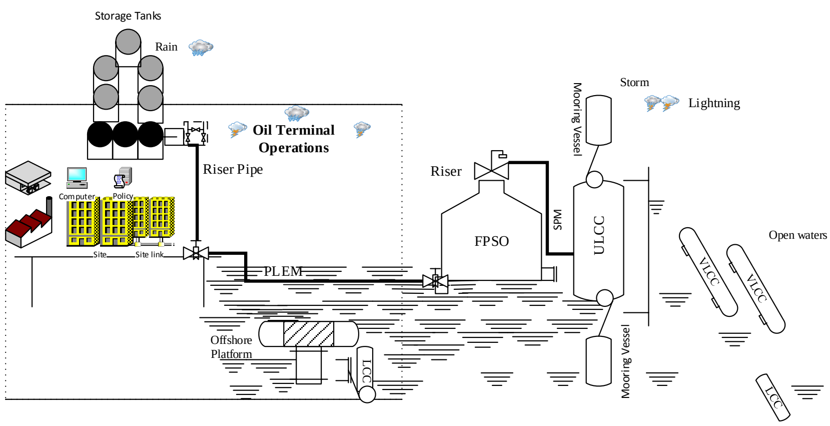


FIGURE 2.16: A generic environment for OTOs

Man-related Hazards

Human error contributed to the causal chain of accidents in the maritime domain. It may be of various origins and part of larger organisational processes that encourage unsafe acts, which ultimately produce system failures (Skogdalen and Vinnem, 2011). The combination of demand characteristics in the maritime industry such as fatigue, stress, work pressure, communication, environmental factors, and long periods of time away from home, are potential contributors to human errors (Hetherington et al., 2006). Rothblum (2000) stated in his research that human induced activities caused economic loss and harm to people (Ren et al., 2008). Data from New Zealand, Taiwan, USCG report and Dutch Shipping Council cited human factors as a cause of shipping accident as shown in Fig 2.17. The UK Marine Accident Investigation Branch (MAIB, 2000) stated that human error is one factor that still dominates the majority of maritime accidents (Hetherington et al., 2006). Furthermore in the maritime domain for the past two decades, 16% of all the accidents that occurred in port cited human factor as the main cause as listed in the Major Hazard Incident Data Service (MHIDAS) (Darbra and Casal, 2004). Amongst the vast consequences related to human error at offshore/onshore platforms includes, fire and explosions, collisions, groundings, and tankers accidents (Ren et al., 2008). 'Human factor' and 'human error' are used interchangeably (Skogdalen and Vinnem, 2011), but they are all underlying causes of accidents. While human factors are the interaction between man and his workstation (e.g. machine, infrastructures etc.), human error on the other hand is the failure of planned operations due to unforeseeable events. In seaport and terminals, pilots, ship's officers and crew and shore personnel's errors were mentioned as the main categories of human errors contributing to major marine loss (Mokhtari et al., 2012) as shown in Fig 2.18. Database has considered seven different categories to designate the place or activity in which accident occurred, this includes (1) process plants (2) storage (3) transport (4) loading/offloading and (5) domestic/commercial and warehouse waste (Darbra and Casal, 2004).

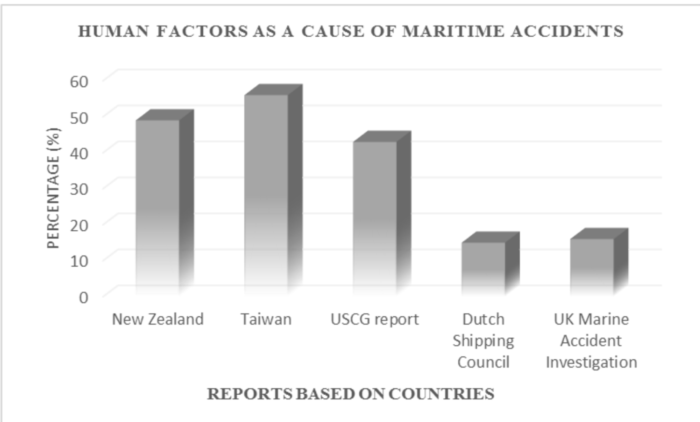


Figure 2.17: Human factors contribution to accidents in the marine domain as cited in (Darbra and Casal, 2004; Hetherington et al., 2006)

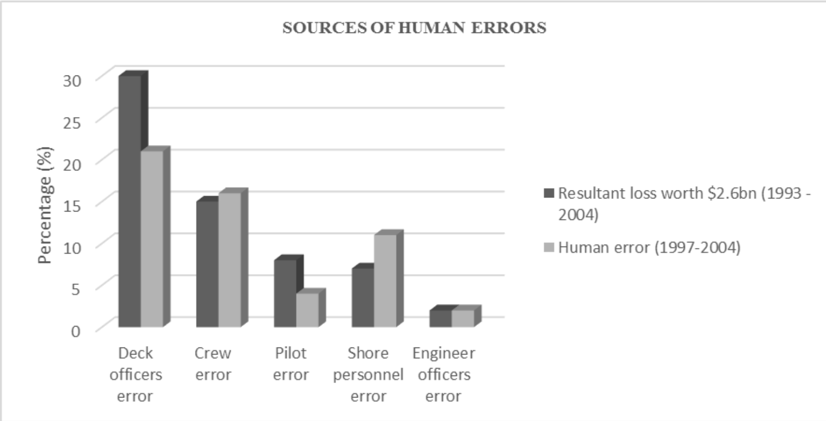


FIGURE 2.18: Cited human errors leading to accidents in the marine domain as cited in (Mokhtari et al., 2012; Lu and Shang, 2005)

Machine-related Hazards

Due to the complexity of operating equipment, operators cannot overlook highly dangerous processes (Shang and Tseng, 2010). As a part of the marine services, dredging and maintenance of port infrastructures, navigational aids, IT and equipment are among the main ”technical factors” and lack of maintenance could contribute towards operational risk (Mokhtari et al., 2012). MHIDAS database records that 14% of accidents occurred in hoses during (un)loading operations at oil terminals and this was purely due to mechanical failure (Darbra and Casal, 2004). The inappropriate use of machine also contributes to technical risk factor resulting to total system failure. Accident due to over reliance of technology as resulted to incident causing 1000 reported injuries and costing the company $7 million (Hetherington et al., 2006). More so, technical risk factor was responsible for a collision risk between Floating, Production, Storage, and Offloading (FPSO) and a shuttle tanker during tandem offloading operation (Yang et al., 2008). Oil release, pool fire, spills, rupture and jet fire radiation could be the consequences of such risk factor during OTOs. According to Alderton (2008), absence of preventive and running maintenance, lack of qualified maintenance personnel, lack of adequate stocks of spare parts and insufficient standardisation of equipment types are reasons for the high proportion of equipment being out of service. The aforementioned risk factors have been identified in previous literatures using the HAZID processes within the risk management framework (Mokhtari et al., 2012).

Coordination and Correspondence-related Hazards

The consequent increase in the transportation of hazardous products is directly related to the increase in port activities thus the frequency of accidents in port is increasing. The ability of an individual to possess mental model to use information from the environment to predict possible future states and events, in order to reduce surprise reflects an adaptation to a potentially critical situation. Between 1987 -2000, 71% of all human error types on maritime accidents were due to communication problem during maritime operations from eight countries (Grech et al., 2002). Lack of communication was responsible for 42% of the 273 incidents reported by the Canadian Transportation and Safety Board (CTSB) while carrying out a mooring operation and navigation. Hetherington et al. (2006) suggested that language problems was the main factor due to misunderstanding and as such communication issues can often result in error leading to accidents. Research on safety operations for ECT at Kaohsiung port in Taiwan identified that the leading factor influencing risk frequency is "communication misunderstanding" (Ding and Tseng, 2012). Mearns et al. (2003) conducted a safety climate surveys on oil and gas installations and communication about health and safety was part of her survey, she argued that addressing the adequacy of communication between two subsets e.g. operator and ship interface on shared activities establishes key accountabilities and responsibilities for preliminary hazard identification.

Management-related Hazards

Research effort has been aimed to reveal, isolate and measure/predict human and organizational factors and their influence on risk (Skogdalen and Vinnem, 2011) and during the past decade, industries and organizations have long measured safety and organizational performance in safety-critical systems, tracking accidents, near misses, lost time, resources, and personnel. Organizational factors are characterized by the division of tasks, design of job positions and selection, training and cultural indoctrination, and coordination to accomplish the activities. Organizational safety factors such as hiring quality personnel, safety orientation, promotion of safety, formal learning system, rewarding safety, and multicultural operations, were all identified by domain experts as having a significant link to safety performance (Grabowski et al., 2010). Organisational error has resulted to a sub-sea gas blow-out i.e. the Snorre Alpha in the Norwegian sector of the North sea in 2004 and what contributed to the accident were failure to follow steering documentation, lack of appreciation and execution of risk assessments, inadequate management involvement and requirements for well barriers not fulfilled (Brattbakk et al., 2004). According to Rothblum (2000), about 75 -96% of marine losses are partly or fully caused by organisational and human error (Ren et al., 2008). Previous reviews have demonstrated that these factors are seen as a cause of major accidents, therefore the need to analyse organizational factors in a more structured way is necessary in safety critical systems.

Nature-related Hazards

Limited research has been carried out on the above risk factor but the majority of research refer to it as "Environmental or safety" risk categories (Ronza et al., 2006; Mokhtari et al., 2012; Skogdalen and Vinnem, 2012). Environmental risk categories attributes 4% to causes of accidents at sea (Trbojevic and Carr, 2000) with extreme weather, winds exceeding port criteria, strong currents, visibility, earthquake, rain/snow and wind direction as specific hazards on operations (Trbojevic and Carr, 2000; Merrick and Van Dorp, 2006; Ronza et al., 2006; Skogdalen and Vinnem, 2012). The Bunga Alpinia disaster (2012) caused severe explosion after apparently being struck by lightning, three deaths were recorded. The New York harbour oil terminal disaster (2012) which damaged infrastructures and the environment due to hurricane Sandy, caused loss of life with high consequences. Mansouri et al. (2010) provides basic natural risk factors, they include hydrologic, geologic, seismic, and atmospheric hazards. They influence a system on a random basis and only little information is known about their occurrence.

The consequences of such risk factors led to economic loss to the operators of such terminals and as such, the challenges of these risks are so enormous that it requires flexible yet robust risk analysis methods in order to tackle their unpredictable outcomes. The key questions in this line of research can be summarized as (1) what are the significant factors that affect risk in OTOs? (2) How do these factors influence risk in OTOs? (3) How much do they contribute to risk in OTOs?

2.6 A Resilience Engineering (RE) Literature Review Relevant to OTOs

There are different definitions of resilience in a resilience engineering context (Madni and Jackson, 2009; Mansouri et al., 2010; Steen and Aven, 2011; Dinh et al., 2012). Most researchers capture more or less the same ideas but a generalised definition of resilience by Wreathall (2006) comes into context in this research; s/he defines resilience as managements ability to recognise, adapt or recover a system rapidly to a stable condition, enabling it to continue its activities during and after a major accident rather than prevent incidents from occurring. In the context of a Port Infrastructure System (PIS), resilience can be defined as a function of systems vulnerability against potential disruption with adaptive capacity of recovering from the face of major shocks within a reasonable timeframe after a major accident (Mansouri et al., 2010). Therefore, resilience as an additional safety measure is needed in complex operational designs (Dinh et al., 2012). In response to any disruptions of various levels of intensity, resilience alongside robustness, flexibility, adaptability, and agility is amongst the strategies that might be adopted and utilised by maritime complex systems. Fig 2.19 shows the nature of resilience modelled in an operational environment.

Adaptability: is the ability to adjust through reconfiguration to cope with unforeseen situation in a dynamic and unpredictable environment. Complex dynamic operational systems need to be tolerant of uncertainty. To achieve adaptability, modelling dynamic operations with adequate safety margins to account for uncertainty and experimenting with alternative operational design to understand the operational impact of various alternative (Madni and Jackson, 2009; Neches and Madni, 2013). Adaptation

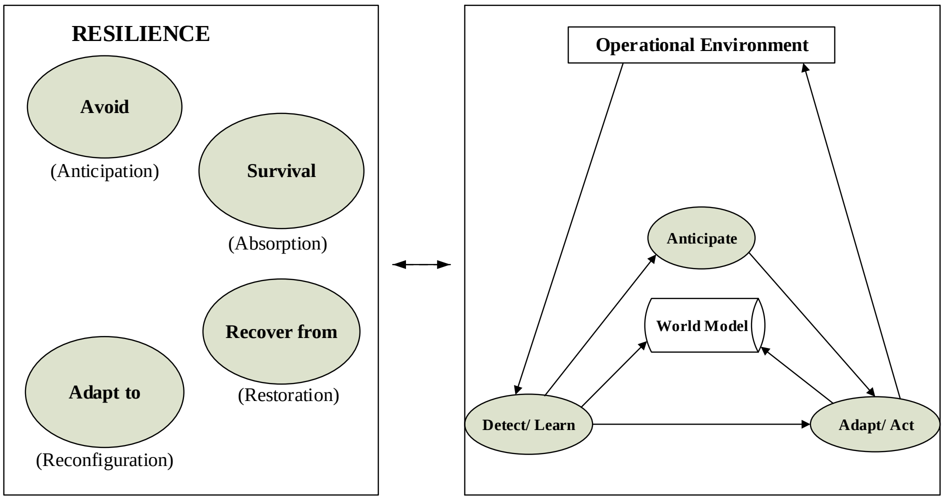


FIGURE 2.19: Many faces of resilience and its system vision, as adapted in Madni and Jackson (2009)

to uncertainty is one of the vital tests of a resilient system (Abech et al., 2006),thus a resilient oil terminal operations should have the capability to adapt and withstand external or internal disruption of unknown magnitude.

Avoidance: is a quality exhibited by a resilient system to anticipate failure without having to wait for serious accidents to occur. Avoidance goes beyond traditional safety system in that it is enabled by predictive capabilities or the ability to preview outcomes and take proactive action on occurrence or consequences of disrupting events (Madni and Jackson, 2009).

Survival: survivability arises from the combination of robustness and adaptability. It is the ability of a critical dynamic system to resist destruction or incapacitation during and after disruptive events. For a critical dynamic system to survive, shock absorbers for example, resource buffers capable of responsiveness within which the system is developed, designed, deployed, operated and maintained (Abech et al., 2006; Madni and Jackson, 2009; Neches and Madni, 2013). Models with representational richness, learning about operational context and uncertainty could help reimburse the survival of critical dynamic operational systems.

Recovery: is the ability of a critical dynamic systems pre-disruption to be restored to as closely as possible to cope with current condition (Madni and Jackson, 2009). Recovery is also the ability of operators to create a new plan or retract and switch to the correct plan at the early stage of responses to disruption (Kontogiannis, 2011). Hence, to advance safety within already ultra-safe system, it is important to focus on strengthening models to provide a good basis for detecting and repairing systems, and its operation to be responsive to the constraints of uncertainty.

Different research reviews have stated that, for a system or an organisation to be resilient enough, it must have the following qualities: the ability to:

- Respond to regular and irregular threats in a robust, yet flexible manner,
- Monitor what is going on, including its own performance,
- Anticipate risks (risk events) and opportunities, and
- Learn from experience.

In the past, operational systems were primarily designed to be effective, but now they also need to be resilient. Due to the current economic competition mechanisms, resilience seems to be a strategic concept dealing with the improvement of safety in complex dynamic systems, since it could reconcile the notions of performance and safety rather than systematically oppose them (Morel et al., 2009).

Resilience Engineering (RE) is about increasing the ability of organisation to make proper adjustment to the current system of operations in such a way that they anticipate adverse events and act in a proactive manner. RE explores ways that enhance organisations ability to be robust and flexible to cope for the unexpected (Hansson et al., 2009). Conventional risk assessment ordinarily treats a small number of possible scenario taken into account as a moment in time, but in the past few years, new ideas such as RE have been suggested to improve and keep safety, have started a revolution in the safety of complex systems (Shirali et al., 2012). Although many efforts have been focused on finding solutions to prevent incidents in major hazardous operations, incidents still occur because of various technical, human factors and random natural events. It seems the unexpected hazards, not being absorbed by the system are leading to catastrophes and this hazards are unavoidable even under good risk management; this seems to be true especially with the more complex systems (Dinh et al., 2012). It has become quite evident that complex systems development invariably demands both high productivity and ultra-high safety levels. It is this recognition that has stimulated the noticeable rise in interest in RE (Madni and Jackson, 2009). According to Hollnagel (2007), RE represents an alternative to conventional risk management approaches which are based on hindsight knowledge, failure reporting and risk assessments, calculating historical data-based probabilities. Furthermore RE consider conventional risk assessment methods to be inadequate for the present day systems (Steen and Aven, 2011; Dinh et al., 2012).

Amongst the different diversities of RE objectives is the ability to anticipate incident that have not yet happen. RE views "failure" as inability of critical dynamic systems to be resilience, rather than a breakdown or malfunction. Thus a key component of RE is robustness in decision aiding system and operating procedures. It helps operators to adapt to work methods as well as limiting the spread of risk factors under extreme natural and man-made hazards (Kontogiannis, 2011). Robustness is a key operational property in RE, that is related to operation failure resistance. The robustness of an operation is influenced by the combination of two factors: (1) structural redundancy and, (2) integrity. These two factors must be quantified to express robustness in a meaningful and measurable manner. The assessment of operational robustness requires a realistic and efficient simulation of operational behaviour under various local failure scenarios, using advanced and experimentally validated modelling methodologies to examine operational system performance.

Flexibility is the ability of a plan to cope with variations and to allow adjustments to the lay-out of the plan (Taneja et al., 2012). Flexibility is a strategy for dealing with uncertainties, thus an operation is flexible if output variation can operate and stay within the desired range under unexpected disruption. Flexibility is considered amongst the attributes of resilience (Dinh et al., 2012). It is required that the design of complex dynamic system, is operated in such a manner that it can exhibit robustness; to respond to less powerful operational and financial fluctuations to show resilience in the face of major shocks and substantial disturbances, that can pause its operating processes either temporarily or for a long period of time (Mansouri et al., 2010; Taneja et al., 2012). Tanja et al. (2012) suggested the following strategies in order to cope with uncertainties: (1) spacious marine layout: terminal areas with sufficient depth and length, (2) long quays to improve the flexibility of operations and vessel berthing; flexibility with regard to allocating terminal concessions and the possibility to extend quays and terminals when necessary without serious constraints created by the need for disproportionately expensive construction, and (3) infrastructures designed in such a way that it can cope with technical changes of the superstructure, equipment etc.

2.7 Approaches on How to Measure Resilience

Performance criteria and metrics for evaluating resilience will enable the development of decision tools for planners and stakeholders to enhance the performance of operations during and after extreme events, thus reducing loss of life, injuries, and economic losses. The following are ways to measure resilience:

1) Vulnerability assessment using performance metrics for evaluating resilience (McManus et al., 2008): it contributes to increased situation awareness, promotes the development of adaptive capacity and gives the organisation something to work on such as using preparedness and criticality information for both response and recovery phase of a crisis.

2) Design and retrofit strategies for resilience: A resilience heuristics plan which rely on experience, judgement and intuition for which results can infrequently be quantified or verified (Madni and Jackson, 2009).

3) Risk-based assessment and decision methods for achieving resilience that are supported by a cost/benefit analysis and performance-based methods for codes, standards, and practices (Wang, 2002; Berle et al., 2011).

2.7.1 Performance Metrics for Vulnerability Assessment

The term vulnerability in the maritime domain is defined as the properties of a critical dynamic system that limits its ability to cope, handle and survive threats and disruptive events which may occur within and outside the system boundaries (Berle et al., 2011). Vulnerability is related to an 'internal weakness' in a system (England et al., 2008). There is considerable confusion over the use of the term vulnerability assessment and the modelling of vulnerability in the real world (McManus et al., 2008), but more emphases should be considered on critical dynamic systems with potentials to have significant negative impact in a crisis situation.

Vulnerability assessment requires investigation or quantification of hazards, focusing on all relevant failure modes. A performance metrics for vulnerability has been used by researchers to measure the effectiveness of resilience. McManus et al. (2008) developed vulnerability matrices for the assessment of vulnerability at an all hazards level to improving organisational resilience. Furthermore they also used susceptibility information to develop a context specific matrix and this was due to the fact that vulnerability should not be assessed across scales because processes causing system vulnerability are different among each scale. Ozyurt and Ergin (2010) developed a coastal vulnerability matrix, using the concept of Thierler and Hammer-klose (2000) and a coastal vulnerability index for the assessment of coastal vulnerability for decision making. The two researchers used parameters with the corresponding range values from very low vulnerability to very high vulnerability. Vulnerability matrix is similar in structure to traditional risk matrix. The challenge of measuring resilience for OTOs in real-world application is to determine the indicators and metrics that allow real-time monitoring of unforeseen events within critical dynamic systems, thereby allowing a continuous view of how vulnarable the system may be.

2.7.2 Resilience Heuristics

Heuristics are typically a function of the type of disruption, systems being monitored, and the resilience needed (Madni and Jackson, 2009). Developing a representative resilience heuristics needs experience, judgement and intuition, to enhance systems resilience to unforeseen events. Resilience heuristics should be verified or quantified by experts before being implemented. Resilience heuristics are more of a holistic method to measure resilience and could be done at the initial stage, for verification or quantification of a resilient system. Examples of parameters used in representative resilience heuristics design are; systems functional redundancy, human backup, predictability, reorganisation, neutral state, drift correction, intent awareness, etc.

2.8 Conclusion

Operational risk within a risk management system has been linked to the complexity and the dynamic performance of the system. Practically this can be described as "organisational acceptance" due to the fact that risk related factors may lead to the disruption of the systems. However, applying a holistic risk analysis to offshore installations could have some hurdles particularly in dealing with OTOs; where different hazardous materials such as petrol, kerosene and diesel are being transported. Important research questions to be asked are:

- What measures can be used to form a proper assessment framework and how are these measures inter-related to each other?

- What method will be used to collect empirical data from oil terminals? There is often inadequate data or imprecise information available when carrying out OTOs analysis. Although several maritime accident databases have been built up, the data contained in them are only marginal.

- How to develop a framework to support the developed model for OTOs RM. This is because offshore risk assessment must take all major risk related factors into account. When these factors are involve in OTOs, modelling becomes very complicated (e.g. exploring the relationships among OTOs needs a deep understanding of oil terminal safety issues, and may involve domain experts personal experiences that are difficult to be treated in a comprehensive way).

The benefits derived from the implementation of resilience in complex systems operations are: the ability to prepare for the unforeseen in such uncertain environment; ability of a system to avoid, adapt and recover in the face of adverse operational scenarios in order to maintain its functionality and to increase focus on proactivity. Finally, many of the cited papers in this literature review lack outcome measures that could assess the influence of risk related factors on OTOs, thus there is a gap to be filled on the assessment of these identified hazards/risks. Ronza et al. (2006) analysed tanker navigation through port waters using the QRA technique for the handling of hazardous materials in oil terminal such as petrol, kerosene, diesel oil, and fuel oil. The lack of literature on oil terminal operation has underscored the need for a new approach (a resilience model) for RM on OTOs.

Chapter 3

RESEARCH METHODOLOGY

Summary

This chapter describes the research methodologies and methods that are fundamental to the study. It identifies the research assumptions that directed the decisions about the research approach adopted. The aim of this study is to investigate the uncertainties in oil terminal operations in order to monitor, control or mitigate risk. Thus, a conceptual framework to enhance operations on ship/terminal interface for OTOs is essential. The development of a generic conceptual framework requires relevant knowledge to be extracted from experts with experience in the related field. After introducing the generic conceptual framework, this chapter will discuss the different research strategies, definition of key terms, types of research methodology and the choice of the most appropriate methodologies to be applied in this thesis.

3.1 Introduction

Research is an organised, systematic, data-based, critical, objective and scientific inquiry into a specific problem undertaken with the aim of finding answers to the research questions or solutions to the problem. In carrying out a piece of research, a choice has to be made between three alternative research methods, which are: qualitative, quantitative or both. The world is essentially knowable; it consists of knowledgeable facts, and, if we ask the right question in the right way, use the right research method and carry out the right kind of processes, we will discover the facts of truth. The role of a piece of research is to test theories and provide materials for the development of laws; thus, this chapter will concentrate on explaining how the research was conducted in order to achieve the research aim and objectives.

The researcher is an observer of common reality. In a similar vein, research methodology is an outline for the researcher's activity which specifies how the researcher intends to carry out the research plan in a methodical way. On the other hand, research methods are processes of data collection, data analysis and interpretation that a researcher performs during research work. A research method is connected to different types of research design/strategy. The data collection method applied in this thesis is mainly expert judgements, and is discussed briefly here and at length in the following chapters.

3.2 Description and Ideas Linked to Research Design

3.2.1 Research Methodology

The research methodology is a strategy, design and plan of action that shapes the choice and the use of specific methods to collect and analyse data as part of the research process (Glassman and Pinelli, 1985; Creswell, 2013). It is an activity blue print for the researcher, which specifies how the researcher intends to carryout research from the beginning to the end. The knowledge of the various methods and the procedures involved in each is important in establishing the justification of such techniques to both the researcher and those who consume the research (Soni and Kodali, 2012).

3.2.2 Research Techniques

Research varies in type but are common in the following categories: historical, descriptive and experimental depending on the advancement of knowledge about the research topic. As such, different techniques are required as tools to collect data and information and identify what is unknown, in a systematic and orderly approach. A technique expresses the reason behind using a method. Research techniques is a process that can be followed to gather data and analyse them to find a result (Tijjani, 2013).

3.2.3 Research Design

A research design can be described as the method formulated to seek and respond to research problems. The research design of this study uses multiple methods to generate and analyse different kinds of data. The distinctive research strategy was to select and synergistically integrate the best techniques from qualitative and quantitative methods to comprehensively solve the various aspects of the research problem. The research design proposes a 'concurrent transformative design' based on the ideology of conceptual framework, specific theoretical perspective, and is guided primarily by qualitative and quantitative data. Questionnaires and surveys, expert opinion and empirical study were used for data collection and research justification. This was based on the belief that *"no specific method is straightforward to solve a problem, because each method reveals different aspect of empirical realism"* (Denzin, 1978, p.28 cited in Abubakar, 2013). Therefore, using multiple theories, combining and collecting data qualitatively and quantitatively in a single research design counterbalances the weakness of one method with the strength of another (Tijjani, 2013).

3.3 Sampling Frame, Data Collection and Analysis

3.3.1 Sampling Frame

The oil industry is considered to be among the largest companies by gross revenue in oil-producing countries. Its primary business activities differ between regions and can include oil exploration, refining, commercial transportation and storage. Within the oil industry, there are differently-sized companies carrying out various activities ranging between small, medium and large scale. The activities on onshore/offshore oil terminal platforms are of importance to this research and respondents for this study were drawn from terminal operators and management.

Selecting a sample representation from all elements in the population allows the researcher to limit the amount of data he/she wishes to collect. Thus, sample selection is limited to certain criteria, depending on the type of research process (Soni and Kodali, 2012). The selection of respondents for data collection was based on specific crude oil-producing countries, where a large amounts of crude oil are being consumed/transported thereby leading to large import/export of these refined products, constitute the target population.

A simple random sampling of professionals and specialists with relative or vast experience on onshore/offshore oil terminal platform operation and management were identified and chosen as respondents. Consequently, the experts in this randomly chosen sample population are aware of the significance of the hazard factors with which they are involved. Their expertise within oil terminal platforms makes them the most suitable participants in this research. A simple random sampling was adopted in order to control bias (Tijjani, 2013). The research used publicly available directories (Lloyds register, CHIRP maritime), LinkedIn and recommended oil terminal professionals in selecting respondents from the appraised companies. Information such as respondent company name, e-mail address, telephone numbers, job position, postal address, and the product and/or services produced by the company were important.

The best way of obtaining basic information quickly and efficiently (Gonzálvez-Gallego et al., 2015)was to consult senior management officers, ship captains, HSE consultants, and academicians with industry experience on oil terminals and vessels. The convenience sampling method was used in this thesis. The sample size was five experts from various countries, as described in Chapters 4, 5 and 6. Hammitt and Zhang (2013) considered that a sample size of N expert (i)(where $i = 1, 2, 3, \ldots, N$) was necessary if the well-calibrated experts are of equal or unequal quality and their judgements are independent, positively or negatively dependent. The aim of having a wider generalisation of representatives as participants is of importance to this research.

3.3.2 Data Collection

The choice of data collection method should be based on the uncertainty of the data in line with the research question. The two prominent data collection methods are: primary data collection, which involves collecting fresh data, and secondary data collection, which entails concentrating on historical data. This thesis adopted primary data collection as the only method used to gather data and this method can be further categorised into qualitative and quantitative research methods.

Qualitative research is carried out when a researcher want to understand meaning, interpretations, ideas, beliefs and values, as well as describe and understand experience. It is a set of multiple practices where words in methodological and philosophical vocabularies attain different meanings in their use. This type of research aims to discover meanings for a problem or issue for an individual or group. As a result, the qualitative research method can be associated with personal experience with people, interview, observations, life history, interaction and visual text in the research setting. The data collection strategies when using this method involve the collection of evidence through document studies, interview studies, literature reviews, descriptive studies, case studies, experts' judgements, naturalistic inquiry and field group (Creswell, 2013; Qrunfleh and Tarafdar, 2014).

On the other hand, quantitative research methods are also referred to as empirical studies and/or statistical studies. Quantitative research is characterised by collection of numerical data, demonstrating the relationship between theory and research. Quantitative research strategies for data collection include: experimental studies, pre-test and post-test design, self-administered questionnaire, structured interview schedules and quasi-experimental studies. The subjects included when carrying out quantitative study are selected at random; this is to reduce error and to cancel bias. The qualitative method has its limitations, such that it is less systematic, it has a limited generalisation to broader groups of people, it results in barely replicable findings and it minimises the possibility of inferences beyond the data. The combination of qualitative and quantitative methods helps acquire credibility in the research field and provides a fairly regular basis as a distinctive research strategy (Tijjani, 2013).

An empirical approach with surveys, followed by a resilience improvement model and a structured case study was adopted. The purpose of empirical research is to verify already existing or newly proposed collected evidence about a piece of research on the basis of empirical data. More so, on the basis of these empirical data, one can postulate a newly proposed model (Singhal et al., 2011; Soni and Kodali, 2012). Empirical studies have both the qualitative and quantitative method. In this thesis, both methods were used to establish the relationship amongst hazard factors and this helps to refine the level of understanding of hazards that could lead to major disruption. Empirical study was conducted separately for Chapter 4, 5 and 6 respectively.

As discussed in Chapter 2, hazard factors associated with OTOs in the form of qualitative data were identified through HAZID, i.e. literature review. Saunders et al. (2007) emphasised the advantages of a literature review; it saves time since the information has already been collected, and it is less expensive than other methods. The data can be used in tandem with the data collected through expert elicitation. In

Chapter 4, the questionnaire is designed to draw out the DM's attitude towards risk by means of the utility elicitation. Ethical approval was obtained to further validate questionnaire contents and participant consent. The questionnaire adopted a seven-point Likert-type scale to evaluate HFs. The content and language used in the questionnaire was revised by two scholars after its initial design, to facilitate understanding. A pilot study was conducted to eliminate inconsistency and vagueness of questions, and also to determine the level of understanding about the identified HFs. The questionnaire was web-based and a link was e-mailed to targeted experts. A total of five experts were chosen at random.

In Chapter 5, significant HFs with the most relative weights are further evaluated quantitatively using a BN. First, a draft version of the developed questionnaire was examined by two academicians and a specialist to comment on the appropriateness of the questions and whether any were confusing. The questionnaire was then reworded for the pilot study. Six different judges were drawn at random to pre-asses the questionnaire. These judges were assembled from the maritime domain and oil terminal focus group, and ranged from an industrialist, academics and experts with experience in both fields. The ratio of judges correct agreement was considered good and the discriminant validity feedback from the pilot study was eliminated. Seven-point Likert-type scale type questions were adopted. The questionnaire was web-based and a link was e-mailed to targeted expert participants as well as a follow-up process. Data were collected through the same web-link as soon as the respondent completed the questions. Measures were considered to eliminate bias.

In Chapter 6, owing to the need to scrutinise identified strategic decisions based on the results, an empirical approach is utilised in order to ensure that the assembled strategies are reliable and consistent. Additional in-depth study was also carried out in each technical chapter (4, 5, and 6) in the thesis, a Case Study or Sensitivity Analysis (SA) (see the detailed processes in relevant chapters).

3.4 Research Structure

The research structure (see Section 1.8) provides a platform upon which the research methods will be combined for the research design/strategy during the research work. The knowledge of the various methods in a research structure involves studying, understanding and presenting a purposeful yet robust procedure to facilitate in defining the research problems.

3.4.1 A Novel Resilience Framework

Fig 3.1 provides an illustrative view of a novel resilience framework proposed for the purpose of this research upon which the research methodology will be directed. The research recognises that there is weak knowledge about the uncertainty that has been highlighted in the UK Offshore Operators Association's (UKOOA) framework for risk-related decision support. Many of the cited papers on offshore/onshore installations and ships presented that the oil industries have constantly adopted new approaches, technology and hazardous cargoes, and each element brings with it a new hazard in one form or another; therefore, there is a lack of reliable safety data and lack of confidence in risk assessment in complex marine operations (CMOs). Thus, the lack of outcome measures that could assess the influence of hazard-related factors (section 2.5.7) has underscored the need for a resilience-modelling framework for risk management for OTOs. The selection of the appropriate conceptual framework that involves all operations is a complex task in order to fill the gap identified for system resilience, and thus needing an intensive evaluation process.

The ideas that have been used for the framework are from an extensive review of resilience engineering papers, experts' opinions and current practice on oil terminal operational platforms. The philosophy behind this novel framework is that of the interpretation of the content and context of the satisfaction of observed DMs choices, which are based on behavioural research. This can be influential in improving system resilience under high uncertainty; therefore, it will take the burden off the oil terminal platform management team. In addition, adopting the resilience concept can help improve awareness of dependencies via deep thought regarding its practical and realistic applications to sustain operation even after a major mishap. Finally, it is important to investigate the uncertainties on OTOs with a view to identifying relative hazards, obtaining successful results relating to their impacts on oil terminal platforms and hence understand and proffer strategic decision support to CMOs. Therefore, the novel framework of this research will investigate vulnerability, optimise adaptability and survivability and aid system recovery against unexpected mishap.

Hazard Identification Phase

The framework encompasses investigated hazards from critical appraisal of relevant literature (see Chapter 2) on the current practices on CMOs, and existing hazard factors. A brainstorming session with assembled experienced and knowledgeable participants on OTOs was carried out in meetings to obtain a thorough examination of identified hazards. The outputs from this session and subsequent literature combine the participants' judgements and human knowledge on the identified hazards to propose a reliable hierarchical structure. A dynamic hierarchical structure was developed via a cluster process involving grouping observations of mutual distances together into manageable numbers of subsets that resemble each other (see Chapter 4).

Risk Assessment Phase

The identified hazards to the system's attributes and disruption will be assessed and assigned relative weights in this phase, and will then be prioritised and ranked using a model designed to determine the resilience level for OTOs, the, $UtiSch_{+}$ model, which

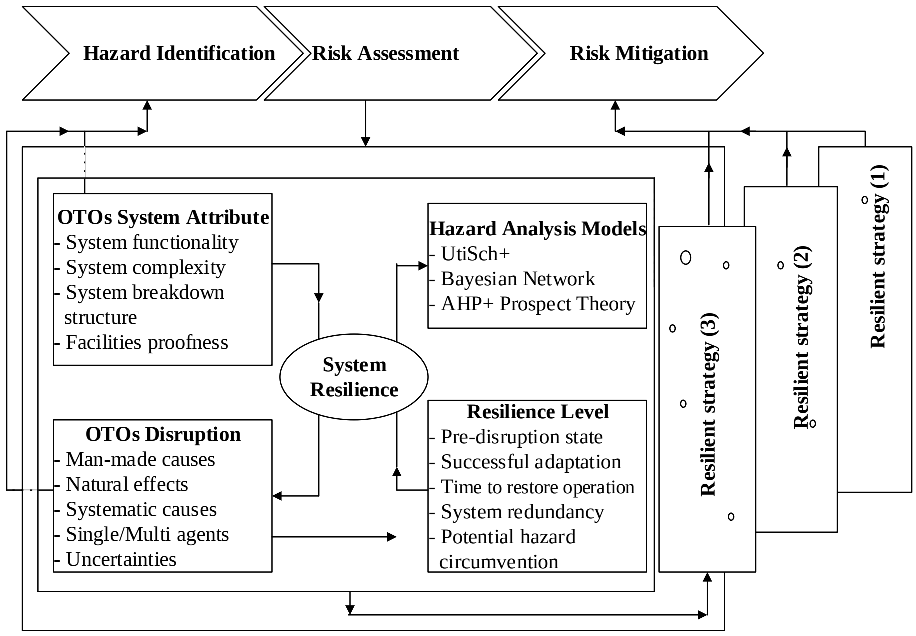


FIGURE 3.1: A Novel Resilience Framework for OTOs

is based on the Utility Theory and Swiss Cheese concepts, as will be fully explained in Chapter 4.

The second phase of assessment is discussed in Chapter 5. The HFs from the $UtiSch_+$ model with the most relative weights were further justified by a subjective expert's opinion. The HFs are thus then established as potential hazards that could lead to an accident scenario on OTOs. The most significant hazard factors previously prioritised in Chapter 4 will be analysed in depth using the BN approach. The flexibility, simplicity and dynamism of the BN technique in addition allows further investigation of the significant hazard factors and their feasible consequences. As a result, the Netica software will compute and obtain crisp numbers for individual hazard factors and this will provide in-depth understanding for DMs, decision analysts and accident investigators to issue comments about lessons to be learnt and to suggest/recommend strategies for decision-making purposes. It is noteworthy to mention that the BN allows new input to be assessed with existing nodes (see Chapter 5).

Risk Mitigation Phase

In Chapter 6, in order to monitor, control and mitigate operational hazard factors in oil terminal platforms, alternatives will be proposed for each attribute that describe each alternative from the set of proposed alternatives. This will be attained with the use of a decision-making tool AHP and PT, motivated by behavioural psychology and uncertainties for decision presentation. The proposed alternatives will be evaluated and the desirable alternative(s) will be selected using experts' elicitation to establish which alternative(s) has more resilience strategic importance.

Testing the Novel Resilience Framework

An empirical study will be used to test the resilience framework in order to explore if it provides a high degree of methodological support to improve system resilience. A real case study will be used in order to validate if the framework can solve or contribute significantly to the enhancement of OTOs even after a major disruption. This thesis aims to provide a resilience concept for industries to set up planning and application philosophies for OTOs under high uncertainties. Where the analysis and the result 'in view' centres towards gains, then the novel resilience framework will have significantly contributed to the web of knowledge.

3.4.2 Analysis of the Existing work and Methodologies for CMOs

OTOs are among the core activities in complex marine operations (CMOs). Oil terminal platforms are structures in which these operations are performed and, as such, there is a high degree of uncertainty while these operations are being carried out. In Chapter 2, a critical review of corresponding studies on oil terminals was carried out. Journal articles, accident reports, historical data, conference papers, workshop papers and relevant seminar on maritime critical infrastructures and transportation formed the primary part of the review; seaports, offshore and onshore platforms became the main sources of secondary appraisal.

3.4.3 Integrated Risk Assessment for Resilience Improvement Methodology

Chapter 4 demonstrates the labile nature of preference judgements towards hazard by means of behavioural research for OTOs using the $UtiSch_{+}$ model. In situations where there is lack of data, quantifying experts' judgement qualitatively allows for a step-by-step analysis of possible hazards with the potential to cause major disruptions to operations. The methodology strategised to investigate the uncertainties on oil terminal operations is as follows: firstly, hazard factors (HFs) were identified through a relevant literature review of journal articles, proceedings and conference papers. Other sources included accident reports, seminars and brainstorming sessions. The information obtained was then categorised by developing a dynamic hierarchical structure using a clustering process. Secondly, an empirical study (section 4.5) was conducted to provide a set of values and consistency for the identified hazard factors to simulate the proposed model. This study was executed in three phases: (1) questionnaire formulation and pilot study, (2) choosing the right experts and (3) survey data collection and description. Fig 3.2 shows the questionnaires forms for the pilot study, see Appendix 4E for final questionnaire and expert elicitation feedback.

Finally, the SChM in tandem with the behavioural utility approach was designed to communicate, analyse and provide weighted measurements of the DMs preference judgements on the HF whose outcome will pose a major catastrophic. A real case study will be used to steward the process of achieving resilience by applying an holistic risk analysis model to integrate the entire hazardous events into a multi-level model to produce an overall picture to identify failures. This can be inter-related to form a proper assessment framework in the following two (2) steps:

- The utility context of the comparisons
- The Swiss cheese Model (SChM)

No		Please Indicate Likelihood						
		Extremely Sad						Excellent
1	Response mood (RM)	☐	☐	☐	☐	☐	☐	☐
		Not satisfied						Satisfactory
2	Individual preference (IP)	☐	☐	☐	☐	☐	☐	☐
		Seldom occur						More likely to occur
3	Recurrent (RO)	☐	☐	☐	☐	☐	☐	☐

4 Year(s) of experience: ☐

RM: *Respondent current state of mind.*
IP: *Respondent perspective of all the chosen risk factors.*
RO: *The reoccurrences of all the risk factors on average within a year*

(a)

No	Risk Factors	Please Indicate Likelihood						
	Nature Related Hazards	Very unlikely	Moderately unlikely	Somewhat unlikely	Not sure	Somewhat likely	Moderately likely	Very likely
1	Hydrologic (HH)	☐	☐	☐	☐	☐	☐	☐
2	Seismic (SH)	☐	☐	☐	☐	☐	☐	☐
3	Atmospheric (AH)	☐	☐	☐	☐	☐	☐	☐
4	Epidemic	☐	☐	☐	☐	☐	☐	☐
Hazards Cluster		*HH: Lightening, Storm, Flood, Snow* *SH: Earthquake, Tsunami, Iceberg collision* *AH: Hurricane/ cyclone, Tornadoes*						

(b)

FIGURE 3.2: Fig (a) and (b) are pilot study questionnaire forms for Utility Swiss Cheese Model

3.4.4 Priority assessment for OTOs hazards methodology

Chapter 5 investigates the top 10 hazard variables (identified in Chapter 4) whose relative weights are most significant in causing unexpected events on oil terminal platforms. The use of a BN model tailored for the resilience improvement of OTOs presents a more advanced technique to evaluate complex operational hazards. The development of a BN model for decision support consists of two major steps: identification of critical variables and their causal network, and the quantification of the significant interrelationship among critical variables. The BN methodology follows four major steps:

- Establish potential hazards of relative importance
- Establish the BN model
- Analyse the model
- Model Validation

An empirical study was conducted (see Sections 3.2 and 3.3) in four phases: (1) questionnaire formulation and pilot study, (2) choosing the right experts, (3) survey data collection and description and (4) BN model application and results. The BN model was then performed using the Netica (Netica, 2002) software. For further detailed information, see Chapters 2 and 5. Fig 3.3 shows the questionnaire form used for the pilot study and see Appendix 5C for the final questionnaire.

No	Risk Factors	Please Indicate Likelihood						
	Man Related Hazards	Very unlikely	Moderately unlikely	Somewhat unlikely	Not sure	Somewhat likely	Moderately likely	Very likely
1	Major Accident Hazards (MAHs)	☐	☐	☐	☐	☐	☐	☐
2	Duty Holders Error (DHE)	☐	☐	☐	☐	☐	☐	☐
	Machine Related Hazards	Very unlikely	Moderately unlikely	Somewhat unlikely	Not sure	Somewhat likely	Moderately likely	Very likely
1	Maintenance Event Hazards (MEHs)	☐	☐	☐	☐	☐	☐	☐
2	Equipment Failure (EF)	☐	☐	☐	☐	☐	☐	☐
3	Well Control System Failure (WCSF)	☐	☐	☐	☐	☐	☐	☐
	Hazards Cluster	***MAHs***: *Collision, Cargo transfer failure, Release from loading arms* ***DHE***: *Operators error , Poor training system, Vessel/terminal personnel related error* ***MEHs***: *Maintenance error, Maintenance omission, Lack of dredging and Navaids maintenance, Residual maintenance problems* ***EF***: *Main equipment failure, Utility failure, Hardware failure* ***WCSF***: *Wellbore error, Formation error*						

Figure 3.3: A pilot study questionnaire form for BN

3.4.5 Strategic Decision Support Methodology

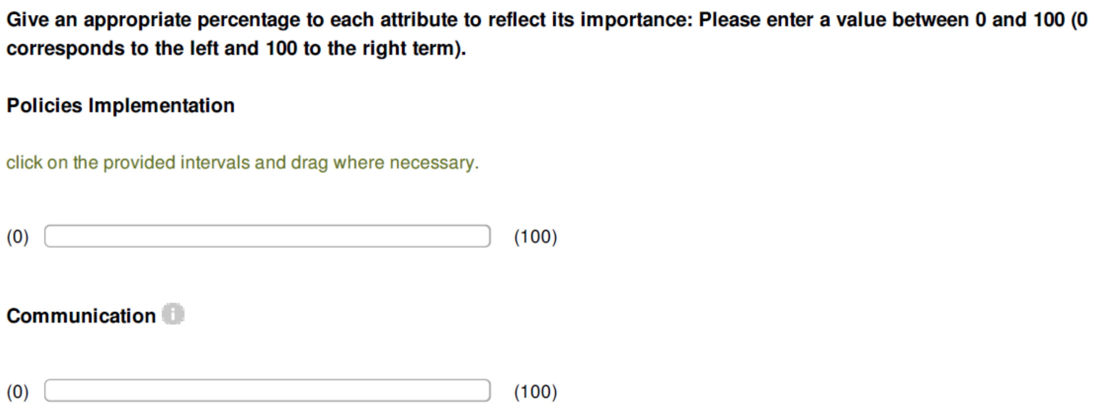
Chapter 6 outlines the selection of an appropriate alternative for decision making. The PT framework provides a menu of the different ways through attribute aspirations expressed in multiple formats by DMs, but formally in the following ways: (1) "would better not be over an nth term", (2) "would better be over an nth term" and (3) "would better be between kth and nth term". These are mental heuristics or how they perceive prospects based on gains and losses to come up with a unifying theory for decision making under risk. Based on the assessment of OTOs in Chapters 4 and 5, the methodology for solving an MADM problem with multiple formats of attribute is given as follows:

- Determine the decision weight of attributes by aggregation, according to experts' preference judgements.
- Determine reference points according to DM's attribute aspirations
- Construct gainloss matrix
- Construct prospect value matrix
- Construct normalized matrix
- Calculate the overall prospect value of each alternative
- Determine the ranking of alternatives according to the obtained overall prospect values.

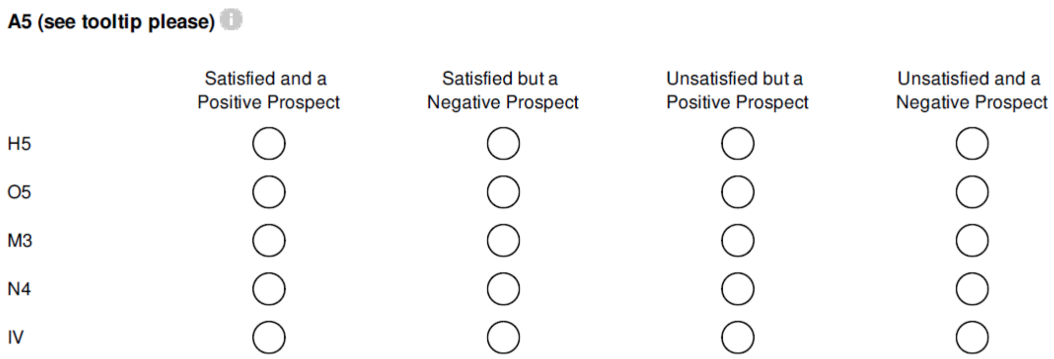
As discussed in sections 3.2 and 3.3, an empirical study was conducted to facilitate general understanding and knowledge on the significance of the developed resilience strategic decision. This study was attained in three phases: (1) questionnaire formulation and pilot study, (2) choosing the right experts, (3) survey data collection and description and (4) test case study. Fig 3.4 shows the questionnaire forms to determine experts' aspiration level and alternatives' importance to OTOs. See Appendix 6C for the final questionnaire.

3.5 Conclusion

This chapter has briefly outlined the research methods adopted in this thesis as well as laying down the foundation for the research viewpoints via the novel framework. The chapter has also clearly stated the research methodology and the novel framework of this research; the utility and Swiss cheese ($UtiSch_{+}$) model, Bayesian Network (BN) and Analytical Hierarchical Process-Prospect Theory (AHP-PT), as well as the research structure. The rationales for using only a questionnaire were also stated, followed by the method used in the questionnaire dissemination. The number of experts used in this research and the justification for using them were also presented. The next chapter will move forward the justification of the research framework, where behavioural research based on DMs' psychology demonstrates the labile nature of preference judgements.



(a)



(b)

Figure 3.4: Pilot study questionnaire forms for Prospect Theory

Chapter 4

AN INTEGRATED RISK ASSESSMENT FOR RESILIENCE IMPROVEMENT OF OTOS USING UTILITY THEORY AND SWISS CHEESE MODEL UNDER HIGH UNCERTAINTY

Summary

This chapter presents an innovative approach towards integrating Utility Theory and Swiss Cheese Model into oil terminal risk assessment. The combined Utility Theory and Swiss Cheese Model ($UtiSch_+$) considers the behaviours based on experts estimation and possible active failures under uncertainty. This approach has been developed and applied to a case study of an oil terminal platform. The simplicity and efficiency of this model will benefit oil terminals in tackling uncertainties their operation to minimise vulnerability and maximise resilience. The Utility Theory and the Swiss Cheese Model ($UtiSch_+$) model was used to determine the relative weights of the identified hazard factors. The model will facilitate the decision-making process for complex decision problems and thus improve resilience.

4.1 Introduction

In the early phases of conceptual design, it is more useful to aspire to create something new than to use the same decision patterns as used in the past. Behavioural research on decision making approach demonstrates the labile nature of preference judgements. Many decision problems involve considerable uncertainty about the outcomes of alternative decisions. Often it is important not only to evaluate the possible outcomes in a decision problem but also to judge the riskiness of various alternatives. Seemingly subtle changes in problem structure, question format, response mode, individual perspective or other aspects of the assessment process can sometimes dramatically change the preference responses of an individual decision maker (DM) (Farquhar, 1984).

A single failure or error seldom causes an accident, but the consequences of a series of failures or errors do (Wu et al., 2009). However, applying a holistic risk analysis to integrate the whole hazardous event into a multi-level model produces an overall picture by which to identify failures, and this can be inter-related to form a proper assessment framework. Several tools have been developed by researchers to support risk analysis. Experts in different domains may use different categories to classify failures, with each category having different sorts of errors. Thus, this requires risk or decision analysts to develop novel methods that are capable of finding the right balance in dealing with overall risk assessment and domain-specific analysis (Ren et al., 2008).

The DMs attitude, as defined by their decision criteria, denotes the relevance of the decision, supported by the method and model. Hazelrigg (1998) stated that there are no right or wrong decision criteria; instead, there are criteria that are more or less important to the DM (Van Bossuyt et al., 2012). The emphasis is on probing the steps in the utility assessment process (Farquhar, 1984), and, in particular, reviewing various methods of comparing person approach focusing on unsafe acts using other approaches in tandem (Wu et al., 2009). Thus, the methodology presented has a wider application than decision problems involving only one attribute.

By methodically substantiating assessment procedures and contextual elements in behavioural research, it has been possible to examine some of their effects on preference judgements (Farquhar, 1984; Reason, 2000; Xue et al., 2013). This information can be helpful in choosing appropriate utility assessment procedures when combined with other approaches for a particular decision situation by decision analysts.

4.2 Appraisal on Resilience Approach for Complex Marine Operations (CMOs)

In response to any unexpected events with various levels of disruption, resilience alongside robustness is amongst the strategies that might be adopted and utilised by the maritime domain. Resilience is an additional safety measure needed in CMOs such as OTO platforms. Zhang (2007) highlighted the lack of distinction between the available definitions of resilience and robustness, and he and a colleague further gave a distinctive definition in the context of operations (Zhang and Lin, 2010). The available conventional risk assessment frameworks for oil terminal platforms ordinarily treat a small number of possible scenarios, taken into account as a moment in time, though of high significance

(Ronza et al., 2006, 2007; Elsayed, 2009; Wang et al., 2009; Mokhtari et al., 2011; Tang et al., 2011; John et al., 2014a). As such, a limited number of studies have been carried out on the resilience of port infrastructures.

Abech et al. (2006) analysed the opportunities and challenges for improving resilience of fuel oil distribution in the downstream sector situated in the southernmost state of Brazil, identifying how the system is resilient in some ways and brittle in others. Hansson et al. (2009) demonstrated how the resilience concept model proposed by Hollnagel et al. (2006) was adapted for reducing occupational injuries in the oil and gas industry. Dinh et al. (2012) proposed the principle and factors that contribute to the resilience of complex organisations that handle hazardous technical/process operations. Mansouri et al. (2010) developed a Risk Management-based Decision Analysis (RMDA) framework that adopted resilience investment plans and strategies for port infrastructure systems (PIS) oil terminal platforms are such infrastructures. John et al. (2014b) further proposed a collaborative modelling approach for the selection of appropriate resilience investment strategies for decision makers for seaport operations. John and colleagues also developed a modelling approach (John et al., 2016) to improve the resilience of a seaport system.

The various researchers adopted methodologies that were suitable for obtaining primary/secondary data on different factors relevant to their individual research, both qualitatively and quantitatively. While John et al. (2014, 2016) presented five and six steps respectively for quantitative data collection, Mansouri et al. (2010) adopted three steps, and port infrastructure authorities were involved in quantitative data collection techniques. Abech et al. (2006), on the other hand, adopted a qualitative data collection technique, observing how latent factors combined to form hazardous situations as well as remaining alert to other incidents occurring within the platform. Moreover, Hansson et al. (2009) adopted a qualitative data collection method based on explanatory and descriptive analysis.

These authors have demonstrated that their work has followed logical steps. Relevant case studies have been used, and the main ideas are represented in tables and figures, and are supported by reliable evidence. The conclusion of each article reflects the issues raised by the study and some suggested recommendations are proposed to tackle the issues based on the results obtained from the qualitative and quantitative analysis.

However, the research areas, scopes and types of goods and services being handled differ between seaports and terminal platforms. As such, risks/hazards differ, especially in ports whose activities are based on handling hazardous materials. With the limited amount of conference papers, journals and articles available on OTOs and a resilience strategy for OTOs optimisation, a further investigation is relevant to improve operations and identify hazards from unforeseen events. The results from such an investigation should be tested and validated. Furthermore, none of the available studies on oil terminal platforms considered uncertainty.

An assured system safety does not mean tighter monitoring, control of disruption, or reducing counting of failures (because systems are already safe), but rather a constant calibration of unexpected hazards. When we see things go right after a disruption, some of which may even fall outside of what the system has been designed to do, it means the system has gone way beyond its traditional safety discipline.

4.3 Risk Assessment Methods for Complex Marine Operations (CMOs)

Rodriguez and Souza (2011) developed a risk-based analysis method aimed at defining the risk profile associated with the risk scenario of a shuttle tanker main engine failure at an offshore offloading operation in Campos Basin, Brazil. Accident Modelling, Failure probability assessment with Bayesian techniques, Evaluation of consequences, and Markovian process to aid decision making were the four basic steps applied (Rodriguez et al., 2011). Other researchers such as John et al. (2016) presented a modelling approach that utilised the Bayesian belief networks, and Fuzzy Analytical Hierarchy process (FAHP) was used to evaluate the relative influence of a number of risk factors. Mokhtari et al. (2011) proposed the integration of the Bow-tie approach into the risk assessment phase for risk management of offshore terminals. Ronza et al. (2006) processed data using Event Trees (ETs) to determine the probability of the various events that initiated accidents for liquefied and crude oil products; due to the proliferation of loading arm failures and tank rupture, the operations they considered were: bunkering operations, tanker navigating through the port, tanker (off)loading bulk hydrocarbons and tanker manoeuvring in the proximity of berths (Ronza et al., 2003). Abech et al. (2006) presented a more qualitative technique based on explanatory and descriptive analysis for an oil distribution plant, whereas Hansson and Herrera (2009) adopted an empirical study technique for reducing occupational injuries on an oil and gas installation.

4.3.1 A Categorisation of Uncertainties by developing a Dynamic Hierarchical Structure

Given that there are several possible failure modes that can affect OTOs, uncertainty in CMOs cannot be completely eliminated. CMOs are often associated with a high level of uncertainty due to the ever-changing environment leading to a range of possible accidents. Assessing uncertainty in OTOs requires the use of a method that combines experts judgement and human knowledge to propose a reliable dynamic hierarchical structure.

HFs for OTOs has been identified through a literature review of relevant journals articles, proceedings and conference papers (see Section 2.5.7). Others include accident reports (MARSH, 2011, 2013) seminars and brainstorming sessions for HAZID procedure. A pilot study was conducted with specialist and academicians to determine the consistency of the identified unexpected events for further experts judgement. There are five major categories of hazards identified to cause an accident scenario on OTOs under high uncertainty; they are described as follows: Tables 4.1, 4.2, 4.3, 4.4, and 4.5.

Table 4.1: Description of Man-related hazards for OTOs

Level 3 risk factors	**Attributes**	**Descriptions**
Sabotage	Unauthorised interference from third party, Internal Crisis	External or internal source of security breach. In 2005, oil fields were taken over by armed Libyans groups or shutdown due to security concerns, according to officials at the Libyan National Oil Co. Resultant loss of crude was from 900,000 b/d to 325,000 b/d.
Cargo transfer failure	Platform struck by Stad Sea, Overfill	A multi-purpose support vessel hits a platform riser during a transfer operation. Problems during transfer from an overfilled internal floating crude oil tank led to fire and explosion.
Accident	Vessel loss power, control or steerage	A well intervention vessel collided with an unmanned platform causing heavy damage to the vessel and the platform, 2009. Resultant loss worth USD 1.3 billion.
Release from loading arm	High-pressurised oil, Pump leak, Gasket failure	California, USA (1992, 1999): a vapour cloud was formed followed by a large fire from the release of escaping hydrocarbon due to high pressure (10_{psi}. An explosion as a result of a ruptured pipeline, releasing hydrocarbon-hydrogen mixture to the atmosphere. Resultant loss worth USD 340 million.

Poor training system	Quality of worker	Educating the operational workforce on hazard identification pertaining to loading/offloading operation and to be able to identify measuring tools that can convince them that "operations are safe" at a terminal..
Operators error	SOPs not followed, Accidentally performed action	In 2004, in Illinois, USA there were wilful safety violations from inadequate inspection of equipment and failing to maintain fire protection equipment. Poor worker training led to the destruction of about 75% of terminal facilities. Resultant loss worth USD 200 million, serious injuries and five deaths..
Vessel personnel error	Human carelessness	Vessel not securely and safely moored; mooring lines out of position and layout (not applied in the correct angle).
Terminal personnel error	Human omission	Terminal personnels not allocating sufficient staffing levels to deal with emergencies during ship stay in terminal.
Mode awareness	Lack of awareness of the mode of operation	lack of awareness and constant vigilance on the part of all workers, to establish safety operations are safe.
Personal issues	Stress, Fatigue	Health and wellbeing.
Under-staffing	Workload	Consequences to operation.

Negligence	Carelessness, Cowardice	In Zimbabwe, 2003, while an offloading operation was ongoing between two petrol tankers, one of the drivers was alleged to have been smoking. One of the tanker caught fire and exploded. Resultant loss worth USD 230 million.
Violation	Quality of worker	Carelessness, cowardice.
Misapplication of good rule	Quality of worker	Competence.
Non-intentional behaviour	Quality of worker	False alarm.
Inattention	Quality of worker	Distraction.
Application of bad rule	Quality of worker	Carelessness, cowardice.

Table 4.2: Description of Machine-related hazards for OTOs

Level 3 risk factors	**Attributes**	**Descriptions**
Maintenance error	Workmanship shortcut, Non-explosive proof tools used	An offshore platform in the South China Sea, 2006 suffered hydrostatic collapse as a result of installation of undersized ring stiffeners; ring stiffeners were fabricated using incorrect construction drawing. Resultant loss USD 150 million.
Maintenance omission	Poor grounding of equipment	Mechanical friction generated sparks that ignited flammable vapours. A seal ignited during a cleaning operation. Incorrect manual setting of transfer system.
Lack of dredging and Navaid maintenance	Workmanship Shortcut	Navaid breakdown.

Residual maintenance problems	Poor fabrication, Pump leak, Circuit Shortcut	Electric sparks generated by electric motor, pump leak.
Equipment failure	Accidental damage to equipment, Pump/Hose failure Loading arm failure	Microbial sulphate-reducing bacteria, low temp oxidation. An FPSO alarm was triggered as a result of a leak emanating from one of the loading arms in Norway, 2006. Upon further investigation, five other risers failed. Resultant loss worth USD 230 million.
Utility failure	Poor Maintenance	Loss of platform utilities due to a chain reaction of other failure. In 1998, an onshore platform in Louisiana, USA lost all utilities due to vapour cloud explosion. The effect greatly limited firefighting efforts for several hours. Resultant loss worth USD 600 million.
Hardware failure	Failure of IT Tech	Lack of flexible IT infrastructure.
Well-bore error	Competency	In Egypt, 2004, a production platform suffered significant damage and collapse following a well control incident caused by a drilling operation. Resultant loss worth USD 2.5 million.
Formation error	Competency	Poor documentation.

Table 4.3: Description of Communication- and Correspondence-related hazards for OTOs

Level 3 risk factors	**Attributes**	**Descriptions**
Communication misunderstanding	Proficiency in language, Ignorance, Drawing up faultless dynamic route	Loss of communication between subsea centre and its platform resulting to damage of offshore assets in Angola, 2009. Resultant loss worth USD 180 million. Ill-advised dynamic route of the operation areas.
Implicit signals/ wrong signal	Interface issue, Illumination, Hidden signage Ignoring signage	Personnel not appreciating the necessity of signal discipline while communicating applicable signals. Signage equipment and facilities in close proximity to hazardous equipment and tankers accessing the terminal; other operating areas are considered faulty and do not meet the requirements of local regulations.
Lack of Situation Awareness	Lack of awareness of crisis situations between multiple parties, and how teams relate to each other.	Awareness and constant vigilance on the part of all terminal workers, to establish safety as a permanent and natural feature for on-the-spot decision-making.
Rare events displaced by more urgent issues	Communication failure	Not following up as discussed.
Lack of leadership	Not influential, Pump/Hose failure Poor leadership qualities	Establishment of safety, general wariness and fear of arrest. Conversation abnormality.

Information not distributed around teams	Poor leadership qualities	No one has the overview. This is a particular problem as staff rotate/-move on.
Inadequate review of technical team record	Neglect	Review of internal email.
Breakdown of relations with third party	Communication failure	Organisation response where most are informal.
Continuity of knowledge	Communication failure	Large volume of command such as ship/shore, within department and during handover.

Table 4.4: Description of Management-related hazards for OTOs

Level 3 risk factors	**Attributes**	**Descriptions**
Decision making error	Little information known about the occurrence	A quick visual check, without referring to the radar, was insufficient to fully assess the danger.
Inadequate planning procedure	Redundancy	Lack of accessed revenue and allocated capital to construct ready-to-use platforms for unexpected operation prior to disruption.
Poor staff selection	Competency	Facilitate critical safety information to act upon unsafe activities.
Organisational changes	Management of change.	
Guiding safety principles	Negligence	Non-compliance with applicable international national and local regulations.
Information not distributed around teams	Poor leadership qualities	No one has the overview. A particular problem as staff rotate/move on.

Inadequate inspection and testing	Quality of Worker, Competency	Procedural error; in Ryazan, Russia 1994 a worker did not meet normal terminal practices and thus creates weaknesses on the safety barriers in place. Resultant loss was worth USD 100 million.
Inadequate safety culture and hazard awareness	Lack of integrated security and safety design	Recognised industry codes of practice, able to demonstrate and document proof of compliance with new regulatory requirements.
Inadequate safety procedures	Lack of integrated safety management	Safety culture.
Inadequate reporting procedures	Lack of integrated safety management	Lack of safety awareness and training.
Poor tracking system	Reliable tracking technologies	Design and implement a security system that monitors the vast territories within the entire operational environment at oil terminal.
Implementation of safety audit	Poor documentation	A survey of the state of installation and operator's performance.
Design error	Workmanship	Significant equipment and structural deformation of installation due to design and lack of modification control. Resultant Loss was worth USD 270 million.
Not updating regulatory changes	Negligence, Frauds	Lack of precision. The possibility that the circumstances in effect initially on regulation may change at a later date.
Professional negligence	Neglect	Improper sampling procedures.

Company policy	Bureaucracy	Inadequate decisions on safety policies and the ability to promote a good safety culture throughout operation.
Financial issues	Access to revenue and allocated capital, Frauds, Bureaucracy	Helicopter operations, competition factor among terminals, customer change in terms of demand for more products (uncertainty in ship size) and services, terminal change factor i.e. potential for global substitution and consolidation among terminals.

Table 4.5: Description of Nature-related hazards for OTOs

Level 3 risk factors	**Attributes**	**Descriptions**
Lightning	Direct strike during operations, Bound charge, electromagnetic/ electrostatic pulse and earth current	A severe thunderstorm passed over a terminal in Labuan, Malaysia, 2005. A tanker was apparently struck by lightning while it was loading resulting in the death of a number of crewmembers. Resultant loss worth USD 150 million.
Flood	Increased water volume due to heavy rain, water released from dams and global warming	In 2011, 638 workers were evacuated when water entered the pontoon of an offshore platform on the Gulf of Mexico, USA and capsized. Resultant loss worth USD 160 million.
Snow	Extremely low temperature	Slippery terminal platforms and poor visibility causing slip and trips hazards.
Storms	Bad weather	Heavy rain and thunderstorm.
Earthquake/tsunami	Earth movement, ocean floor slides	A $9.0M_w$ earthquake at Tohoku in Japan and an $8.8M_w$ earthquake off the coast of Chile in 2011 and 2010 respectively. These events triggered a tsunami that travelled up to 10km, causing large-scale structural damage and loss of life. Resultant loss worth USD 22.3 billion.
Hurricane/cyclone	Atmospheric hazards	Hurricanes Andrew, Ike, Rita, and Katrina in 1992, 2005, 2005 and 2008 respectively made landfall, causing flooding and widespread destruction to onshore/offshore facilities resulting to shutdowns. Resultant combined loss worth USD 24.3 billion.
Tornadoes	Atmospheric hazards	Triggers the release of hazmat from onshore/offshore terminals and facilities causing disruption to operations.
Ice-berg	Navaid failure	Collision of large floating ice feature with massive offshore structure.
Epidemic	Diseases	External or internal breach of human wellbeing using viruses/bacteria e.g. bird flu / Ebola outbreak, resulting in closure of oil terminal and borders if not contained.

4.3.2 Clustering Process for Developing a Sub-hierarchical Structure

A hierarchical cluster process involves grouping observations of mutual distances together into related subsets. It could group the universe of possible uncertainties into a manageable number of subsets so that all the elements are present. Xin and Huang (2013) constructed a scenario cluster as a process for building fire risk analysis (Hall Jr

TABLE 4.6: Description of Man-related hazards after a cluster process

Hazard Category	**HFs undergoing clustering process**	**Group name**
Man-related hazards	Cargo transfer failure Accident Release from loading arm	R_1: Major Accident Hazards(MAHs)
	Operators error Poor training system Vessel personnel error Terminal personnel error	R_2: Duty Holders Error (DHE)
	Mode awareness Personnel issues	R_3: Personal Issues (PI)
	Sabotage	R_4: Sabotage (S)
	Under-staffing Negligence Violation Misapplication of good rule Non-intentional behaviour Inattention Application of bad rule	R_5: Indirect Contributing Factors (ICF)

TABLE 4.7: Description of Machine related hazards after a cluster process

Hazard Category	**HFs undergoing clustering process**	**Group name**
Machine-related hazards	Maintenance error Maintenance omission Lack of dredging and Navaid maintenance Residual maintenance problems	R_{11}: Maintenance Event Hazards (MEHs)
	Equipment failure Utility failure Hardware failure	R_{12}: Equipment Failure (EF)
	Well-bore error Formation error	R_{13}: Well Control System Failure (WCSF)

and Sekizawa, 2010; Xin and Huang, 2013). A cluster process was proposed to form a working group (Lu and Shang, 2005).

The clustering process involves three major steps, namely: (a) identification of elements of a similar kind in the hierarchical structure, (b) grouping of observable elements together into a smaller group on the basis of self-similarities, and (c) developing the sub-hierarchical structure. Fig 4.1 shows a hierarchical structure for OTOs while Tables 4.6, 4.7, 4.8, 4.9 and 4.10 describe the clustering process for the HFs in related subsets.

Table 4.8: Description of Communication and Correspondence related hazards after a cluster process

Hazard Category	**HFs undergoing clustering process**	**Group name**
Communication and Correspondence-related hazards	Communication Misunderstanding Implicit signals/ wrong signal	R_{21}: Platform Communication Misinterpretation (PCM)
	Lack of Situation Awareness Rare events displaced by more urgent issues	R_{22}: Situation Awareness (SA)
	Lack of leadership Information not distributed around teams Inadequate review of technical team record Breakdown of relations with third party Continuity of knowledge	R_{23}: Lack of Proper Crew Interaction (PCI)

Table 4.9: Description of Management related hazards after a cluster process

Hazard Category	**HFs undergoing clustering process**	**Group name**
Management-related hazard	Decision making error Inadequate planning procedure Poor staff selection Organisational changes	R_{31}: Human Resources Error (HRE)
	Guiding safety principles Inadequate inspection and testing Inadequate safety culture and hazard awareness Inadequate safety procedures Inadequate reporting procedures Poor tracking system Implementation of safety audit	R_{32}: Latent Error (LE)
	Not updating regulatory changes Professional negligence	R_{33}: Job Safety Rules and Regulation (JSRR)
	Design error	R_{34}: Design error (DE)
	Company policy Financial issues	R_{35}: Business Risk (BR)

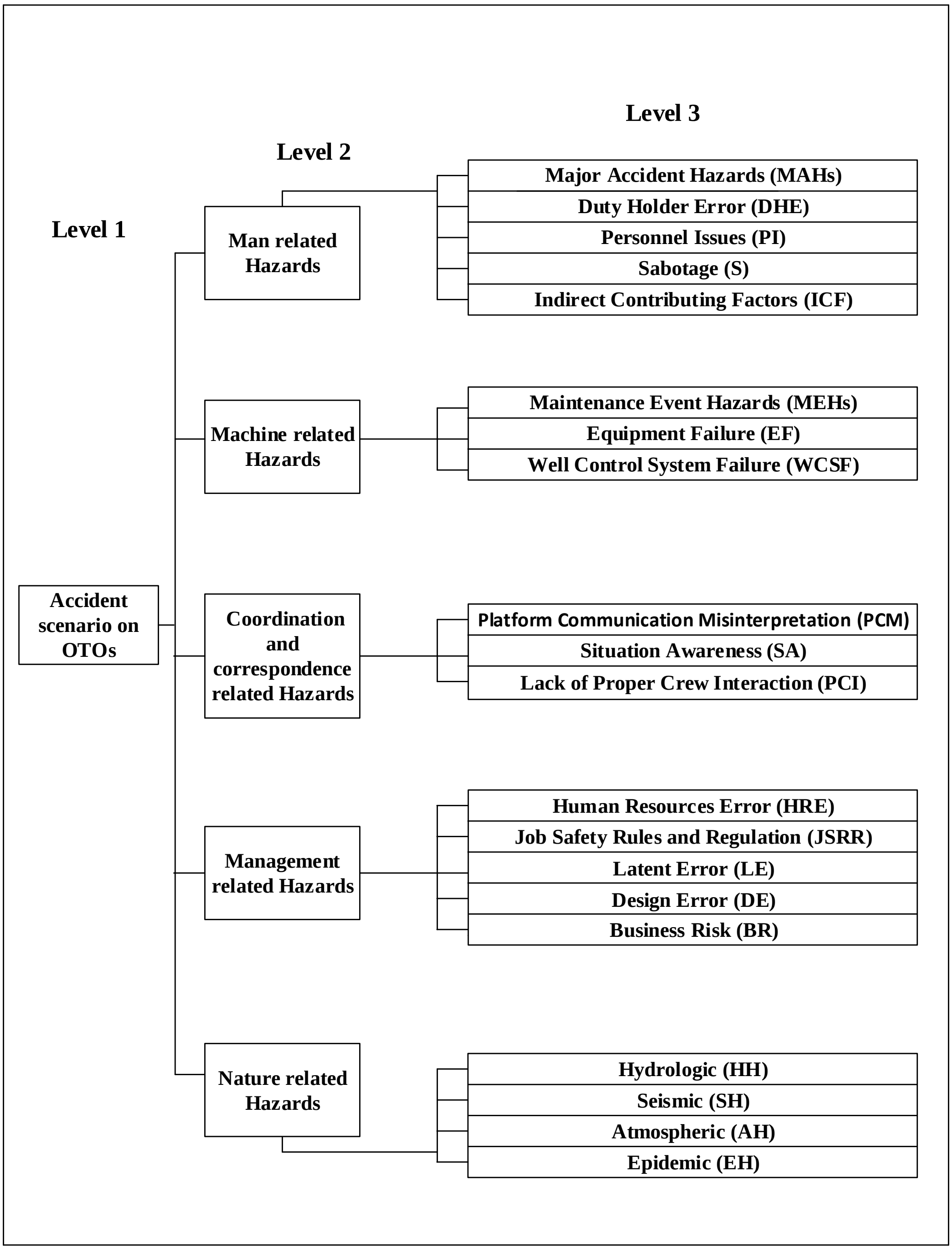


FIGURE 4.1: A Dynamic Hierarchical Structure for Resilience Improvement for OTOs using Clustering Process

TABLE 4.10: Description of Nature related hazards after a cluster process

Hazard Category	**HFs undergoing clustering process**	**Group name**
Nature-related hazard	Lightning Flood Snow Storm	R_{41}: Hydrologic Hazards (HH)
	Earthquake/ tsunami Ice-berg	R_{42}: Seismic Hazards (SH)
	Hurricane/cyclone Tornadoes	R_{43}: Atmospheric Hazards (AH)
	Epidemic	R_{44}: Epidemic Hazards (EH)

4.4 The Utility Theory and Swiss Cheese Model

In psychology, Pratt (1964) provided a classical definition of risk as the parameter that differentiates different individuals utility functions. A function that specifies the utility (measure of satisfaction of a preference) of a DM for all the combinations made qualitatively or quantitatively is termed utility function. Psychology extends this to treat perceived risk as a variable that differentiates individuals based upon content and context interpretations. Keeney and Raiffa (1993, 1996 cited in Van Bossuyt et al. 2012) elaborated how the utility function of individuals is generally expressed as well as elucidated that Utility Theory presents an axiomatic approach that can assess the DMs behaviour with regard to risk (Brito et al., 2010; Van Bossuyt et al., 2012).

Riskiness refers to the riskiness of an option, which is equated to its variance. It can arise from normal behaviours or the normal variability of established work practice. Psychology perceived risk as a variable that differentiates individuals based upon content and context interpretations. Therefore, the suitability of a decision is based on the DM appetite towards risk as defined by the DMs decision criteria. Saatys (1980) pairwise comparisons were primarily used to estimate relative weight of attribute in several approaches including the eigenvector method, its matrices have also been used to assess alternatives with respect to a particular attribute such as in AHP/FAHP (Yang, 2001). The method presented below adopts an innovative approach based on Utility Theory and Swiss Cheese Model (SChM).

4.4.1 The Utility Context of the Comparisons

Since the context of an assessment can have significant effects on the derivation and interpretation of a utility function, the discussion below analyses the effects of the four different context for comparing DM choice on the likelihood of the risk indicator p with equivalence methods. Also, it distinguishes between the DMs individual preference, experience, recurrent and response modes. For the purpose of discussion, suppose the attribute of interest is the consequence X. Let S denote one's initial level of risk tolerance, and let p be the likelihood of the risk indicator under consideration. One's status is thus represented by *(x,t)*, where x is the current risk tolerance and t indicates whether or not the DM makes the right decision (denoted by p or *0*,respectively).

A common question in evaluating the risk indicator p is to ask the decision maker to specify a certainty equivalent c for which s/he is indifferent between the following two alternative choices:

$$(s + c, 0) \sim (s, p) \tag{4.1}$$

Although each context is distinguished by a different status quo position, one is always asked to find c such that Eq (4.1) holds. The interpretation of the certainty equivalent c depends upon the context given by the status quo position. In the individual preference context, c is the minimum preference given to p that the DM possesses. In the response mode context, p is the mode in which the DM is indifferent, between either c or p. In the recurrent context, one is forced to give up either the amount c or *(p or 0*; c is the indifferent point between these two choices. In the experience context, the DM begins with c; the DM is asked to specify p with c for which s/he is indifferent between alternative choices (Farquhar, 1984).

	No consequences	**Consequence is certain (*c*)**
Likely (0)	**Response mood *(s, 0)***	**Experience *(s + c,0)***
More likely (*p*)	**Individual Perspective (*s, p*)**	**Recurrent *(s + c, p)***

Figure 4.2: Status Quo positions for Four Situations in Assessing DM'S Certainty Equivalent as adapted in (Farquhar, 1984)

According to Farquhar (1984) it is important to note that the minimum preference for p is occasionally difficult to elicit from a DM who has two or more choices. The following scenario helps to overcome this inertial effect (Hershey *et al.* 1982). The decision analyst derives a threshold on the DM preference, k. Once k is set, the DM preference of k becomes the more likely. With a weak restrictions on the probability distribution of k as well as the decision maker utility function, Toda and MacCrimmon (1972) prove that k which maximizes expected utility is indeed the DM's minimum preference. This technique is analogous to a "proper scoring rule" for motivating an individual to report his/her true value on probability assessment (Hogarth, 1975; Lichtenstein *et al.,* 1982; Spetzler and Von Holstein, 1975; Wallsten and Budescu, 1983; Winkler and Murphy 1968). For example, in the individual preference and experience contexts, the status quo position is one of the two alternative choices in Eq (4.1). Assessments in either case can suffer from inertial effects that can distort one's judgement (Hershey *et al.* 1982). On the other hand, the status quo position is bound to change in either the response mode or recurrent context, because the initial position is not among the alternative choices in Eq (4.1). Thus the response mode and recurrent contexts are not subject to inertial effects.

For other possible combinations e.g. the experience context, which begin with a status quo of $(s, 0)$, the DM is asked to specify the maximum years *(b)* for *(p)* to lead to a failure, such that $(s, 0) - (s - b, p)$ hold. Raiffa (1968, pp. 89-91) noted that c is not constant across contexts, instead useful qualitative properties of a utility function can be determined by establishing relationships between certainty equivalent assessed in different contexts. For example, if the minimum years (b_i) equal the maximum DMs preference (c_i) for all $p \in P$ and $s \in X$, then the underlying utility function must either be linear or exponential (Pfanzagl, 1959; Pratt, 1964). Other examples can also be considered. According to Fishburn (1968), Green (1963), Schlaifer (1959, 1969) and Swalm (1966) the regulations of gamble comparison also involve ways at which outcomes are shown to decision makers; for many years, the accepted practice in utility analysis was to consider p over the final assets in X (Farquhar, 1984). With additional research, perhaps questions about the choice of an appropriate context for behavioural utility assessment comparisons or an appropriate representation for the outcomes can be better resolved.

Preference Comparison

Friedman and Savage (1952), Davidson *et al.* (1957), Suppes and Walsh (1959), DeGroot (1963), Meyer and Pratt (1968), Bradley and Frey (1975), and Novick *et al.* (1981) noted that in a preference comparison between the risk $[x, \alpha, y]$ and the certain outcome w, an individual specifies the relation R (*either* $>, <, or \sim$) such that the expression $[x, \alpha, y]$ R w holds. It involves a sequence of such comparisons, $[x_i, \alpha_i, y_i]\underline{R_i}w_i$ for $i = 1, 2, 3, \ldots, n$, where the probabilities, values, and standards are chosen in a particular way. More so, the preference comparison method often uses only even-chance on risk, $\alpha_i \equiv \beta_i \equiv \frac{1}{2}$, and this can be used to construct an ordered metric scale for utilities. As such, it offers an advantage for elicitation simplicity and reduce bias. There are two common uses of preference comparison methods in utility assessment;

- Investigating risk attitudes in a preliminary analysis and checking the consistency of an assessed utility function, and

- In converging on an indifference point where $[x_{n,}\alpha_{n,}y_n] \sim w_n$. Such convergence techniques iteratively adjust either the probabilities, values, or standards until indifference occurs.

Preference comparison provides a linear constraint that the utility function must satisfy. However, other researchers have applied linear programming procedures to the constraints generated by the preference comparisons such as $[x_{i,}\alpha_{i,}y_i]\underline{R_i}[w_{i,}\beta_{i,}z_i]$ to estimate a utility function. With a sufficiently large set of constraints, the decision analyst can develop fairly tight bounds on either admissible utility functions or consistent future responses (Farquhar, 1984). Fig 4.3 is an example for x and y risk:

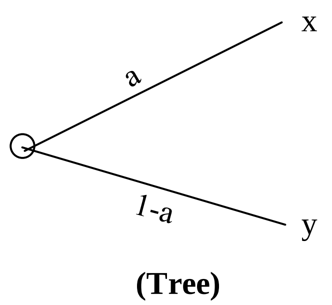


FIGURE 4.3: An example of preference comparison analysis

Probability Equivalence

Researchers such as von Neumann and Morgenstern (1947), Mosteller and Nogee (1951), Luce and Raiffa (1957), Myers and Sadler (1960), Myers and Katz (1962), Fishburn (1964,1967), Officer and Halter (1968), Schlaifer (1969), Hull et al. (1973), Ronen (1973), Kneppreth et al. (1974), Tversky and Kahneman (1974), Hogarth (1975), Keeney and Raiffa (1976), Johnson and Huber (1977), Moore (1977). LaValle (1978), Karmarkar (1978), Fischhoff et.al. (1980), Hogarth (1980), Novick et al. (1981), Zagorski (1981), Hershey et al. (1982), and Kahneman et al. (1982) have each contributed to the emergence of probability equivalence. Probability equivalence methods require that an individual specifies an indifference probability for which $[x, \alpha, y] \sim w$ where w is between x and y. These methods apply to either discrete or continuous attributes, X. We begin by selecting two reference points, x_0 and x_{n+1} in X, where $x_0 < x_{n+1}$. These points may either be catastrophic or a no-risk outcome in X, or some other convenient benchmarks. The task is to assess the utilities of the points $x_0 < x_1, \ldots, < x_{n+1}$ using the adjacent risk method (Farquhar, 1984).

Extreme risk: $[x_{n+1}, \underline{\alpha_i}, x_0] \sim x_i$. This method uses the reference points of the risk attribute X as the extremes in every risk. If $u(x_0) \equiv 0$ and $u(x_{n+1}) \equiv 1$, then obviously $u(x_i) = \alpha_i$. Thus, the elicited indifference probabilities themselves are the utilities of the x_i values. If x_0 and x_{n+1} are not the endpoints of X and it is necessary to find the utilities of points above x_{n+1} or below x_0, additional questions can ask $[y, \underline{\alpha}, x_0] \sim x_{n+1}$ for $y > x_{n+1}$ or $[x_{n+1}, \underline{\alpha}, y] \sim x_0$ for $y < x_0$ Although using the extreme risk method could be quite easy, there are susceptibilities to serial dependence in the responses and to biases from range effects if x_0 and $x_(n+1)$ are too extreme. A decision analyst might try to alleviate these potential problems by permitting the sequence $1, 2, \ldots, n$ of comparisons and taking other precautions to de-bias the responses. The possibilities for the probability equivalence methods using paired-gamble comparisons for extreme risk are estimated as follows:

$$[x_{n+1}, \underline{\alpha_i}, x_0] \sim [x_{i+1}, x_{i-1}] \tag{4.2}$$

Let: $x_1 \equiv x_0,$ and $x_{n+2} \equiv x_{n+1}$ for this method.

Adjacent risks: $[x_{n+1}, \underline{\alpha_i}, x_{i-1}] \sim x_i$. Instead of using risk over extreme values (best and worst outcomes) this method uses risk over the "locally best and worst" values for each x_i. Each of the DM's n responses generates an equation of the form $u(x_i) = \alpha_i u(x_{i+1}) + (1-\alpha_i)u(x_{i-1})$. With $u(x_0) \equiv 0, u(x_{n+1}) \equiv 1, f_0 \equiv 1$, and $f_i \equiv \frac{1-\alpha_i}{\alpha_i}$, Novick and Lindley (1979) solve the resulting system of n equations in n unknowns to get:

$$u(x_i) = \sum_{k}^{i=1} f_k(x_i).exp(\lambda_i x) \tag{4.3}$$

$$u(x_i) = \alpha_i u(x_{i+1}) + (1 - \alpha_i)u(x_{i-1}) \tag{4.4}$$

$$u(x_i) = \sum_{i=1}^{j=0} \prod_{j}^{k=0} f_k / \sum_{n}^{j=0} \prod_{j}^{k=0} f_k \text{ for } i = 1, \ldots, n. \tag{4.5}$$

A key advantage of the adjacent risks method over extreme risk is "*provided we do not ask the subject to assess probabilities near zero or one (numerically large log-odds), the utilities will be relatively insensitive to a lack of precision in probability assessments* (Novick and Lindley 1979, p. 308)" as cited in (Farquhar, 1984). Points outside the range are easily determined by additional comparisons of the form $[y, \alpha, x_n] \sim x_{n+1}$ if $y > x_{n+1}$ or $[x_i, \alpha, y] \sim x_0$ if $y < x_0$. The possibilities for the probability equivalence methods using paired-gamble comparisons for adjacent risk are as follows:

$$[x_{i+2}, \underline{\alpha_i}, x_{i-2}] \sim [x_{i+1}, x_{i-1}] \tag{4.6}$$

Let: $x_1 \equiv x_0,$ and $x_{n+2} \equiv x_{n+1}$ for this method.

Probability equivalence methods offer several advantages over preference comparison of utility assessment. One is that chaining of responses (i.e. the use of earlier responses in subsequent risk comparisons) does not occur; serial dependence between comparisons can be sharply reduced with permuted sequences. Secondly they are less susceptible to risk distortions, path dependence, and some other cognitive biases. Although individuals may find it difficult to make probability judgements, training procedures and aids are available. The adjacent risk method is fairly robust for probabilities not close to zero or one, so probability judgements need not be precise in that case (Farquhar, 1984).

4.4.2 The Swiss Cheese Model (SChM)

Over the past few years, the oil industry has continued to develop and strengthen control barriers to prevent potential catastrophic consequences to people or the environment resulting from accidental releases of oil cargo. The SChM has been used for three different purposes: (1) as a heuristic explanatory device (communication),(2) as a framework for accident investigation (analysis) and (3) as a basis for measurements (measurements). The SChM uses broad practical experience for risk investigation in the $UtiSch_+$. In the $UtiSch_+$ approach, the cheese slices are categorised into avoid, prevent, control, mitigate and active failure barriers respectively. The slices (barriers) have holes representing the opportunities for a risk indicator to cause an incident (barrier penetration). When the slices are stacked such that holes are aligned, there is an opportunity for all the barriers to be penetrated; thus, the barriers' weaknesses combine and grow into large failures, with the potential to cause an accident. Systematically, the combination of an active risk and a latent risk results in a major accident or catastrophe. Fig 4.4 elaborates more on the Swiss Cheese Model in the $UtiSch_+$.

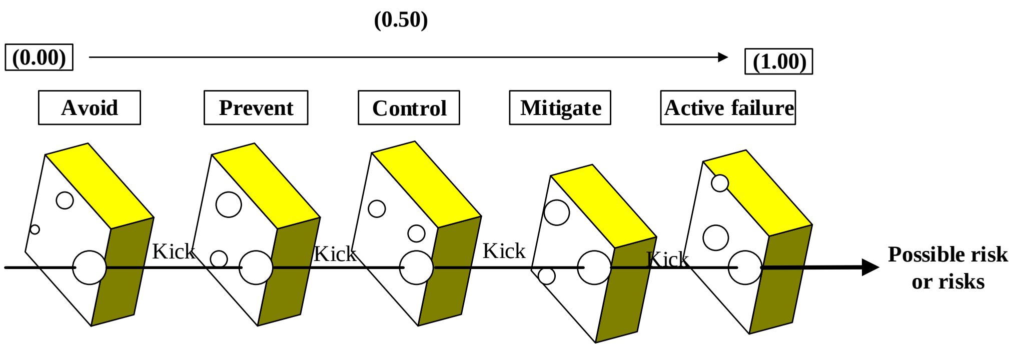


FIGURE 4.4: The concept of SChM in the $UtiSch_+$ model

Weighted measurements of the DMs preference judgements on all the risks whose outcomes will pose a major catastrophe can be ascertained using the probabilities not close to zero or one. Thus, an expression $u(x_0) \equiv 0$ and $u(x_(n+1)) \equiv 1$. Fig 4.5 shows how the analysis in the SChM for hazard factor(s) would be performed, using the ETA techniques for each barrier for a generic accident scenario for OTOs.

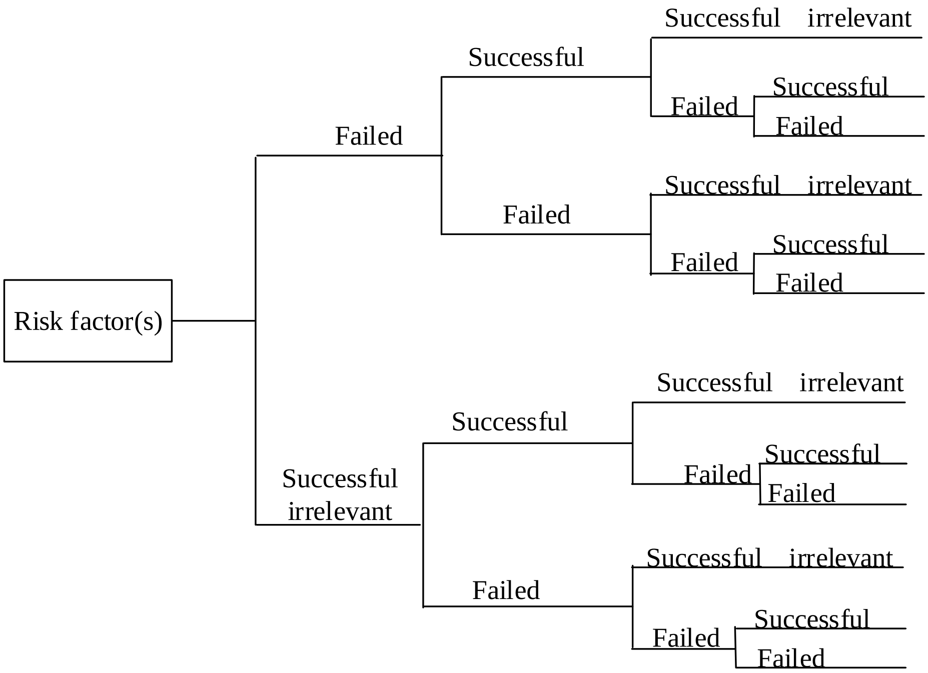


Figure 4.5: Example of SChM analysis as adapted in (Xue et al., 2013)

Specification of quantitative restrictions on the decision maker's preference is accomplished by comparing various risk attitudes over the attribute under consideration.

4.5 The Utility Swiss Cheese ($UtiSch_+$) Model

The SChM can be developed along with a consideration of approaches used in risk management for dynamic sociotechnical systems (Wu et al., 2009). SChM in tandem with Utility Theory approach is design to communicate, analyse and provide weighted measurements of the DM's preference judgements on the risk whose outcome will pose a major catastrophic. Section 4.4 elaborated the innovative approach behind the integration of the Utility Theory and the Swiss Cheese Model; While the Utility Theory assess the behavioural variables that differentiate the DM appetite towards risk, the Swiss Cheese Model was used as a basis for measurement for accident analysis in the

($UtiSch_+$) Model context. The novelty of this method will steward the process of achieving a resilient decision-making approach, with a basis for making a decisive assessment among alternative choices on operational risk. Fig 4.6 shows a novelty model for ranking risk.

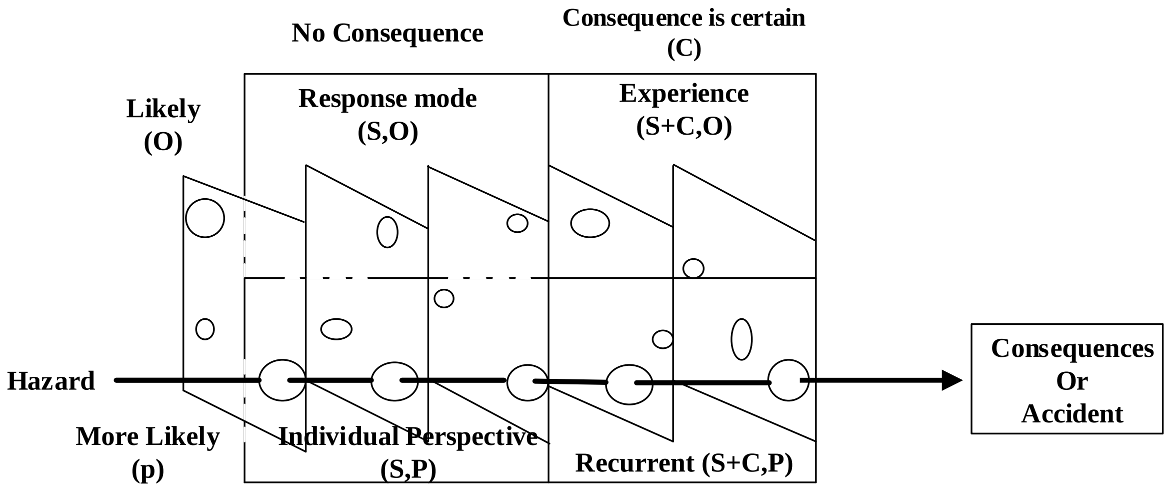


FIGURE 4.6: The Utility and Swiss Cheese Model ($UtiSch_+$)

A certainty equivalent value (CE (V)), based upon the Utility Theory, is developed and found in conjunction with the probability of an outcome in order to find the equivalent value of a specific risk.

A safety barrier is implemented to protect people, the environment and assets from hazards or dangers. Though different terms with similar meanings (safety element, defence, protection layer, etc.) have been used in various industries, sectors and countries (Xue et al., 2013), the specific strengths of the barriers are to avoid, prevent, control and mitigate risk; when a barrier is bridged, it results in an active failure (Broadribb et al., 2009).

The proposed theory and model of the decision making under risk provide as much robust information as possible about the risky prospect (He and Huang, 2008). There are two(2) steps in assessing paired method expected utility functions; these are:

- The utility context of the comparisons
  - Preference comparison and probability equivalence (hybrid method)
- Other approach
  - The Swiss Cheese Model (SChM)

The risk-return framework shows that a DMs perception of risk affects the choices s/he or makes (Van Bossuyt et al., 2012).

4.6 $UtiSch_+$ Process

In a situation where there is lack of data, quantifying of expert's (DMs) judgement qualitatively allows for a step-by-step analysis of the possible risks that might pose a major hazard with the potential to cause disruption to operations with long-term consequences. This study uses a questionnaire design to address the DMs attitude towards risk by means of the utility elicitation. The selection of experts will be based on expertise in and experience of OTOs, and three experts on loading and unloading operations as well as two executive directors will be chosen. The content and language used in the questionnaire will be revised by two scholars after initial design to facilitate understanding (Shang and Tseng, 2010). The questionnaire adopts a seven-point Likert-type scale to evaluate risks. Estimating risk mostly emphasises damage frequency and severity. Damage frequency means the average rate of risk accidents and damage severity means the consequences of the damage of risk accidents. Fig 4.7 represents the goal of $UtiSch_+$.

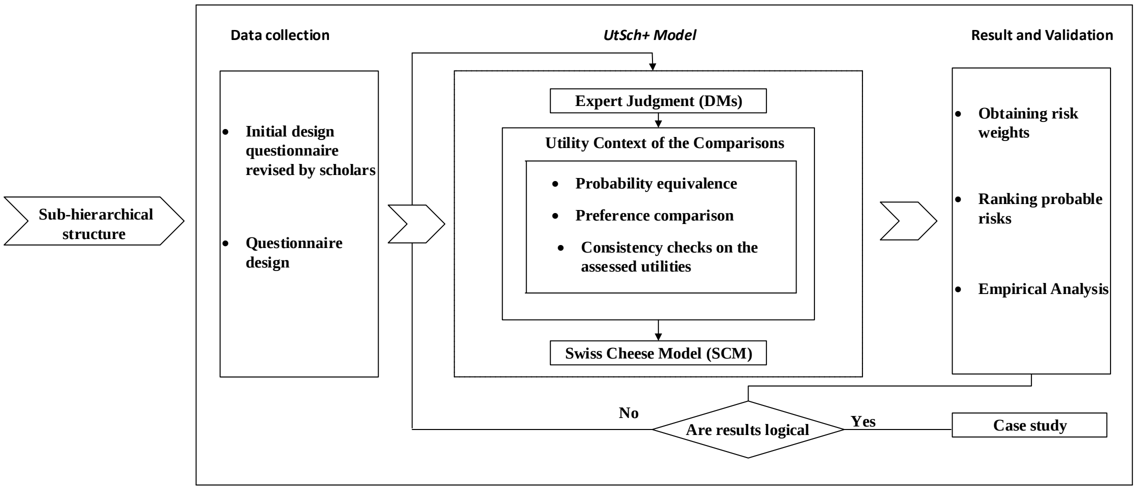


FIGURE 4.7: Method for the proposed $UtiSch_+$ for ranking probable risk

4.7 An Empirical Study on the Uncertainties of OTOs

To investigate the uncertainties for oil terminal operational hazards, firstly, OTOs hazards have to be determined. Empirical study provides a set of values and consistency to simulate the proposed model. More so, it is an investigative platform where there is no extent research on significant hazards causing unexpected events on CMOs. This study was executed in three phases: (1) questionnaire formulation and pilot study, (2) choosing the right experts and (3) survey data collection and description. We discuss each of the phases below:

4.7.1 Procedure for questionnaire design and pilot study

The questionnaire is systematically designed with the help of the sub-hierarchal structure. Based on this information, data collection and content validity was performed to improve the clarity of the questionnaire. First, a draft version of the questionnaire and cover letter was developed. The questionnaire was examined by two academicians and three specialists to comment on the appropriateness of the questions and whether any were confusing. Based on their feedback, the questionnaire was reworded for the pilot study. The pilot study was conducted by asking different judges to pre-asses the questionnaires effectiveness, accuracy and unambiguous communication with the respondents. The six judges were drawn at random from an assembled maritime domain and oil terminal focus group comprising an industrialist, academics, and experts with both types of experience. All items on the questionnaire were measured on a seven-point Likert-type scale with response options ranging from 1 (very unlikely) to 7 (very likely). The ratio of the judges' correctness was considered good and the discriminant valid feedbacks from the pilot study were eliminated. Ethical approval was also obtained to further validate the questionnaire content and participant consent. The questionnaire (see Appendix 4C) as represented at the end of the pilot study was used for data collection.

4.7.2 Selection of Experts (DMs) for OTOs

As an exploratory study in this research area, a cross-section of experts or decision makers (DMs) was considered to participate in the survey. Experts with relative (onshore/offshore oil fields) and vast (academic, maritime domain, oil and gas refineries) experience related to this research were drawn at random. Experts service times and academic qualifications were used as the selection threshold (John et al., 2014b).Another factor being considered as a criterion for choosing experts was the region/country; it has to be a crude oil-producing region or somewhere refined crude oil is consumed in large amounts, thereby leading to large import of these refined products. Publicly available directories, LinkedIn and recommendations from safety consultants and senior lecturers from the department of maritime and mechanical engineering, Liverpool John Moores University were used to identify these experts.

The questionnaire was web-based and a link was e-mailed to the targeted expert participants. A cover letter appeared to respondents prior to the main question page (see Appendix 4C). As an example, five experts with the following background assigned possible failure outcomes regarding OTOs given their experience:

- A Doctor of maritime technology and marine industry for more than 20 years; having both academic and onshore/offshore industrial experience in the field of oil terminal management and marine operations.

- A senior maritime safety engineer with a PhD who has been involved with Quality, Health, Safety and, Environment (QHSE), on offshore/onshore oil installation and port safety for more than 20 years.

- A Very Large Crude Carrier (VLCC) vessel captain of maritime transportation system who has been involved with (un)loading operation on offshore/onshore oil terminal platforms for more than 12 years

- A senior operation manager who has been involved with oil terminal operational services for more than 20 years.

- An assistant manager with a Master's degree in marine operation who has been involved in port management and applicability of modelling tools for OTOs for more than 20 years.

Similarly, when these five experts made their judgements, they assigned values to each question. Their evaluation for each question is presented in Table 4.11

4.7.3 Data Collection and Description

After a follow-up process, data were collected through a web-based questionnaire. Six uncompleted and completed questionnaires were returned. Twenty-five questionnaires were started, five of which were completed; one incomplete one was also submitted, and 19 were not returned. In all, the five valid responses obtained yield the final response rate of 20%. This response rate can be compared to other studies conducted in the literature (Mokhtari et al., 2012; Hammitt and Zhang, 2013; Alyami et al., 2014; John et al., 2016). Table 4.11 shows the consistency of HFs based on experts responses.

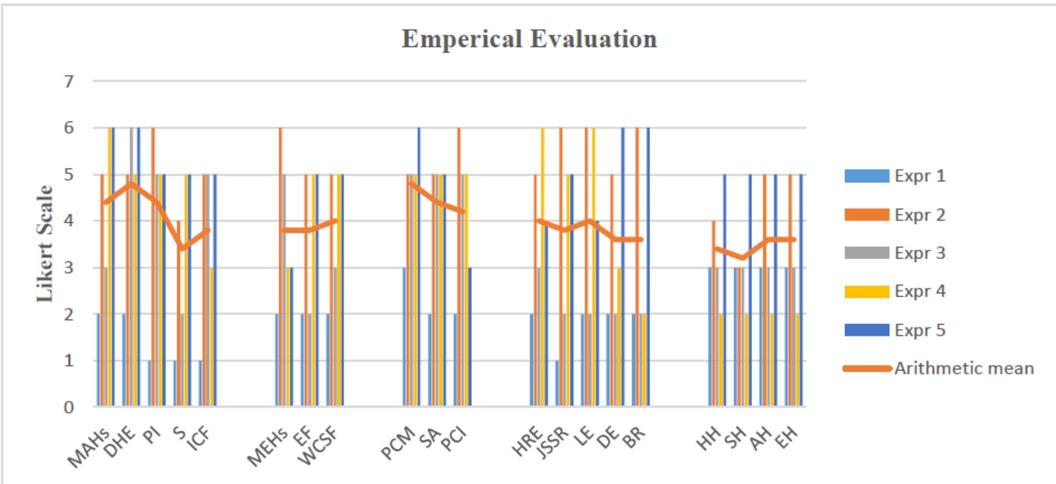


FIGURE 4.8: A graph showing the Empirical evaluation of HFs

From the questionnaire, the research revealed that 100% of the participants showed a good awareness and knowledge about the Hazard Factors (HFs), as well as the possible

TABLE 4.11: Consistency of HFs based on experts' responses

Hazards/Failures	**HFs**	**Arithmetic mean**
Man-related Hazard	Major Accident Hazards	4.40
	Duty Holder Error	4.80
	Personnel Issues	4.40
	Sabotage	3.40
	Indirect Contributing Factors	3.80.
Machine-related Hazard	Maintenance Event Hazards	3.80
	Equipment Failure	3.80
	Well Control System Failure	4.00.
Coordination and correspondence-related Hazard	Platform Communication Misinterpretation	4.80
	Situation Awareness	4.40
	Lack of Proper Crew Interaction	4.20.
Management-related Hazard	Human Resources Error	4.00
	Job Safety Rules and Regulation	3.80
	Latent Error	4.00
	Design Error	3.60
	Business Risk	3.60.
Nature-related Hazard	Hydrologic	3.40
	Seismic	3.40
	Atmospheric	3.60
	Epidemic	3.60.

consequences of these HFs for OTOs. In addition, Fig 4.8 shows the consistency of participants responses. The participants are all senior employees with experience all over the world, which also represents around 100% of the whole sample. In order to eliminate the presence of response bias, participants were chosen from the United Kingdom, Iran, United Arab Emirates, China and Nigeria. These represent the major oil importing and exporting countries where OTO activities are being performed at a large scale.

According to participants, the probabilities of these HFs occurring on oil terminal platforms spans very unlikely (1) to moderately likely (6). The quantitative data collected were to be used for the application of the $UtiSch_{+}$ model in a case study, as described below.

4.8 Case Study

Company A is one of the leading suppliers of crude oil and refined petroleum in Kaohsiung oil terminal, in south China. The company needs to choose a risk attribute(s) that will result in accident/catastrophe as a result of the weakness of the safety barriers at the oil terminal. This enables the forecasting of operational risk factors with high chances of causing a failure. With the aim of improving the process of achieving resilience at Kaohsiung oil terminal, decision-making methods have been used to ascertain possible risk attributes, but a major problem is how to rank the risk attributes according to their weight. A robust risk ranking method has been proposed, the $UtiSch_{+}$, to promote adaptability and safety.

To address this problem, five experts from external organisations were invited to form a committee. A normative individual response model that included models of individual perspective, response mode, recurrence and experience was developed. The model led to managerial actions that were able to improve maritime critical system adaptation to catastrophe by roughly 50 percent. The committee comprises of:

- A senior operations manager who has been involved with port operational services for over 20 years.
- A senior marine and safety engineer who has been involved in maritime and port operational management for over 20 years
- A chief superintendent of maritime transportation systems who has been involved with maritime operations for over 20 years.
- A scholar from a renowned maritime academy.
- A professor from the department of engineering, technology and maritime operations at a renowned university.

The committee was tasked with developing a list of possible hazard attributes and also determining the attributes' ranking and weights. Each expert was requested by the committee to participate in a study that would require completion of a questionnaire.

In the utility assessment, four perceptual attributes of the DM were identified, namely: individual perspective, response mode, recurrence and experience. These were deduced from previous study and literature. These perceptual attributes were rated on a seven-point Likert-type scale (e.g. 1 (extremely poor), 2 (very poor) , 3 (poor), 4 (satisfactory), 5 (good), 6 (very good) , and 7 (excellent)) and for the hazard attributes (very unlikely (1), moderately unlikely (2), somewhat unlikely (3), not sure (4), somewhat likely (5), moderately likely(6) and very likely (7)).

After the investigation and survey, 100% of the questions were answered by all five DMs ($expr1, expr2, \ldots, expr5$). The committee (DMs) finalised the attributes deduced from the dynamic hierarchical structure. Some of the attributes considered were as follows:

- R_1: Major Accident Hazards (MAHs),
- R_2: Duty Holder Error (DHE),
- R_3: Personnel Issues (PI),
- R_4: Sabotage (S),

- R_5: Indirect Contributing Factors (ICF).

Table 4.12 represents the five experts' (DMs) comparisons for $R_1 - R_5$ using the seven-point Likert-type scale questionnaire (see Appendix 4A for $R_1 1 - R_{44}$). The first expert's judgements were between 'low importance', (1 and 2), the second and fifth experts estimated the comparisons between 'high importance' (5 and 6), and the third and fourth experts evaluated the comparisons between 'low' and of 'high importance' (2, 3, 5 and 6). Table 4.13 represents experts' perceptual attributes for utility assessment.

Table 4.12: DMs' decision on hazard attributes

	Experts				
HF	**Expr 1**	**Expr 2**	**Expr 3**	**Expr 4**	**Expr 5**
MAHs (R_1)	2	5	3	6	6
DHE (R_2)	2	5	6	5	6
PI (R_3)	1	6	5	5	5
S (R_4)	1	5	2	5	5
ICF (R_5)	1	5	5	3	5

where: $(Expr)$ = expert, and(HF) = Hazard factor

Table 4.13: DMs' Utility assessments

	Experts				
UCC	**Expr 1**	**Expr 2**	**Expr 3**	**Expr 4**	**Expr 5**
YOE	20 yrs	20 yrs	12 yrs	20 yrs	21 yrs
RM	7	5	3	6	6
IP	7	5	3	4	6
RO	1	5	1	3	5

where: (UCC) = Utility context of comparison,(YOE) = years of experience, (RM) = response mood,(IP) = individual perspective, and(RO) = recurrence

Where recurrence is correlated with trust, prevention and availability of good documentation of threats/incidents/hazard/accidents, individual perspective reflected preference of *x,y,z* attributes, response mood was not just how the DMs responded but the DM mood of the day and experience reflected years.

4.8.1 $UtiSch_{+}$ Model and Application

A 2 × 2 matrix is constructed and calculated manually to obtain each DM's certainty equivalent value *(c)*, for the Utility assessment. Similarly, when the experts made their judgements for the UCC, they assigned values to each criterion until all the elements in the matrix were obtained, such as Fig 4.2:

In the individual preference context, c is the minimum preference given to p that the DM possesses. In the response mode context, c is the mode where the DM is indifferent, between either c or p. In the recurrent context, one is forced to give up either the amount c or (p or 0); c is the indifferent point between these two choices. In the experience context, the DM begins with c; the DM is asked to specify p with c for which s/he is indifferent between alternative choices. A 2 × 2 matrix is constructed for the UCC as follows:

using the coefficients of $\aleph\beta$ *and AB for the* 2×2 *matrix for the above linear equation,* the Certainty Equivalent Value (CE(V)) for each expert can be obtained. Table 4.15 represent the certainty equivalent for each expert utility assessment.

	Expert 1	
	nc	**cc**
O	7	20
P	7	1

Let: $nc = 2, cc = 7$ and $O = 2, P = 7$
$[1\aleph + 20\beta = 7] \sim [1\aleph + 7A = 7]$
$[7A + 7B = 2] \sim [20\beta + 7B = 2]$

Where: $\aleph$ and β are the coefficients of RO and YOE, respectively, and A and B are the coefficients of IP and RM, respectively.

$$\left[\begin{array}{cc|c} 1 & 20 & 7 \\ 7 & 7 & 2 \end{array}\right] \sim \left[\begin{array}{cc|c} 1 & 7 & 7 \\ 20 & 7 & 2 \end{array}\right]$$

$$\frac{1}{1}(R_1)\cdot\left[\begin{array}{cc|c} 1 & 20 & 7 \\ 7 & 7 & 2 \end{array}\right] = \left[\begin{array}{cc|c} 1 & 20 & 7 \\ 7 & 7 & 2 \end{array}\right] \sim \left[\begin{array}{cc|c} 1 & 7 & 7 \\ 0 & -133 & -138 \end{array}\right] = -20(R_1) + (R_2)\cdot\left[\begin{array}{cc|c} 1 & 7 & 7 \\ 20 & 7 & 2 \end{array}\right]$$

$$-7(R_1) + (R_2)\cdot\left[\begin{array}{cc|c} 1 & 20 & 7 \\ 7 & 7 & 2 \end{array}\right] = \left[\begin{array}{cc|c} 1 & 20 & 7 \\ 0 & -133 & -47 \end{array}\right] \sim \left[\begin{array}{cc|c} 1 & 7 & 7 \\ 0 & 1 & 1.0376 \end{array}\right] =$$

$$-\frac{1}{133}(R_2)\cdot\left[\begin{array}{cc|c} 1 & 7 & 7 \\ 0 & -133 & -138 \end{array}\right]$$

$$-\frac{1}{133}(R_1)\cdot\left[\begin{array}{cc|c}1 & 20 & 7\\ 0 & -133 & -47\end{array}\right]=\left[\begin{array}{cc|c}1 & 20 & 7\\ 0 & 1 & 0.3534\end{array}\right]\sim\left[\begin{array}{cc|c}1 & 0 & -0.2634\\ 0 & 1 & 1.0376\end{array}\right]=$$

$$-7(R_2)+(R_1)\cdot\left[\begin{array}{cc|c}1 & 7 & 7\\ 0 & 1 & 1.0376\end{array}\right]$$

$$-20(R_1)+(R_2)\cdot\left[\begin{array}{cc|c}1 & 20 & 7\\ 0 & 1 & 0.3534\end{array}\right]=\left[\begin{array}{cc|c}1 & 0 & -0.068\\ 0 & 1 & 0.3534\end{array}\right]\sim\left[\begin{array}{cc|c}1 & 0 & -0.2634\\ 0 & 1 & 1.0376\end{array}\right]$$

$$\text{therefore } \aleph=-0.0680, \beta=0.3534 \text{ and } A=-0.2634, B=1.0376$$

In solving group decision-making problem under uncertainty, importance weights of various criteria and the ratings of qualitative criteria are considered as linguistic variables. These weights can be obtained by directly assigning grades to evaluate the importance(Chen, 2000) of a specific criterion with respect to the various criteria. Table 2 represents the probabilities assigned to the seven-point Likert-type scale in Eq (4.4) for the utility assessment.

TABLE 4.14: Criteria for assigning probabilities, as adapted from Chen (2000)

Occurrence likelihood	**Grade**	**Probabilities**
Very Low (VL)	1	$(0, 0, 0.1)$
Low (L)	2	$(0, 0.1, 0.3)$
Medium Low (ML)	3	$(0.1, 0.3, 0.5)$
Medium (M)	4	$(0.3, 0.5, 0.7)$
Medium High (MH)	5	$(0.5, 0.7, 0.9)$
High (H)	6	$(0.7, 0.9, 1.0)$
Very High (VH)	7	$(0.9, 1.0, 1.0)$

To calculate the utility function of an expert judgement $(expr1, expr2, \ldots, expr5)$ for each HF, the outcomes can be obtained using Eq (4.17), as follows:

$$u(x_i) = p_1 u_1(x_i) + (1 - p_i)u_1(x_i) \tag{4.7}$$

where:

$u(x_i)$ = utility function of $(x_1, x_2, \ldots, x_n)$ attributes, and

$(x_1, p_1, x_2, 1 - p_1)$ = probability in which one has a p chance of an outcome x_1 and a $1 - p$ chance of an outcome x_2.

The case study demonstrates how the methodology can be implemented to assess probable hazard factor(s) affecting the smooth operation of OTOs. Behavioural utility of a DM can have different results when made based upon the information produced by this method. Based on the generic possible failures identified in the SChM for Kaohsiung oil terminal, as shown in Fig 4.9 and the available information in the Tables C.14, A.2, a decision analyst can identify key systems elements, and areas that require a great deal of attention to ensure a resilient system.

4.8.2 Results Analysis

The introduction in the questionnaire defines the scope of the generic OTOs to help the experts understand what is required in answering the questions. The lottery questions were asked to assess risk aversion and check for utility independence. The questionnaire was used to assess attribute importance and check for preferential independence. The responses plus one combined lottery and trade-off question supplied enough data to manually calculate each respondent's multiplicative utility function over the four attributes for utility assessments.

Based on the utility parameters, predictions were made for the first choice among all attributes given to experts in the written questionnaire. The ratings of preference, response mode, recurrence and experience for each concept were used as independent variables and the concept with the highest utility was designated as the first choice.

A pre-test of the lottery questions indicated that a constantly risk-averse function was a reasonable approximation for the experts, thus concentrating on a parameter estimation with testing of utility and preferential independence of the HFs.

Useful qualitative properties of the utility function can be determined by establishing relationships between certainty equivalents assessed in different contexts. The underlying utility function must be either linear or exponential and preference comparison provides a linear constraint that the utility function must satisfy. A common question in evaluating the risk indicator p is how to investigate attitudes in a preliminary analysis to specify a certainty equivalent c for which the DM is indifferent between the following two alternative choices ("locally best and worst" outcomes), and checking the consistency of an assessed utility function. Although each context is distinguished by a different status quo position, one is always asked to find c such that (1) holds.

The decision analyst further derived a threshold for the DM preference, k. Once k is set, the DM preference above k becomes the more likely. With very weak restrictions on the probability distribution on k and the decision maker's utility function, Toda

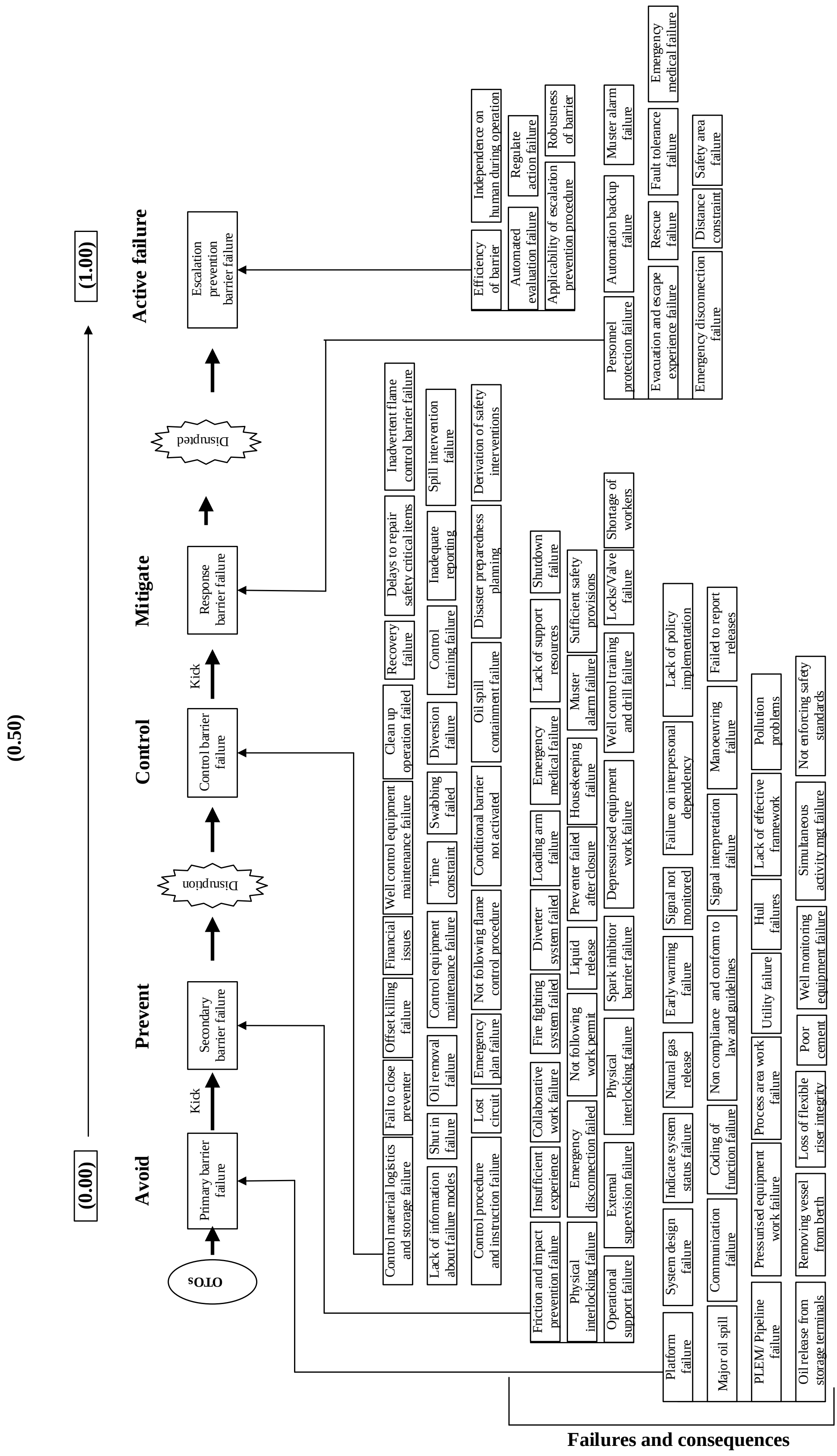


FIGURE 4.9: Failures of barriers in the proposed model

TABLE 4.15: Certainty equivalent for each Expert's utility assessment

	Certainty		Likelihood			
Experts	ℵ	β	**A**	**B**	**C ≥ or ≤ L**	**Probability(P)**
expr 1	−0.0680	0.3534	−0.2634	1.0376	$nC \leq L$	$0.0 \geq 0.1 \leq 0.3$
expr 2	0.0668	0.3333	−0.3333	1.7333	$nC \leq L$	$0.0 \geq 0.1 \leq 0.3$
expr 3	0.0909	0.5758	−0.4545	2.4545	$nC \leq L$	$0.0 \geq 0.1 \leq 0.3$
expr 4	−0.0323	0.3548	−0.5484	2.1613	$nC \leq L$	$0.0 \geq 0.1 \leq 0.3$
expr 5	0	0.3333	−0.3125	1.4271	$nC \leq L$	$0.0 \geq 0.1 \leq 0.3$

and MacCrimmon (1972) prove that k which maximises expected utility is indeed the DM's minimum preference. This technique is analogous to a "proper scoring rule" for motivating an individual to report his/her true values in probability assessment. For many years, the accepted practice in utility analysis has been to consider p over the final assets in dealing with x such that:

$$u(c_1, c_2, \ldots, c_n) = p_1 u_1(c_1, c_2, \ldots, c_n) + (1 - p_1) u_1(c_1, c_2, \ldots, c_n) \tag{4.8}$$

Assume that the assumptions of utility independence and constant risk aversion for a sequence of risk factors as well as the preferential independence for each pair of attributes has been verified; in practice, these would be checked by pre-tests and/or repeated measures. Mainly based on Farquhar (1984), the multiplicative function is given by:

$$\begin{aligned} &u(c_1, c_2, c_3, c_4, c_5) = \\ &p_1u_1(c_1) + p_2u_2(c_2) + p_3u_3(c_3) + p_4u_4(c_4) + p_5u_5(c_5) + xp_1p_2p_3p_4u_1(c_1)u_2(c_2)u_3(c_3)u_4(c_4) \\ &\quad + xp_1p_2p_3p_5u_1(c_1)u_2(c_2)u_3(c_3)u_5(c_5) + xp_1p_2p_4p_5u_1(c_1)u_2(c_2)u_4(c_4)u_5(c_5) \\ &\quad + xp_1p_3p_4p_5u_1(c_1)u_3(c_3)u_4(c_4)u_5(c_5) + xp_2p_3p_4p_5u_2(c_2)u_3(c_3)u_4(c_4)u_5(c_5) \\ &\quad + xp_1p_2p_3p_4p_5u_1(c_1)u_2(c_2)u_3(c_3)u_4(c_4)u_5(c_5) \end{aligned} \tag{4.9}$$

where: $u_1(c_1, c_2, c_3, c_4, c_5 = max) = 1$ and $u_1(c_1, c_2, c_3, c_4, c_5 = min) = 0$.

Then substituting Equation 6 in Eq (4.17), and cancelling terms for $u_5(c_5)$ yields:

$$u(c_1) = p_1 u_1(c_1 = max) + (1 - p_1) u_1(c_1 = min) \tag{4.10}$$

The only options required for utility assessment are simple outcomes (riskless outcomes) and binary lotteries (lotteries with two outcomes). The basic claim of Expected Utility assumption is that the preference ordering among lotteries is the same as the ordering of the lotteries by their expected utilities. This claim can be stated in terms of binary lotteries as follows:

$$(c_1, p_1; c_2, 1-p_1) > (x_1, q_1; x_2, 1-q_1)$$
$$\text{iff}$$
$$p_1u_1(c_{1max}) + (1-p_1)u_1(c_{1min}) > q_1u_1(x_{1max}) + (1-q_1)u_1(x_{1min}) \tag{4.11}$$

$$(c_1, p_1; c_2, 1-p_1) \sim (x_1, q_1; x_2, 1-q_1)$$
$$\text{iff}$$
$$p_1u_1(c_{1max}) + (1-p_1)u_1(c_{1min}) = q_1u_1(x_{1max}) + (1-q_1)u_1(x_{1min}) \tag{4.12}$$

One special case of condition (10) is especially useful in utility assessments, namely the case where one observes an equivalence between a certain outcome W and a gamble $(c_1, p_1; c_2, 1-p_1)$. From Eq (4.11), we may infer that:

$$W \sim (c_1, p_1; c_2, 1-p_1) iff U(W) = p_1u_1(c_{1max}) + (1-p_1)u_1(c_{1min}) \tag{4.13}$$

As an alternative to the piecewise linear utility function, one could fit a parametric utility function like a power or exponential utility function to the pairs, $[x_1, U(x_1)], \ldots, [x_n, U(x_n)]$, by means of a non-linear regression procedure. Let A designate the best outcome, and Z designate the worst outcome. As noted above, we are free to assign the utilities $U(A) = 100$ and $U(Z) = 0$. To assess the utility of any other outcome,B, the client is asked to judge the probability p^* that satisfies the relation:

$$B \sim (A, p^*; Z, 1-p^*) iff U(W) = p_1u_1(c_{1max}) + (1-p_1)u_1(c_{1min}) \tag{4.14}$$

If p^* is the probability that creates the equivalence in Eq (4.14), then p^* will be called the probability equivalent of B with respect to the endpoints A and Z. By Condition (11), we infer that:

$$U(B) = p^*U(A) + (1 - p^*)U(Z) = p^*(100) \quad (4.15)$$

or

$$U(B) = p^*U(c_{1max}) + (1 - p^*)U(c_{1min}) = p^*(c_{1max}) \quad (4.16)$$

the scaling also gives:

$$U(B) = (1 - exp[-r_1(c_1 - c_{1min}]/(1 - exp[-r_1(c_{1max} - c_{1min}]$$

therefore, non linear regression

$$(r_1) = (\frac{1}{c_{1min}})ln[p_1/(1 - p_1)$$

To illustrate this approach (Eq (4.11), let $c_1, \ldots, c_n$ be a list of risk factors, and let $c_{1min} = 0$ and $c_{1max} = 1$ denote the worst and the best outcomes of the risk factors respectively. Let $p_1^*, \ldots, p_n^*$ denote the probability equivalents of $c_1, \ldots, c_n$ with respect to the endpoints, c_{1min} and c_{1max}, and let $U(c_1), \ldots, U(c_n)$, be the corresponding utilities inferred by means of the standard gamble method. According to the power QALY model, $U(c_i) = k \cdot X_i^r$ for every i. Because utilities were assigned under the specification $U(c_{1max}) = 1$ (Eq (4.14) assumption), we must have $1 = U(c_{1max}) = k \cdot c_{1max}^r$, or $k = 1/c_{1max}^r$. By (Eq (4.11), $U(x_i) = p_1^*(1)$, where p_1^* is the i^{th} probability equivalent; therefore, $p_1^*(1) = U(c_i) = (1/c_1max^r) \cdot C_1^r$, i.e.:

$$p_1^* = c_1^r/c_1max^r = (c_1/c_1max)^r \quad (4.17)$$

where:
p_1^* = serves as the dependent variable,
Values of $(c_1/c_1max)^r$serve as the predictor variable in a non-linear regression that solves the value of r,
The constant k is an arbitrary constant chosen so that the utilities range over a convenient interval of numbers, i.e. $k = \frac{100}{25}^r$causes the utilities to range between 0 and 100.

The power QALY model implies that a utility function of an outcome is risk averse if $r < 1$, it is risk neutral if r = 1, and it is risk seeking if $r > 1$. With a sufficient set of constraints, the decision analyst can develop fairly tight bounds on either admissible utility functions or consistent future responses.

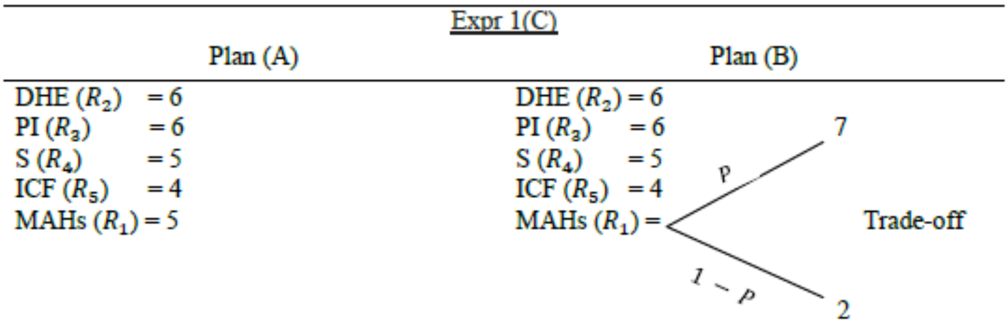


FIGURE 4.10: Schematic of lottery for MAHs

$u(c_1) = p_1 u_1(c_1 max) + (1 - p_1)u_1(c_1 min)$ Eq. 4.7
$u(c_1 = 5) = p_1 u_1(c_1 max = 7) + (1 - p_1)u_1(c_1 min = 3)$
where:
$u_1(c_1 = 7) = 1 and u_1(c_1 = 3) = 0, p_1 = 0.5, 0.7, 0.9$
But $p^* = \frac{C_1^r}{c_1 max^r} = (c_1/c_1 max)^r$ or $(\frac{5}{7})^{0.4236} = 0.8670$
$U(c_1 max) = k \cdot c_1 max^r$, or $k = \frac{1}{c_1 max^r}$, therefore $k = \frac{1}{7^{0.4236}} = 0.4385$
The constant k is an arbitrary constant chosen so that the utilities range over a convenient interval of numbers, i.e. causes the utilities to range between 0 and 1.
Under the EU assumption, the power parameter r= 0.4236 Substituting for equation Eq. 4.7
$u(c_1 = 5) = 0.8670(1) + (1 - 0.8670)(0)$
$U(c_1) = 0.8670$
Power QALY model
$U(b, x) = k \cdot H(b) \cdot x^r . U(c_1) = k \cdot H(b) \cdot x^r$
$U(c_1) = 0.4385 \cdot (1) \cdot 5^{0.4236} = 0.8670$

Utility Belief Limit for certainty equivalent utility assessment: The criterion for each certainty equivalent is revealed in the utility belief limit, such that it influences the probability for obtaining the weight of each hazard factor (HF) in the SChM. The utility belief limit is considered as the mechanism for the integration in the $UtiSch_+$ model. For example, the belief limit associated with the third condition states that " the utility for the nth expert indicate the likelihood L of certainty c for an unexpected event to occur with no consequences, is at 50% utility function for all combination made". Based on the data obtained from all experts, the certainty equivalent and the utility assessment result as calculated, is then analysed based on the developed utility belief limits for OTOs.

- The belief limit associated with $cC \sim mL$ indicates that expert's certainty equivalent level is at 100% utility function.

- The belief limit associated with $cC \sim L$ and $cC \leq mL$ indicates that expert's certainty equivalent level is at 75% utility function.
- The belief limit associated with $nC \leq L$ and $nC \sim mL$ indicates that expert's certainty equivalent level is at 50% utility function.
- The belief limit associated with $nC \sim L$ indicates that expert's certainty equivalent level is at 25% utility function
- The belief limit associated with $nC \sim cC$ and $nC \leq cC$ indicates that expert's certainty equivalent level is at 0% utility function.

By evaluating the certainty equivalent for each DMs utility assessment and the utility function of each hazard factor, the weight and ranking of the risk can be obtained using the $UtiSch_{+}$ model. This was calculated manually to determine the extent of failure of each hazard factor, represented by different colours in the SChM. The colours used identifies the path of progression towards active failure barrier. For instance, MAHs (R_1) is represented in a sky blue colour, and the extent of (R_1) failure was at the response barrier failure, measured as 0.75 in the SchM. Fig 4.11 shows the extent of failure for each HFs ($R_1 - R_5$) as embodied in Table 4.16 (see Appendix 4B for $R_11 - R_{44}$). The results of all evaluated HFs of all experts are represented in Table 4.17

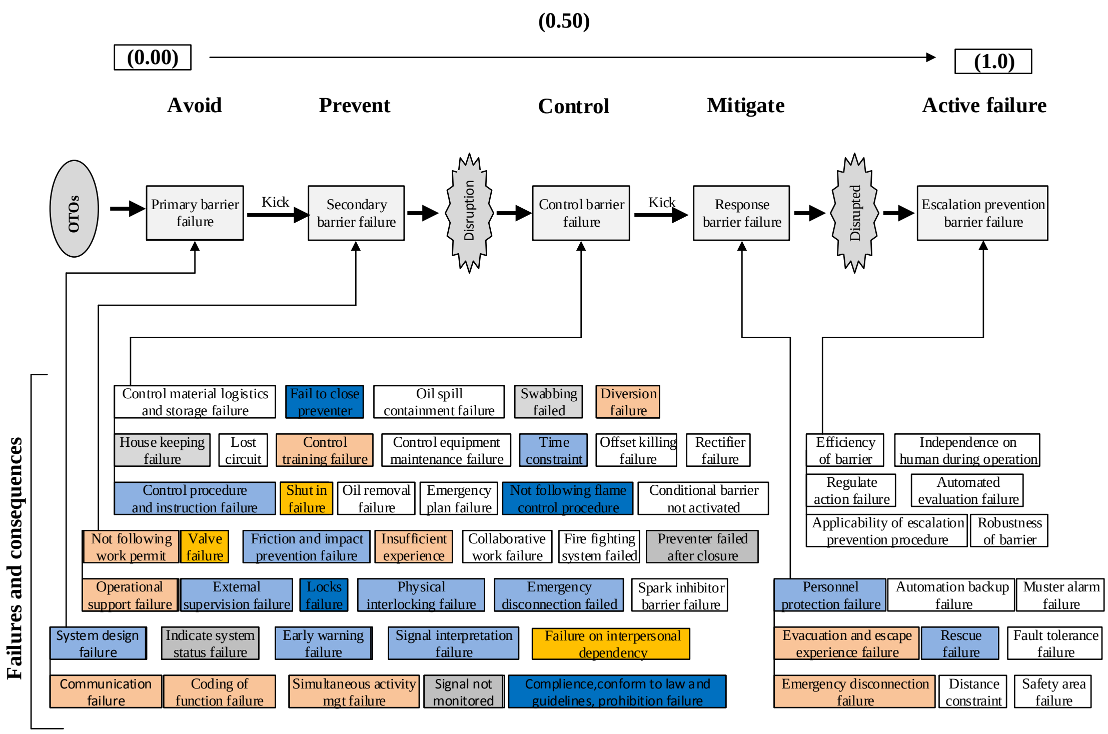


Figure 4.11: Extent of barriers failure for each HFs in the proposed model

	Expr 1(C)				Expr 2(B)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_1	0.5882	$c_1 < 0.75$	0.2206	1	0.8671	$c_1 < 0.75$	0.3250	1
R_2	0.5882	$c_2 < 0.75$	0.2206	1	0.8671	$c_2 < 0.75$	0.3250	1
R_3	0.4385	$c_3 < 0.50$	0.1096	3	0.9368	$c_3 < 0.50$	0.2342	3
R_4	0.4385	$c_4 < 0.50$	0.1096	3	0.7889	$c_4 < 0.50$	0.1973	5
R_5	0.4385	$c_5 < 0.50$	0.1096	3	0.8671	$c_5 < 0.50$	0.2168	4

	Expr 3(D)				Expr 4(Q)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_1	0.6984	$c_1 < 0.75$	0.2619	2	0.9368	$c_1 < 0.75$	0.3513	1
R_2	0.9368	$c_2 < 0.75$	0.3513	1	0.8671	$c_2 < 0.75$	0.3250	2
R_3	0.8671	$c_3 < 0.50$	0.2168	3	0.8671	$c_3 < 0.50$	0.2168	3
R_4	0.5882	$c_4 < 0.50$	0.1471	5	0.8671	$c_4 < 0.50$	0.2168	3
R_5	0.8671	$c_5 < 0.50$	0.2168	3	0.6984	$c_5 < 0.50$	0.1746	5

	Expr 5(W)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_1	0.9368	$c_1 < 0.75$	0.3513	1
R_2	0.9368	$c_2 < 0.75$	0.3513	1
R_3	0.8671	$c_3 < 0.50$	0.2168	3
R_4	0.8671	$c_4 < 0.50$	0.2168	3
R_5	0.8671	$c_5 < 0.50$	0.2168	3

TABLE 4.16: Experts assessments using the $UtiSch_+$ model

According to Eq (4.11) and (4.12), the utility function $[u(x)]$ for each expert can be represented by the following notations if and only if the equations are satisfied. From the result of the five experts, Fig 4.12 shows how the notations apply.

The weights of each HF was obtained based on the $UtiSch_+$ model for all expert as shown in Table 4.18. A graphical representation of the weighted values of all HFs are presented for ranking probable hazards, as shown in Fig4.13.

The ranking of uncertain and imprecise data in a decision-making process requires the assessment of the importance weight for each expert. Here, a vertex method which is elective and simple is proposed to rank the risk factors. The standard mean for $R_1, R_2, \ldots, R_4 4$ is calculated for all five experts, and the ranking can then be assigned. Although the proposed method presented in this thesis is illustrated by personal selection, it can also be applied to many other areas of management decision problems. Table 4.19 shows the highest-ranked hazard factor (R_2), which can lead to a disruption, and also shows the one with the lowest possible effect (R_4).

TABLE 4.17: Results for all Hazard Factors based on $UtiSch_+$

	Expr 1(C)			Expr 2(B)			Expr 3(D)			Expr 4(Q)			Expr 5(W)		
HF	**u(x)**	**UtiSch$_+$**	**W**	**u(x)**	**UtiSch$_+$**	**W**	**u(x)**	**UtiSch$_+$**	**W**	**u(x)**	**UtiSch$_+$**	**W**	**u(x)**	**UtiSch$_+$**	**W**
R_1	0.5882	< 0.75	0.2206	0.8671	< 0.75	0.3250	0.6984	< 0.75	0.2619	0.9368	< 0.75	0.3513	0.9368	< 0.75	0.3513
R_2	0.5882	< 0.75	0.2206	0.8671	< 0.75	0.3250	0.9368	< 0.75	0.3513	0.8671	< 0.75	0.3250	0.9368	< 0.75	0.3513
R_3	0.4385	< 0.50	0.1096	0.9368	< 0.50	0.2342	0.8671	< 0.50	0.2168	0.8671	< 0.50	0.2168	0.8671	< 0.50	0.2168
R_4	0.4385	< 0.50	0.1096	0.7889	< 0.50	0.2168	0.5882	< 0.50	0.1471	0.8671	< 0.50	0.2168	0.8671	< 0.50	0.2168
R_5	0.4385	< 0.50	0.1096	0.8671	< 0.50	0.2342	0.8671	< 0.50	0.2168	0.6984	< 0.50	0.1096	0.8671	< 0.50	0.2168
R_{11}	0.4197	< 0.75	0.2361	0.9368	< 0.75	0.3513	0.8671	< 0.75	0.3250	0.6984	< 0.75	0.2619	0.6984	< 0.75	0.2619
R_{12}	0.4197	< 0.75	0.2361	0.8671	< 0.75	0.3250	0.5882	< 0.75	0.2206	0.8671	< 0.75	0.3250	0.8671	< 0.75	0.32503
R_{13}	0.4197	< 0.75	0.2361	0.8671	< 0.75	0.3250	0.6984	< 0.75	0.2619	0.8671	< 0.75	0.3250	0.8671	< 0.75	0.3250
R_{21}	0.6984	< 0.50	0.1746	0.8671	< 0.50	0.2168	0.8671	< 0.50	0.2168	0.8671	< 0.75	0.2168	0.9368	< 0.75	0.2342
R_{22}	0.5882	< 0.50	0.1471	0.8671	< 0.50	0.2168	0.8671	< 0.50	0.2168	0.8671	< 0.75	0.2168	0.8671	< 0.75	0.2168
R_{23}	0.5882	< 0.50	0.1471	0.9368	< 0.50	0.2342	0.8671	< 0.50	0.2168	0.8671	< 0.75	0.2168	0.6984	< 0.75	0.1746
R_{31}	0.5882	< 0.50	0.1471	0.8671	< 0.50	0.2168	0.6984	< 0.50	0.1746	0.9368	< 0.50	0.2342	0.7889	< 0.50	0.1973
R_{32}	0.4385	< 0.50	0.1096	0.9368	< 0.50	0.2342	0.5882	< 0.50	0.1471	0.8671	< 0.50	0.2168	0.8671	< 0.50	0.2168
R_{33}	0.5882	< 0.50	0.1471	0.9368	< 0.50	0.2342	0.5882	< 0.50	0.1471	0.9368	< 0.50	0.2342	0.7889	< 0.50	0.1973
R_{34}	0.5882	< 0.50	0.1471	0.8671	< 0.50	0.2168	0.5882	< 0.50	0.1471	0.6984	< 0.50	0.1746	0.9368	< 0.50	0.2342
R_{35}	0.5882	< 0.50	0.1471	0.9368	< 0.50	0.2342	0.5882	< 0.50	0.1471	0.5882	< 0.50	0.1471	0.9368	< 0.50	0.2342
R_{41}	0.6984	< 0.75	0.2619	0.7889	< 0.75	0.2958	0.6984	< 0.75	0.2619	0.5882	< 0.75	0.2206	0.8671	< 0.75	0.3250
R_{42}	0.6984	< 0.75	0.2619	0.6984	< 0.75	0.2619	0.6984	< 0.75	0.2619	0.5882	< 0.75	0.2206	0.8671	< 0.75	0.3250
R_{43}	0.6984	< 0.75	0.2619	0.8671	< 0.75	0.3250	0.6984	< 0.75	0.2619	0.5882	< 0.75	0.2206	0.8671	< 0.75	0.3250
R_{44}	0.6984	< 0.50	0.1746	0.8671	< 0.50	0.2168	0.6984	< 0.50	0.1746	0.5882	< 0.50	0.1471	0.8671	< 0.50	0.2168

Notation	What it stands for:
C, B, D, Q *and* W	Experts (expr).
$u(D) = (R_{1max}, p_{1;} R_{1min,} 1 - p_1)$	A lottery in which $u(D)$has a p-chance of outcome R_{1max} and a 1-p chance of an outcome R_{1min}.
$[u(Q) \sim u(W)] > [u(B) > u(D) > u(C)]$	$[u(Q), u(W)]$ is preferred to$[u(C), u(B), u(D),]$ for R_1
$[u(D) \sim u(W)] \geq [u(B) \sim u(Q) > u(C)]$	$[u(W), u(D)]$ is equally more preferred than $[u(B), u(Q)]$ is preferred to $u(C)$ for R_2.
$[u(B)] \geq [u(D) \sim u(Q) \sim u(W) > u(C)]$	$[u(B)]$ is equally or more preferred than $[u(D), u(Q), u(W)$ is preferred to $u(C)$ for R_3
$[u(Q) \sim u(W)] \geq [u(B) > u(D) > u(C)]$	$[u(D), u(W)]$ is equally or more preferred than $[u(B)]$ is preferred to $u(D)$, $u(C)$ for R_4
$[u(B) \sim u(D) \sim u(W)] > [u(Q) > u(C)]$	$u(B), u(W), u(D)$ is more preferred to $u(Q)$ is preferred to $u(C)$ for R_5

FIGURE 4.12: Co-relation between experts' judgements based on the utility function

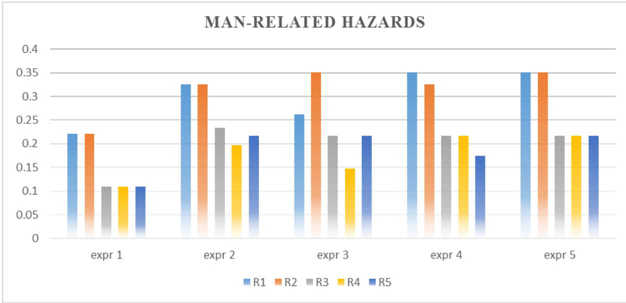
With additional research, perhaps questions about the choice of an appropriate context for behavioural utility assessment comparisons or the representation of the outcomes can be better resolved.

4.8.3 Discussion

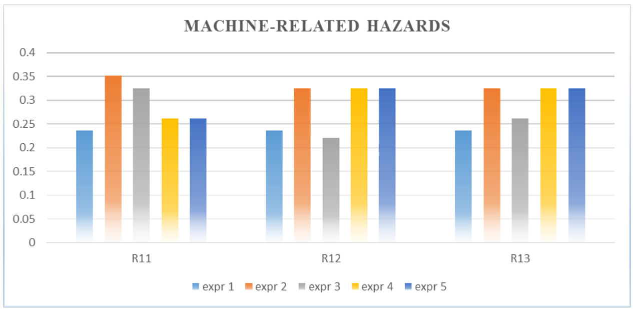
The onus on every decision the DM makes in regard to each hazard is the utility function. This tends to affect proactive inputs upon identification of the risk for OTOs. The majority of the events that result in an accident/catastrophe are a result of the weakness of safety barriers, and as such can provide some predictive correlation to operational failures. The uncertainties around OTOs require a concise and precision decision analysis in a manner that considers all internal, personal and external factors that have an effect on the DM. For OTOs to achieve system resilience in order to anticipate operational hazard factors under high uncertainty, developed risk assessment techniques based on innovation, tends to improve the process of achieving resilience.

A seven-point Likert-type scale was proposed, which was used to obtain data for the utility assessment and hazard attributes (See Appendix 4A). After the investigation, 100% of the questions were answered by all five DMs. Table 4.15 is very important in the $UtiSch_+$ model, such that the utility assessment for each expert in regard to utility belief limit for certainty equivalent utility assessment influences the probability for obtaining the weight of each HFs in the SChM. The certainty equivalent for experts 1-5 is $nC \leq L$ respectively. The probabilities (p_1) were adapted from Chen (2000), but the actual probability (p^*) was calculated using Eq (4.17). A non-linear regression (r_1) was also considered for the best and worst outcome.

The result in Table 4.19 can be established to forecast possible failures where uncertain and imprecise data may probably cause disruption. With the aid of the expert



(a)



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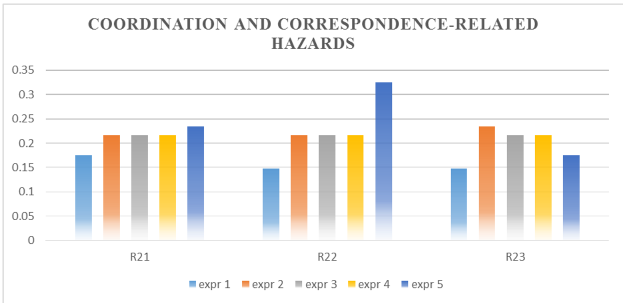

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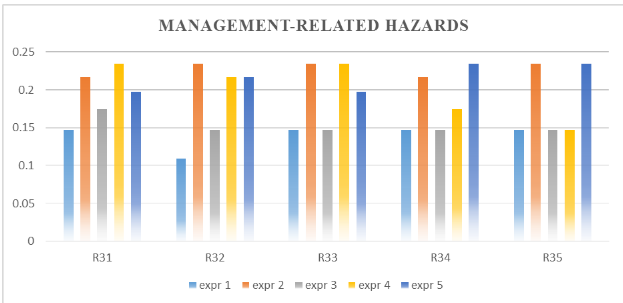

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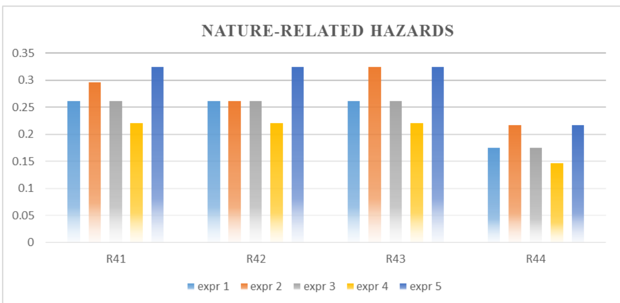


(e)

FIGURE 4.13: Fig (a),(b),(c),(d) and (e) are $UtiSch_{+}$ graphs for ranking probable hazards

Table 4.18: Experts' weighted values for each hazard factor

HFs	Expr 1	Expr 2	Expr 3	Expr 4	Expr 5
R_1	0.2206	0.3250	0.2619	0.3513	0.3513
R_2	0.2206	0.3250	0.3513	0.3250	10.3513
R_3	0.1096	0.2342	0.2168	0.2168	0.2168
R_4	0.1096	0.1973	0.0.1471	0.2168	0.2168
R_5	0.1096	0.2168	0.2168	0.1746	0.2168
R_{11}	0.2361	0.3513	0.3250	0.2619	0.2619
R_{12}	0.2361	0.3250	0.2206	0.3250	0.3250
R_{13}	0.2361	0.3250	0.2168	0.3250	0.3250
R_{21}	0.1746	0.2168	0.2168	0.2168	0.2342
R_{22}	0.1471	0.2168	0.2168	0.2168	0.2168
R_{23}	0.1471	0.2342	0.2168	0.2168	0.1746
R_{31}	0.1471	0.2168	0.1746	0.2342	0.1973
R_{32}	0.1096	0.2342	0.1471	0.2168	0.2168
R_{33}	0.1471	0.2342	0.1471	0.2342	0.1973
R_{34}	0.1471	0.2168	0.1471	0.1746	0.2342
R_{35}	0.1471	0.2342	0.1471	0.1471	0.2342
R_{41}	0.2619	0.2958	0.2619	0.2206	0.3250
R_{42}	0.2619	0.2619	0.2619	0.2206	0.3250
R_{43}	0.2619	0.3250	0.2619	0.2206	0.3250
R_{44}	0.8671	0.2168	0.1746	0.1471	0.2168

judgement on the dynamic hierarchical structure, the probabilities of the identified related hazards caused by the HFs $R_1, R_2, \ldots, R_{44}$ can be reviewed. The analysed results show that $R_2, R_1, R_{13}, R_{11}, R_{12}, R_{43}, R_{41}, R_{42}, R_{22}$ and R_{21} need a proactive approach combined with a robust yet flexible model for the resolutions of the problems in oil terminals.

The utility assessment for each DM was calculated as well as the utility function (See Appendix 4A, 4B). The combined utility assessments was analysed using the proposed $UtiSch_+$ model. Table 4.19 shows the hazard ranking, achieved using the proposed model. The graph shows the weighted distribution of each expert hazard factor. Although HFs $R_4, R_{35}R_{34}, R_{32}, R_{44}, R_5, R_{33}, R_{31}, R_{23}$ and R_3 might not pose much threat

Table 4.19: Ranking of hazard factors (HFs)

HFs	**Expr 1**	**Expr 2**	**Expr 3**	**Expr 4**	**Expr 5**	$M = \sum x \frac{1}{n}$	**R**
R_1	0.2206	0.3250	0.2619	0.3513	0.3513	0.3020	2
R_2	0.2206	0.3250	0.3513	0.3250	10.3513	0.3146	1
R_3	0.1096	0.2342	0.2168	0.2168	0.2168	0.1988	11
R_4	0.1096	0.1973	0.0.1471	0.2168	0.2168	0.1775	20
R_5	0.1096	0.2168	0.2168	0.1746	0.2168	0.1869	15
R_{11}	0.2361	0.3513	0.3250	0.2619	0.2619	0.2872	4
R_{12}	0.2361	0.3250	0.2206	0.3250	0.3250	0.2863	5
R_{13}	0.2361	0.3250	0.2168	0.3250	0.3250	0.2946	3
R_{21}	0.1746	0.2168	0.2168	0.2168	0.2342	0.2118	10
R_{22}	0.1471	0.2168	0.2168	0.2168	0.2168	0.2245	9
R_{23}	0.1471	0.2342	0.2168	0.2168	0.1746	0.1979	12
R_{31}	0.1471	0.2168	0.1746	0.2342	0.1973	0.1940	13
R_{32}	0.1096	0.2342	0.1471	0.2168	0.2168	0.1849	17
R_{33}	0.1471	0.2342	0.1471	0.2342	0.1973	0.1919	14
R_{34}	0.1471	0.2168	0.1471	0.1746	0.2342	0.1839	18
R_{35}	0.1471	0.2342	0.1471	0.1471	0.2342	0.1819	19
R_{41}	0.2619	0.2958	0.2619	0.2206	0.3250	0.2730	7
R_{42}	0.2619	0.2619	0.2619	0.2206	0.3250	0.2662	8
R_{43}	0.2619	0.3250	0.2619	0.2206	0.3250	0.2788	6
R_{44}	0.8671	0.2168	0.1746	0.1471	0.2168	0.1859	16

to operations, they have also weakened the safety barrier, which may lead to a disruption. It is thus important that OTOs are resilient enough to anticipate such failures.

According to the ranking from the $UtiSch_+$ model, Duty Holder Error (DHE) is considered the most highly ranked HF as well as Major Accident Hazards (MAHs) from Man-related hazards. The hazard considered to be very low ranked are Sabotage (S), Business Risk (BR) and Design Error (DE). The $UtiSch_+$ model is a novel approach for port practices and can also be suitable for risk management at industrial pots, with the aim of deciding which HFs could be ranked as most likely to cause a disruption.

4.9 Conclusion

Oil terminal platforms are vital complex marine operations, thereby facilitating global trade. The assessment of significant events disrupting OTOs tends to suffer from a lack of data to explain such events, and also from their infrequent occurrence. The risk within these operational infrastructures requires attention in respect to their identification, assessment and mitigation with the use of an appropriate RM approach. For OTOs to remain responsive to strategic needs and future challenges, subjective judgements of disruptive events were employed to model the imperfection associated with OTOs under high uncertainty.

This chapter has presented a quantitative approach, a generic risk assessment model based on the integration of Utility Theory and Swiss Cheese Model to determine the relative weight of the identified hazard factors. This approach intends to facilitate the process involved to significantly tackle uncertainties on oil terminal platforms for resilience improvement. Accident reports and literature review were used to identify hazard factors. An empirical study was further conducted to provide a set of values and consistency for the identified hazard factors to simulate the proposed model. Evidently, for a resilience-based modelling approach, input data can be expressed by an expert's (DMs) measure of satisfaction with a preference (utility) with the utility belief limit. This approach presents a favourable means with flexibility where subjective judgements and imprecise data can be modelled in a unified manner. The SChM approach employed provides a procedure for precise data aggregation of the original features where the safety barriers experienced multiple weakness under high uncertainty.

The usefulness of the $UtiSch_{+}$ model is demonstrated for resilience-based decision making. Experts provided a subjective assessment for the investigation of the risk of disruption in a stochastic manner. This approach provides a reliable, justifiable and unblemished method for determining the relative weight of the identified hazard factors. It can therefore be reasonably expected that the application of the novel model will serve as an impetus for the development of a resilient and enhanced marine environment for CMOs.

This chapter has explained the measure of satisfaction of a DM observed preference and presented a novel research technique behind the research methodology for the present study. Eventually, as revealed in the final result, the developed $UtiSch_{+}$ model does provide some level of confidence as a step towards preventing the risk of disruption for OTOs. However, the $UtiSch_{+}$ model cannot deal with the dependencies of the criteria; therefore, a BN approach is developed to complement this shortfall systematically and can be deduced in the next chapter.

Chapter 5

PRIORITY ASSESSMENT FOR OTOs HAZARDS USING BAYESIAN NETWORKS

Summary

This chapter presents a modelling approach that employs Bayesian Networks to evaluate the probabilities of the HFs with the most relative importance. A symmetrical method was used to assign prior probability for the variables responsible for OTO disruption under high uncertainties. The use of Bayesian Networks provided a flexibility to the model such that, in the event of new evidence, the model can be updated. The variables in the Bayesian Network are grouped into three categories of target node or goal, intermediate node and starting nodes. $UtiSch_+$ *model is mapped into BNs and the unconditional and conditional prior probability are calculated for each starting node. The Conditional Probability Table (CPT) for each intermediate node (child node) was determined for the associated starting node (parent node) and the marginal prior probability was calculated based on the strength of their direct dependence. A Bayesian Network Sensitivity Analysis method* ($_+BN-SAM$) *was performed accordingly. The evaluation of the HFs facilitates the process of determining the probability of the target node for strategic decision making towards OTOs resilience improvement and management.*

5.1 Introduction

The operation of offshore/onshore oil terminal platforms is prone to high levels of uncertainty because such operations usually take place in a dynamic environment where man, nature and organisational hazards may cause possible accidents. Offshore and onshore oil terminal platforms need to constantly adopt new approaches and technologies, and have to transport the latest hazardous materials, etc., each of which brings a new hazard in one form or another. A typical hazard is fire on an offshore oil terminal installation. Though the majority of incidents on oil terminal platforms occur when oil cargoes are offloaded, other related activities such as organisational influences are also taken into consideration. Furthermore, the development of models for hazardous materials' discharge during offloading using actual data where possible or an exploratory data modelling approach due to reasons based on uncertainty, shows that the outer influence of the environmental context is dynamically affected by other factors, both directly and indirectly. As such, there is a demand to develop a simple yet effective model to represent these affiliations between variables of each operational subsystem.

Studies have been actively carried out looking at how similar accidents may be prevented both at the national and international levels. Several methodologies have been used for the analysis of different accident scenarios, each of which benefits from different techniques. For example, Ren et al. (2008) developed a methodology capable of accommodating the modelling of multiple risk factors considered in offshore operations, which also has the ability to deal with different types of data that may come from different.

However, it is challenging to find a single yet flexible technique to wholly capture different phases of an accident from the beginning to the end, and which is also robust enough to fit a variety of accident types (Khakzad et al., 2013). Information about rare risk events inherently suffers from a meagreness of accident data. With an increasing awareness of environmental protection and associated safety issues, research of various kinds into maritime risk assessment and analysis therefore forms an important research domain.

The fundamental concepts of probabilistic graphical models or probabilistic networks have become an increasingly popular paradigm for reasoning under uncertainty. However, even though probabilistic networks provide an intuitive language for constructing knowledge-based models for reasoning, one can often benefit from a deeper understanding of the principles underlying these models. Nevertheless, having a basic understanding of the structure of a model and the relation between probabilistic network and the complexity of inference may prove useful in the model development phase.

A few authors have used Bayesian inference, in which uncertainty handling and belief updating are inherent characteristics (Khakzad et al., 2013). Despite the remarkable effort performed at different levels to achieve safety, the occurrence of accidents and incidents at seaports is still increasing (Ronza et al., 2007). We take a novel approach to risk analysis of activities relating to onshore and offshore offloading of hazardous materials performed on oil terminal platforms, using the Utility and Swiss Cheese Model ($UtiSch_{+}$) in the risk framework. Bayesian Network (BN) is tailored to fit into the framework to construct a causal relationship model for OTOs.

5.2 Bayesian Networks' (BNs) Applications

A simple Bayesian Network (BN) is a directed acyclic graph (DAG), in which the nodes denote variables, arcs signify direct causal relationship between the linked nodes, and Conditional Probability Tables (CPTs) assigned to the nodes represent conditional dependencies. BNs are now being used in a variety of applications. Their application has been used in different domains, e.g. for diagnostics in medicine and complex nuclear power systems, prediction in complex maritime critical systems, control and modelling for human understanding, ecological risk assessment and machine learning, e.g. finance, robotics and Google. A few researchers have adopted the BN method for risk management in large engineering projects (Ordonez, 2007), mainly focusing on the application. Various applications of BNs as a modelling tool in maritime risk analysis have been widely developed (Ren et al., 2008; Trucco et al., 2008; Ren et al., 2009; Clark and Besterfield-Sacre, 2009; Lu et al., 2011; Fernàndez-Garcia et al., 2012; Li et al., 2014). However, some difficulties arise when using BNs in offshore safety assessment (Ren et al., 2008), such as how to deal with incomplete and vague information that largely exists both at the early system design stage and during normal operations. Eleye-Datubo et al. (2006) used a BN to examine a typical ship evacuation in an accidental risk scenario. Trucco et al. (2008) developed a Bayesian belief network to model a maritime transport system, by integrating human and organisational factors into risk analysis. Ren et al. (2008) assessed offshore safety by combining Reasons Swiss Cheese model and a BN where prior probabilities were obtained by experts judgements. Ren et al. (2009) used a Fuzzy Bayesian Network (FBN) to quantify the collision risk between a Floating Production, Storage and Offloading (FPSO) unit and authorised vessels due to human error during operation. Anto et al. (2009) developed a model for maritime accidents by applying Bayesian belief networks, and the maritime accident database of the Portuguese Maritime Authority was used. Eleye-Datubo et al. (2008) developed a BN model to examine system safety during the transfer of oil to an oil tanker. Lu et al. (2011) innovative approach, integrated logistic regression and Bayesian networks (BNs), was applied to a case study for maritime risk assessment in the maritime industry. Alyami et al. (2014) evaluated the criticality of hazardous events in a container terminal using Fuzzy Rule-based Bayesian Network (FRBN). Salleh et al. (2014) used a Bayesian Belief Network as an assessment model for helping liner shipping operators to conduct a self-assessment of operational reliability in the container shipping industry. The application of BNs for maritime risk assessment is more skewed towards proactive and predictive purposes. John et al. (2014a, 2014b) proposes a novel fuzzy risk assessment approach to facilitating the treatment of uncertainties in seaport operations. Many criteria need to be considered and modelled under an uncertain environment and the oil terminal is one such environment. The application of BNs on an oil terminal platform to optimise the operational efficiency is a gap which needs to be bridged. Selecting dynamic model needs to be developed in order to select the appropriate resilience strategy, and BNs have been proven by various researchers to handle missing and/or incomplete data. BNs also have the ability to incorporate new observations into the network and to predict the influence of possible future observations onto the results obtained (see Chapter 2, Section 2.5.5 for BN advantages).

5.2.1 Dynamic Risk Analysis of OTOs for Resilience Modelling

The selection of an appropriate resilience investment strategy to optimise the performance effectiveness of terminal operation often requires analysts to provide data in a quantitative or qualitative assessment form for the analysis of complex operational systems (John et al., 2014b). The use of intelligent dynamic risk analysis techniques has become a critical part of building resilience in OTOs to enhance the ability to process large volumes of data in real-time situations. An holistic approach dependent on a step-by-step analysis to identify all influencing hazards for modelling under high uncertainty is required (Mostashari et al., 2011). This in turn assists decision makers to have a clear insight into the operations in order to propose resilience strategies for the improvement of OTOs.

While early research efforts were devoted to the protection of systems against disruptive events, be they malicious attacks, man-made accidents or natural disasters, recent attention has been shifted towards the ability of a system to 'bounce back' from these disruptive events (resilience) (Pant et al., 2014; John et al., 2016). When critical operational systems such as OTOs cannot substantially recover in the face of disruption due to a lack of robustness, they present themselves at any point within their operation as prone to disastrous consequences. Building resilience in maritime operations entails stakeholders' involvement in creating proficiencies and maintaining a sustained engagement in critical operational systems John et al. (2014a).

Critical infrastructure systems provide the essential physical basis for modern societies, and have a multi-dimensional impact on public safety and economic prosperity at regional and national levels (Shafieezadeh and Burden, 2014). Intelligent decision tools with systematic procedures tailored dynamically to handling complex systems such as OTOs are required to identify all causes of unexpected events with the potential for disruption to operations within complex critical systems.

Uncertainties in complex critical systems are mainly due to vagueness, randomness, ignorance and lack of data. Vagueness is mainly caused by ill-defined concepts in observation or inaccuracy and poor reliability of instruments used to make the observation. Wang et al. (1995) and Ren et al. (2005) developed a fuzzy reasoning approach to deal with vagueness of data used in maritime risk assessment. Randomness is due to unpredictable events, whilst ignorance is due to weak implications, caused by experts unable to establish a strong correlation between postulation and conclusion.

The literature highlights several reasons why a BN is suitable for use as a resilience modelling tool for enhancing the resilience of OTOs. They are based on its ability to model randomness and capture discrete causal relationships in complex critical operational systems, based on the modeller's expertise and the capability in adapting the system's behaviour from past experience. Individual probabilities of variables are combined using BNs to calculate the overall probability that a specific hazard is present (Lane et al., 2010). BNs can provide a powerful risk analysis modelling tool due to their flexibility and they have been widely used in a range of applications (Wang et al., 2013; Feng et al., 2014; Garcez and de Almeida, 2014).

However, a common criticism of BNs is that they are limited due to the fact that they require too much information in the form of prior probabilities, which is usually difficult to obtain in risk assessment, although research has revealed that a mapping algorithm can be used to relax these limitations (Zhou et al., 2011; Khakzad et al., 2013).

5.2.2 BNs model for OTOs

The BN is a single technique which completely captures different phases of an accident starting from accident causes to minor/major mishap. Since complex system operation involves uncertainty, we consider an approach to model causal relationship networks among hazard factors which may cause possible accidents in OTOs. The kernel of incorporating observations in the network to predict the influence of possible future observations is that it can be adapted or attuned to be used for a specific oil terminal platform.

Graphical structures are used to represent knowledge about an uncertain domain. In the structure of a DAG, each node in the graph denotes a random variable and is drawn as a circle labelled by the variable name, while the edges drawn by arrows between the nodes represent direct probabilistic dependencies among the corresponding random variables. The identified hazard factors as discussed in Chapter 4 are used to develop a dynamic model of possible accidents in OTOs. This represents the visualisation of the potential variables and forms the basis for the resulting assessment process. Fig 5.1 is the graphical representation of a sub-criterion from the dynamic BN model structure.

Decision makers should understand and have a clear insight of the whole operational problem before attempting to solve it. This is especially true when there are many criteria to be considered. Based on the outcomes of the $UtiSch_+$ model, a sub-dynamic BN model of OTOs was deduced to form the basis for the resulting assessment process. A mapping process was conducted to transform the quantified important variables from the $UtiSch_+$ model into a deterministic weight vector. A symmetric model was used to determine the conditional probabilities (Riahi et al., 2014; Salleh et al., 2014) and is also flexible enough to allow variables to be updated in the network either by addition or removal without impacting on all the information in the same universe. The main feature of the symmetric model in a BN ensures that expert opinions are distributed by the relative importance of each parent node to its child nodes in an intelligent manner; therefore, the strength of dependence of each parent node to its connected child nodes is determined by the parent's normalised weight.

The relations between variables and the corresponding states of each variable gives the quantitative part in the form of a Conditional Probability Table (CPT), whereas

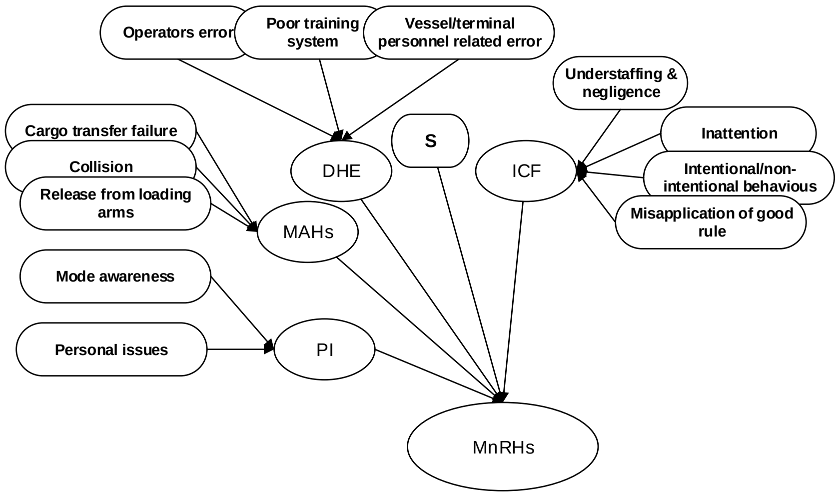


FIGURE 5.1: A graphical structure of Man-related hazards and their causal network

the graphical representation of each variable gives the qualitative part in the form of a structural network. Using a BN model is a unique and strong technique which will compensate or support the weakness of the $UtiSch_{+}$model. It takes the advantage of Bayes theorem to update failure probability of events (propagation) given new information. This new information usually becomes available during the operation process. The BN helps to understand which possible combination of parent nodes and child nodes will lead to an accident on oil terminal platforms. Based on the BNs graphical structures, it is evident that it offers assistance to decision makers in amassing different information in an uncertain domain reliably and reasonably, accounting for uncertainties inherent within the operational framework for decision making. A concise representation of BN analysis can be found in research by Zhou et al. (2011), Riahi et al. (2012), Khakzad et al. (2013), John et al. (2014) and Salleh et al. (2014). Fig 35 shows a proposed dynamic OTOs BN model structure.

5.2.3 Identification of Interrelationships between the Critical Hazards

The task of maintaining a balance between safety, resilience of operations and the impact of disruption due to uncertainties is arguably adjudged to be mitigated by shifting towards a cognitive-based system. This tends to adapt its behaviour based on past experience and is able to anticipate, recover and respond to situations in a proactive manner by maintaining the functionality of the system's operations.

Critical hazards impacting on operational systems can be analysed proactively. If a database exists, after careful analysis, an influencing factor for these hazards can be selected to be represented on the DAGs. In this study, a dynamic BN model hierarchical structure was developed from the ranked HFs with most relative weight using the $UtiSch_+$ model. For any case of uncertainty, influencing factors and their interrelationships were identified through a structured and systematic brainstorming session conducted using a Hazard and Operability technique and literature review. The level of detail for these hazards was chosen according to the objective of the study and, if no relevant historical or experimental data were available, expert's opinion was sought to confirm the correctness and completeness of the proposed BNs.

The identified hazards are presented in Tables 4.1, 4.2, 4.3, 4.4, and 4.5. The HFs are grouped into four categories as shown in Fig 5.2, to ease the computational difficulty that may be experienced during the modelling process. The importance of each root node to its associated child node has to be shown. The utilisation of the model is based on analysing proactively how vulnerable OTOs are, by calculating the likelihood of each root node to its associate child node with respect to causing disruption of operational systems under high uncertainty.

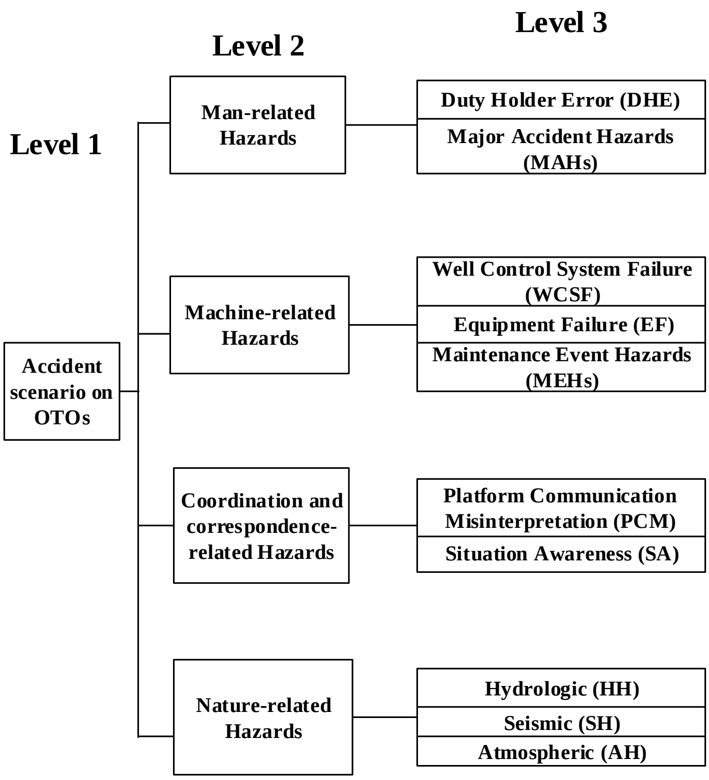


FIGURE 5.2: A dynamic hierarchical structure with the most relative weight for the BN model

Following the establishment of a draft BN showing the conditional dependence relationship among the set of influencing variables, assessment grades were then assigned. Experts assigned these grades in order to confirm the correctness and completeness of the proposed BN. More so, the influencing factors had to be transformed into the same universe such that the experts were able to distribute weights among them. These weights define the relative importance of the parent nodes associated with their child nodes. The DAGs only considered significant weighted influencing variables that could cause disruptions.

5.3 Representation of Joint Probability Distribution (JPD)

Imagine trying to model a risky situation in which a casual relation plays a role in the structure of a BN, even though our understanding of what is actually going on is incomplete. A probabilistic independence assumption determines what probability information is required to specify the probability distribution for the modelled situation. A graphical BN is a compact representation of JPD over a set of random variables, and is uniquely defined by the product of the individual distribution of each random variable. JPDs can be obtained using the combined qualitative and quantitative variable relationship in terms of intrinsic conditional distribution.

Suppose a JPD is defined across a set of random variables $x_1, x_2, \ldots, x_n$ represented as $P(x_1, x_2, \ldots, x_n)$ for all values of X. If each random variable n is binary valued, one needs to specify $2_n - 1$ numbers for the complete distribution of joint probabilities. It should be obvious that the exponential requirement over X computational complexity will be based on the chain rule from probability theory. Thus, when defining a JPD, probabilities need to be assigned to all the possible events in the BN structure. As such, for a network and any combination of values, the JPD can be calculated in this form:

$$
\begin{aligned}
&P(x_1, x_2, \ldots\ldots, x_n) = P(x_1|x_2, \ldots\ldots, x_n) \times p(x_2, \ldots\ldots, x_n) \qquad (5.1)\\
&= P(x_1|x_2, \ldots\ldots, x_n) \times P(x_2|x_3, \ldots\ldots, x_n) \times p(x_3, \ldots\ldots, x_n)\\
&= P(x_1|x_2, \ldots\ldots, x_n) \times P(x_2|x_3, \ldots\ldots, x_n) \times \ldots P(x_(n-1)|x_n) P(x_n)
\end{aligned}
$$

Assuming the variables in $X = (x_1, x_2, x_3, x_4)$ are dependent on each other, as represented in Fig 5.3, the JPD of the BN can be calculated as:

$$p(x_1, x_2, x_3, x_4) = P(x_1 x_2) \times P(x_2 x_3, x_4) \times p(x_3) \times p(x_4) \qquad (5.2)$$

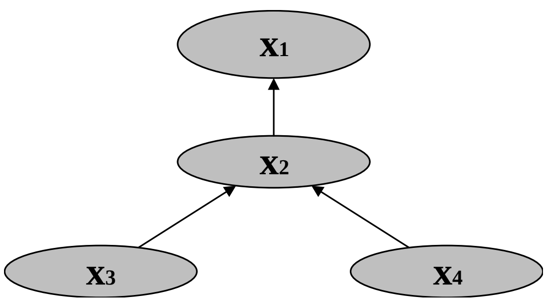


FIGURE 5.3: Conditional dependence

5.4 Modelling Concept and Hypotheses

5.4.1 Definition and Description of the Modelling Concept

The The use of a BN model tailored to the resilience improvement of OTOs presents a more advanced technique to evaluate complex operational hazards or risk. This in turn optimises stochastic behaviours of subsequent operations on oil terminals, even after a major disruption.

The BN established for the purpose of resilience improvement is based on a presented model. It is composed of critical variables categorised into four different groups by their function: (a) Goal, (b) starting nodes, (c) intermediate nodes and (d) target nodes (Bayraktar and Hastak, 2009; Riahi et al., 2012). Goal nodes are nodes that are added to accommodate the outcome of the $UtiSch_{+}$; they are nodes that define the problem under consideration, and are dependent on other nodes in the network. Meanwhile, starting nodes are nodes with no parents, and cannot be easily modified when modelling, although they are input nodes which are reflected in the child nodes through conditional probabilities. The intermediate nodes are the nodes that convey conditional probabilities, from the decision and starting nodes to the target nodes. They have both parent and child nodes. Finally, the target nodes represent performance indicators, and they have both parent and child nodes.

5.4.2 Hypotheses

In the proposed BN, three main hypotheses are to be considered.

- H_1: Nodes with at least one parent node can only be influenced by their parent node(s); thus they are conditionally dependant.
- H_2: A node without a parent variable denotes marginal probability, which may be made available by expert(s).
- H_3: The child nodes in the influence pattern provide the mutual exclusivity of the node required for analysis; this is ideal for the use of certain probability distributions during the course of analysis.

The developed hypotheses will ease computational complexities as well as create flexibility in the modelling process.

5.5 BN Processes

To assess the influence of each critical variable on accident scenarios in OTOs under high uncertainty in order to test the resilience, the use of a BN as a model is proposed (see Fig 5.1). The processes involved in the development of the BN model for decision support consist of two major steps: identification of critical variables and their causal network, and quantification of the significant interrelationship among critical variables.

Section 4.3 highlighted the preliminary questions and problems on how an holistic approach could be used to enhance the ability to process large volumes of data in real-time situations. However, the dependency of critical variables was not considered in the hierarchical relationship, as referred to in Chapter 3, so, to overcome this difficulty, a Bayesian Network Sensitivity Analysis Method ($_{+}BN - SAM$) is presented using a Bayesian reasoning mechanism to conduct analysis. Therefore, to transform experts' opinions into subjective conditional probabilities in the BN model remains the prerequisite of this approach.

When considering a group of variables for evaluation, judgements on the relative importance of these variables should be considered, in order to permit a quantitative interpretation of them. Based on this compromise, the methodology follows four major steps:

Step 1: Establish potential hazards of relative importance

- Mapping process

Step 2: Establish the BN model

- Update the values of all the variables
- Graphical representation of the relationship between nodes
- Specify states and assign inputs for CPT of each variable

Step 3: Analyse the model

- Elicit CPT for the child nodes in the BN using the symmetric model
- Marginal probability for the root nodes

Step 4: Model validation

- Sensitivity analysis

5.5.1 Step 1: Establish potential hazards of relative importance

The formulation of the problem to capture what can go wrong and why this is a potential hazard with relative importance to OTOs and their potential consequences will provide inputs concerning what should be investigated and included in the modelling. A mapping process (see Subsection 2.5.5) by transforming data from $UtiSch_{+}$ into a BN is adopted as shown in Fig 5.4. The details of the $UtiSch_{+}$ can be seen in Chapters 2 and 4 respectively.

Mapping algorithm

The important degree of influencing variables (T and X) on a system failure can be assessed using the $UtiSch_{+}$ model. The mutual information between $UtiSch_{+}$ and BN is the total uncertainty reducing potential of X, given the original uncertainty in T prior to consulting X. Intuitively, mutual information is the information that variables T and X share.

The influencing variables are divided into ten sub-criteria with parent nodes associated with the intermediate and target nodes at the first stage, and are defined as the starting node in the equivalent BN. Let A be a qualitative sub-sub-criterion and n^{th} be an associated qualitative sub-criterion, by formulating a mapping process and having all the information in the same universe, A at the ith stage (level 3) is converted to an associated b qualitative criterion at the $(i+1)^{th}$ stage (level 2). Then the resultant criterion undergoes another mapping process into an associated c qualitative criterion (if any) at the $(i+2)^{th}$ stage. The process continues until the $(i+n)^{th}$ stage and up to the decision node (level 1), with all the influencing variables having a place in the DAG as well as each nodes being accounted for. β_A^i stand for the degree of expert elicitation (if any) and it signify the relationship between qualitative variables of different levels. Fig 5.4 shows an example of a mapping process.

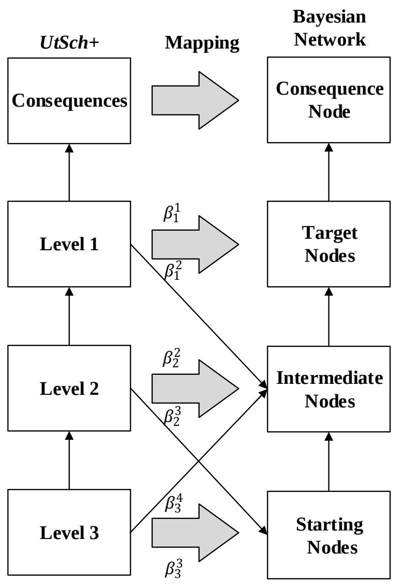


FIGURE 5.4: Using the D-Separation concept in mapping $UtiSch_+$ into BN as adapted in Khakzad et al. (2013)

5.5.2 Step 2: Establish the BN model

To establish the BN model, a sub-hierarchical structure was designed from the output of the prioritised variables ($UtiSch_+$) according to their relative weights. This serves as an input for the proposed BN structure. Given these occurrences, developing a kernel generic BN model for solving issues relating to a specific operational resilience system requires the model to have the ability to adjust to any change of input. The causal relationships among hazard variables are then demonstrated; they are organised by acyclic arrows to represent what possibility could lead to disruption. Having certified that, a qualitative graphical representation will be constructed using the BN model as shown in Fig **??**.

The states of the variables in the network established will be specified, with the sole objective being to appropriately assign prior probabilities. The threat or attempted threat of the variable will become the premise for defining the actual state. Further consolidation of the qualitative description of the BN process will then be properly understood for the construction of the CPT.

5.5.3 Step 3: Analyse the Model

To analyse the model, the conditional and unconditional probabilities will be calculated in the CPT. A symmetrical model will be used to synthesise the mapped $UtiSch_+$ to determine the conditional probabilities.

(a) *Determining the Unconditional Probabilities Table (UCPT) of Starting nodes*

To determine the unconditional probabilities of each starting node, ranked variables were used as a mirror image for the unconditional probabilities (Fenton et al., 2007) prior to empirical analysis (see Chapter 4). However, this denotes the input value for each parameter to enable the calculation of the actual prior probabilities, which comprises of 10 parent nodes with utmost relative weights. All ranked nodes are labelled and defined on an underlying unit interval [0, 1]. In attempting to construct a UCPT for parent variable $X_r(wherer = 1, 2, 3, \ldots, n)$ indicated by the assigned weight $W_w($ where $w = 1, 2, 3, \ldots, n)$ for the n^{th} number of state, normalising the weights assigned by experts $E_i($ where $i = 1, 2, 3, \ldots, n)$ is considered a natural function that could be used as a measure of central tendency associated with the causal network model. The normalising process can be calculated as

$$P(X_r, V) = P(V/X_r) \prod_{r=1}^{n} P(X_r) \tag{5.3}$$

to normalisze the n^{th} number of states:

$$P(X_r, V) = T_{n^{th}}(\frac{\sum_{i=1}^{n} w_1}{\sum_{r=1}^{n} W_{w_{max}}} \tag{5.4}$$

to calculate for x_1

$$P(X_1, V_1) = T_{n^{th}}(\frac{w_1}{\sum_{r=1}^{n} W_{x_1+x_2+,\ldots,x_n}} \tag{5.5}$$

where:
X_1serves as the parent variable
W_1 represents the weight for the value of X_1
V represents the state for the value of X_1 represented by W_w
Tn^th is assumed to be the truncated normalised distribution of X_1
n^th represents the number of states, and
P represents the probability value of the n^th outcome on an underlying unit interval $[0, 1]$

(b) *Determining the Conditional Probabilities Table (CPT)*
The *Symmetrical model* best reveals the relationship among variables and it is more concerned about the causal mechanism of each parent node in a normalised space, to its associated child nodes. Given that the conditional probability of a child variable Z, upon a parent variable $X_r($ where $r = 1, 2, 3, \ldots, n)$ indicated by their assigned normalised weight $(\xi_1, \xi_2, \ldots\ldots, \xi_n)$, this can be estimated as follows (Riahi et al., 2012; Salleh et al., 2014):

$$\begin{aligned} P(Z = present|X_1 = present) &= \xi_1 \\ P(Z = present|X_2 = present) &= \xi_2 \\ &\vdots \\ P(Z = present|X_n = present) &= \xi_n \\ \sum_{r=1}^{n} \xi r = 1 \end{aligned} \tag{5.6}$$

Based on (**??**) and considering the status quo of the symmetry approach (i.e. normalised space), the probability of the variable Z upon parent variable $X_r(wherer = 1, 2, 3, \ldots, n)$ can be evaluated as follows:

$$P(Z = present|X_n = present) = \sum_{r=1}^{n} \xi r = 1 \tag{5.7}$$

$\xi_r = \xi r$
If the state of the r^{th} *parent variable is identical to the state of its child*
$(\xi_r) = 0,$ and
If the state of the r^{th} *parent variable is different from the state of its child*

The amount of data that needs to be input in a CPT can be calculated using:

$$N^{y+1} \tag{5.8}$$

(c) *Determining the marginal probabilities*

To generate the marginal probability for the consequence node, the JPD in the CPT is evaluated and aggregated. Once the structure and parameters have been determined in the CPT, the BN is ready to draw inferences. Thus, the marginal probability of all hazard variables can be calculated using the marginalisation rule:

$$P^{*}y = y_i \cong \sum_{r}^{n} P(X = x_r) \times P(Y = y_i | X = X_r) \tag{5.9}$$

5.5.4 Step 4: Model Validation

In order to ensure consistency in tackling inaccuracies or incompleteness on OTOs, Sensitivity Analysis (SA) is utilised. SA is a process used as a partial model validation, particularly for investigating model performance by changing the parameters' values. The analysis allows the studying of uncertainties in the output of a model. It further tests the logicality and sensitivity of the output result. The model can be verified by satisfying certain axioms tailored to at least reflect logical and robust inference reasoning, and also monitoring the effects of these changes on the posterior probabilities. The following two axioms must be met in order to achieve consistent SA processes:

Axiom 1 : A slight increase or decrease of any states of an input variable will result in a relative increase or decrease in the states of the model output. **Axiom 2** : A minor decrease or increment in the input data, i.e. belief degrees for any individual hazard factor, should result in a decrease or increase in the overall average scores correspondingly.

5.6 An Empirical Study on the Applicability of the Model

To investigate the uncertainties of oil terminal operational hazards, a BN model has been developed. The developed model provided a set of values in order to simulate the model. However, this chapter intends to investigate the top 10 HFs whose relative weights are most significant to cause unexpected events on oil terminal platforms. This study was executed in four phases: (1) questionnaire formulation and pilot study, (2) choosing the right experts, (3) survey data collection and description and (4) BN model and results. We discuss each of the phases below.

5.6.1 Questionnaire Formulation and Pilot Study

The BN was systematically constructed with the help of the dynamic hierarchical structure. Based on the information, the relationship of the connecting nodes at a particular level has to be modified or adjusted. Our discussion in Chapter 3 formed the basis for the initial hazard and uncertainty modelling. Prior to actual data collection, content validity was performed to improve the clarity of the questionnaire. A cover letter and a questionnaire was drafted specifically for the BN to reflect the significant result from the $UtiSch_{+}$ model. The drafted version of the questionnaire was further examined by three academicians and two specialists to comment on any ambiguity of the questions. Their feedbacks was useful for the final drafted questionnaire, which was used for a pilot study. See subsection 4.7.1 on how the questionnaire was measured and approved as well as the conducted pilot study. The final questionnaire included in Appendix 4C was used for data collection.

5.6.2 Choosing the right Experts (DMs) for OTOs

A cross-section of decision makers (DMs) were considered to participate in the survey. See subsection 4.7.2 for the criteria and the randomness for choosing experts (John et al., 2014b). Experts where identified based on LinkedIn, publicly available directories, and recommendation designated by oil and gas industry consultants.

5.6.3 Survey Data Collection and Description

The questionnaire was web-based and a link was e-mailed to the targeted expert participants. A cover letter appeared to respondents prior to the main question page (see Appendix 5C). Experts assigned possible outcomes regarding the 10 parent variables considered for the BN given their experience. A number of undelivered, incompleted and completed questionnaires were returned. In all, 5 valid responses were obtained yielding the final response rate of 20%. This response rate can be compared to other studies conducted in the literatures Mokhtari et al. (2012); Hammitt and Zhang (2013); Alyami et al. (2014); John et al. (2016). The five experts selected at random have the following backgrounds:

- A senior safety consultant in an oil and gas industry with experience of more than 20 years; having an onshore/offshore industrial experience in the field of oil and gas terminal operations.
- A senior maritime Health and Safety Executive (HSE) with a Masters degree who has been involved in offshore oil installation and port safety for more than 20 years.
- A General Purpose tanker captain who has been involved with (off)loading operation on offshore/onshore oil terminal platforms for 16 years.
- A senior operation manager who has been involved with offshore oil platforms operation for more than 20 years.
- A senior maritime engineering lecturer with a PhD, having both academic and industrial experience for more than 20 years.

Similarly, when these 5 experts made their judgements, they assigned values to each question. The evaluation for each question is presented in Fig 5.6 .

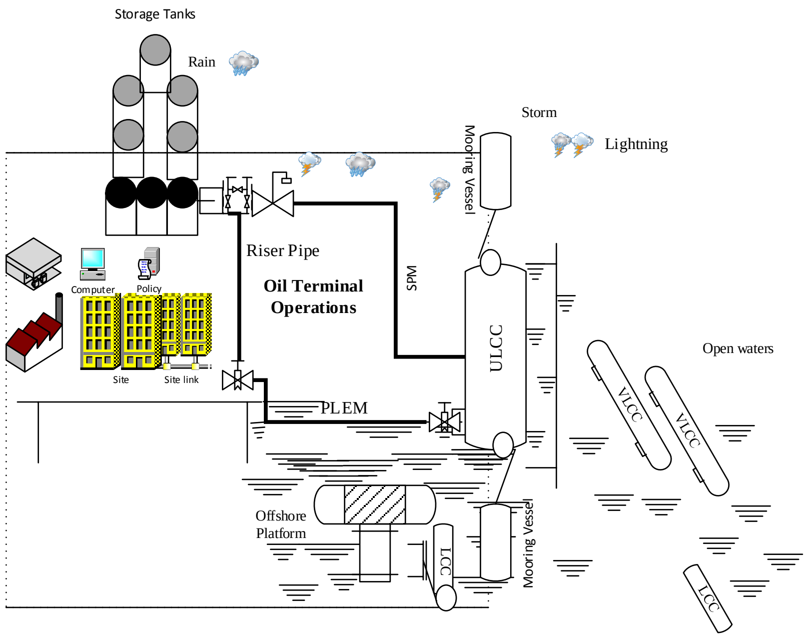


FIGURE 5.5: Representation of a terminal operational platform requiring resilience improvements

A port's infrastructure system takes a long time to design, construct and operationalise. Upon its completion, it becomes a facilitating national and international hub for economic activities. Oil terminal platforms provide fundamental activities through enabling the transfer of goods and providing services for national and international economies to sustain and grow their economies. Fig 5.5 is a representation of a terminal operational platform as envisaged according to available conference papers and professional and academic journal articles. There is therefore the need for such a complex infrastructure system to be subjected to a variety of operational and environmental uncertainties to show resilience in the face of major operational disruption.

From the questionnaire feedback, it was revealed that 100% of the participants discerned the Hazard Factors (HFs), as well as the possible consequences of these HFs to OTOs. In addition, Table 5.1 above shows the consistency of participants' responses. The participants are all senior employees with experience all over the world, which also represents around 90% of the whole sample. In order to eliminate the presence of response bias, participants were chosen from the United Kingdom, Angola, Saudi Arabia, Russia and the USA. These represent the major oil importing and exporting countries where OTO activities are being performed at a large scale.

According to participants, as shown in Fig 5.6, the probability of these HFs occurring on oil terminal platforms spans averagely across somewhat unlikely (3) to somewhat

TABLE 5.1: Consistency of HFs based on empirical study for BN inputs

Hazards/Failures	HFs	Arithmetic mean
Man-related Hazard	Major Accident Hazards	4.00
	Duty Holders Error	4.40
Machine-related Hazard	Maintenance Event Hazards	5.00
	Equipment Failure	5.40
	Well Control System Failure	3.80
Coordination and correspondence-related Hazard	Platform Communication Misinterpretation	5.20
	Situation Awareness	5.20
Nature-related Hazard	Hydrologic	4.40
	Seismic	3.60
	Atmospheric	4.40

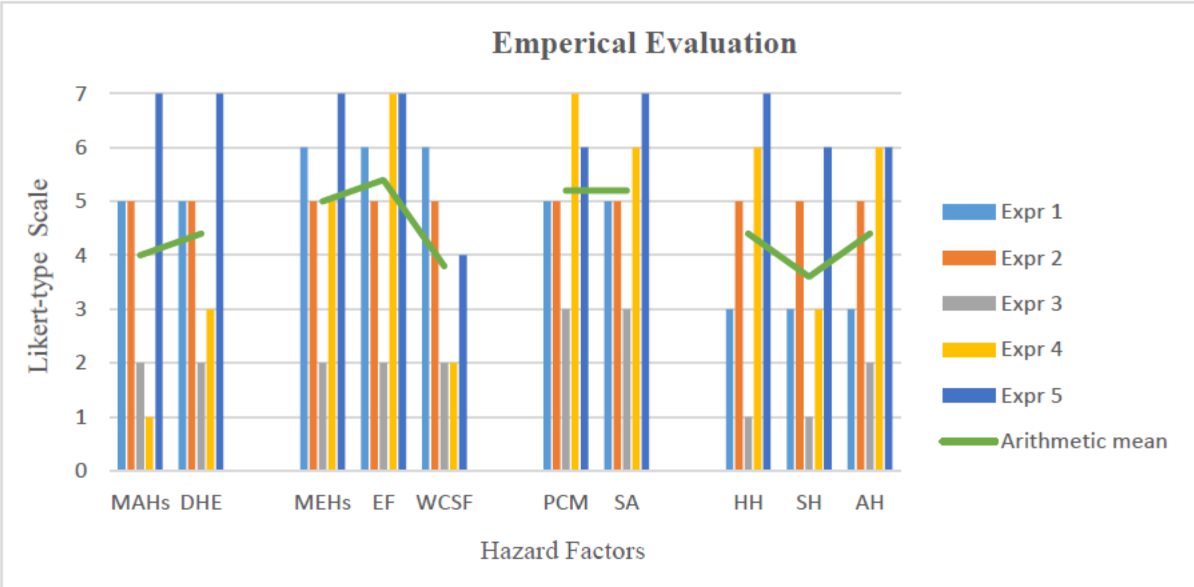


FIGURE 5.6: A graph showing the empirical evaluation of HFs for BN inputs

likely (5). The quantitative data collected were used for the proposed BN model and its application, to determine the likelihood of accident for OTOs.

5.7 BN model and Application

As previously discussed in section 5.6.3, the HFs from the $UtiSch_+$ model with the most relative weights were further justified by expert's opinion. The HFs are thus established as potential hazards that could lead to major disruption in OTOs. Given what should be investigated and included in the model, a mapping process was conducted by converting the outcome from the $UtiSch_+$ model into a BN. The concept of mapping (see section 5.5.1) was used for transforming the qualitative criterion of the sub-dynamic hierarchical structure (Fig 5.4) with a belief degree at 100% to a BN model (Khakzad et al., 2013). Therefore, it is a mirror image of the hierarchical structure. The belief degree (if any) varies (Riahi et al., 2012) with the relationship between qualitative variables at different levels of the mapping process.

A BN model provides a platform for graphical representation of the causal relations between HFs. As part of a resilience strategy framework, the network captures the uncertain dependencies between HFs via a list of probability distributions. Normally, a BN consists of a set of variables, causal links and a probability. A number of specific compelling reasons are responsible for mapping the $UtiSch_{+}$ model into BN: (1) BNs can be executed to predict as well as diagnose a failure given evidence of the starting or intermediate nodes, (2) the calculations in BN is exact where the network is discrete, (3) BNs guarantee a richer, more realistic model due to their flexible nature and robustness and (4) BNs assume that all nodes are dependent, especially in the presence of a common cause of failures.

Based on the mapping process, potential hazards as input data are fed into the Netica BN software to showcase the qualitative graphical representation of a customised BN model for OTOs. As presented in Fig 41, the outcome with the most relative weight from the $UtiSch_{+}$ is mapped into a BN.

5.7.1 (Step 1)

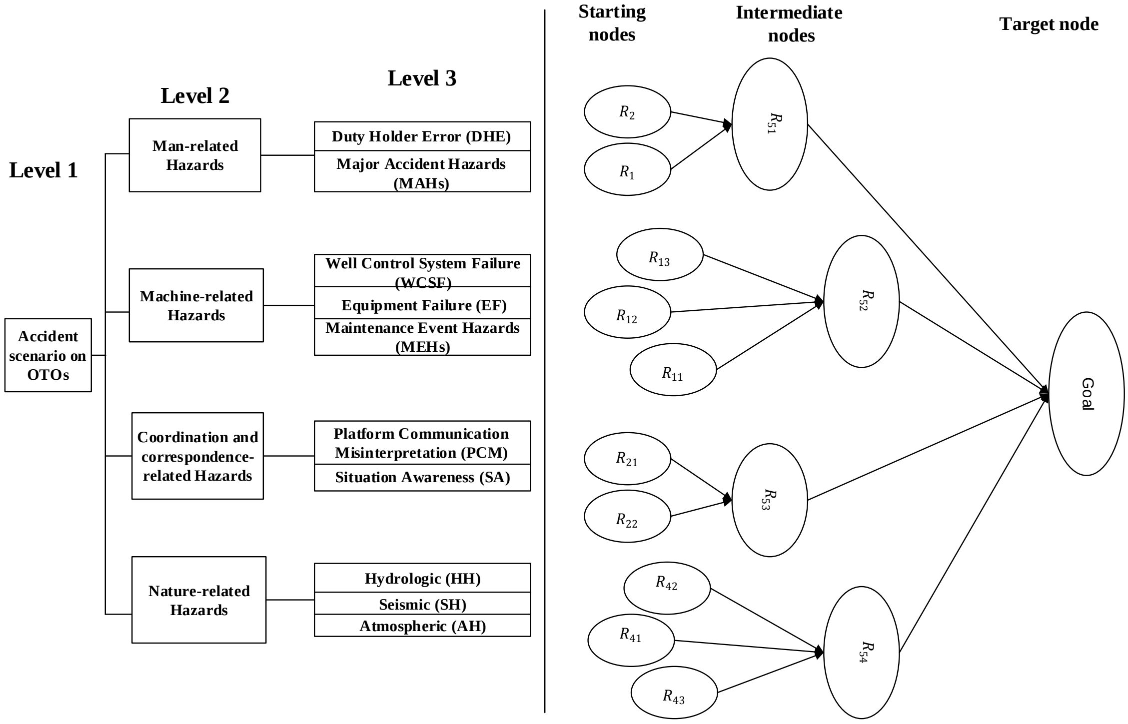


FIGURE 5.7: A BN model of an accident scenario for OTOs

Table 5.2: Generated normalised weight for HFs

HFs	**expr 1**	**expr 2**	**expr 3**	**expr 4**	**expr 5**	**Rw**	**Nw**
R_1	0.2206	0.3250	0.2619	0.3513	0.3513	0.3020	0.4898
R_2	0.2206	0.3250	0.3513	0.3250	0.3513	0.3146	0.5102
$R_1 1$	0.2361	0.3513	0.3250	0.2619	0.2619	0.2872	0.3308
$R_1 2$	0.2361	0.3250	0.2206	0.3250	0.3250	0.2863	0.3298
$R_1 3$	0.2361	0.3250	0.2619	0.3250	0.3250	0.2946	0.3394
$R_2 1$	0.1746	0.2168	0.2168	0.2168	0.2342	0.2118	0.4854
$R_2 2$	0.1471	0.2168	0.2168	0.2168	0.2168	0.2245	0.5146
$R_4 1$	0.2619	0.2958	0.2619	0.2206	0.3250	0.2730	0.3337
$R_4 2$	0.2619	0.2619	0.2619	0.2206	0.3250	0.2662	0.3254
$R_4 3$	0.2619	0.3250	0.2619	0.2206	0.3250	0.2788	0.3408

5.7.2 Customised BNs (Step 2)

The causal relationships among the HFs variables are demonstrated; they are the acyclic arrows which represent what possibility would lead to the goal. Nodes can be assigned to various states according to their individual characteristics. In hazard-based nodes, the BN constructed was assigned two exclusive states, "Yes and No" and "high and Low". "No" means the probability of a related node being safe and "Yes" means the probability of the corresponding nodes being unsafe."High" means the probability of occurrence of an unwanted event is significant and "Low" means the likelihood of the occurrence of an unwanted event is insignificant. It was possible to choose these states based on the fact that the "likelihood" nature of the event occurrence frequency well matches the probability requirements in the BN. The weights of the states (High and Low) of the parent nodes was determined by the relative weight *(Rw)* generated in Table 5.2.

The Netica software is a robust, widely used tool, which comes with a Bayesian network software package that provides an applicable programmer's interface (API). The user has to define the model structure but the software provides an Expectation-Maximisation (EM) algorithm to support the execution of probability calculations (CPT). Given the data and the model structure being known beforehand, the EM algorithm in Netica repetitively calculate maximum likelihood estimates for the variables. The EM algorithm in Netica can also handle randomly missing data problems which are dependent on the states of other variables. Netica also supports the use of decision and utility variables, and, once the bins in the network are defined, it allocates continuous data into the correct bins. Netica and its influence diagram features have been used in many

Table 5.3: List of Influencing HFs for OTOs disruption

Abbreviations	**Hazard Factors (HFs)**	**Node Type**
R_1	Major Accident Hazards (MAHs)	Starting node
R_2	Duty Holders Error (DHE)	Starting node
R_{11}	Maintenance Event Hazards (MEHs)	Starting node
R_{12}	Equipment Failure (EF)	Starting node
R_{13}	Well Control System Failure (WCSF)	Starting node
R_{21}	Platform Communication Misinterpretation (PCM)	Starting node
R_{22}	Situation Awareness (SA)	Starting node
R_{41}	Seismic Hazard (SH)	Starting node
R_{42}	Hydrologic Hazard (HH)	Starting node
R_{43}	Atmospheric Hazard (AH)	Starting node
R_{51}	Man-related Hazards	Intermediate node
R_{52}	Machine-related Hazards	Intermediate node
R_{53}	Coordination and Correspondence-related Hazards	Intermediate node
R_{54}	Nature-related Hazards	Intermediate node
Goal	Accident scenario on OTOs	Target Node

studies (Ramin et al., 2012a, 2012b; Saleh et al., 2014). The general strategy for using a Netica BN model can be seen in section 4.2. Fig 5.8 shows a tailored BN for the resilience improvement of an accident scenario for an oil terminal platform.

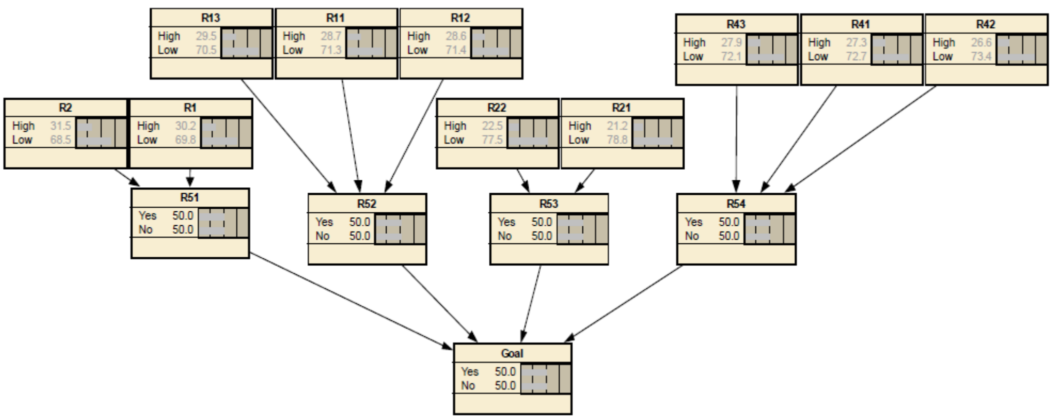


Figure 5.8: A BN model of an accident scenario for OTOs

5.7.3 Evaluation of Analysis and Results (Step 3)

To analyse the model, the Netica software enables the computation of the conditional and unconditional probabilities for the child and parent nodes respectively in the Conditional Probability Table (CPT). The symmetrical model was used to synthesise the mapped $UtiSch_+$ to determine the conditional probabilities.

Symmetrical model: Expert's opinion is distributed by relative importance of each parent node for their associated child nodes. The strength of direct dependence of each child node to its associated parent is indicated by their normalised weights (N_w) (Eq. 5.7, Table 5.2). Thus, in normalised space $P(Z = present|X_1 = present) = P(\dot{\widehat{B_1}})$ represents the relative importance of the first parent node for its associated child node as an entity **?**; therefore:

$$
\begin{aligned}
& P(Z = present|X_1 = present) = P(\dot{\widehat{B_1}}) = \frac{P(B_1)}{\sum_{a=1}^{n} p(B_1)} \\
& \vdots \\
& P(Z = present|X_n = present) = P(\dot{\widehat{B_1}}) = \frac{P(B_1)}{\sum_{a=1}^{n} p(B_1)} \\
& \therefore \\
& P(\dot{\widehat{B_1}}) + P(\dot{\widehat{B_2}}) + P(\dot{\widehat{B_3}}) + \cdots + P(\dot{\widehat{B_n}}) = 1
\end{aligned} \tag{5.10}
$$

Based on the axioms of probability theory, and owing to normaliszation and in normalised space, $\dot{\widehat{B_1}}, \dot{\widehat{B_2}}, \dot{\widehat{B_3}}, \ldots, \dot{\widehat{B_n}}$ remain disjointed:

$$
\begin{aligned}
& P(\dot{\widehat{B_1}} \cap \dot{\widehat{B_2}}) = P(\dot{\widehat{B_2}} \cap \dot{\widehat{B_3}}) = \cdots = 0 \\
& \therefore \\
& P(\dot{\widehat{B_1}} \cup \dot{\widehat{B_2}} \cup \dot{\widehat{B_3}} \cup \cdots \cup \dot{\widehat{B_n}}) = P(\dot{\widehat{B_1}}) + P(\dot{\widehat{B_2}}) + P(\dot{\widehat{B_3}}) + \cdots + P(\dot{\widehat{B_n}})
\end{aligned} \tag{5.11}
$$

Thus, based on Eq. (5.4), and according to the probability distribution, the following can be obtained within the CPT:

$$
\begin{aligned}
P(Z = Likely|X_1, X_2, \ldots\ldots, X_n) &= 0 \\
P(Z = Unlikely|X_1, X_2, \ldots\ldots, X_n) &= 1 \\
P(Z = Likely|X_1, X_2, \ldots\ldots, X_n) &= 1 \\
P(Z = Unlikely|X_1, X_2, \ldots\ldots, X_n) &= 0
\end{aligned}
$$

Accordingly, the results obtained by evaluating a CPT based on synthesising the "symmetric" methodology and using the relative weight in Table 5.2, an illustrated example is presented to obtain the values of probability distribution

$$\omega_1 = \frac{w_1}{w_1 + w_2 + w_3} = \frac{0.2872}{0.2872 + 0.2863 + 0.2946} \approx 0.3308,$$
$$\omega_2 = \frac{0.2863}{0.2872 + 0.2863 + 0.2946} \approx 0.3298,$$
$$\omega_3 = \frac{0.2946}{0.2872 + 0.2863 + 0.2946} \approx 0.3394,$$
$$P(\widehat{\dot{B_1}}) + P(\widehat{\dot{B_2}}) + P(\widehat{\dot{B_3}}) = 1, \text{ therefore, } 0.3308 + 0.3298 + 0.3394 = 1$$

Based on Eq. 5.7, the CPT, as shown in Fig 5.9 can be computed.

	R_{51} (L)				R_{51} (U)			
	R_{13}		R_{11}		R_{11}		R_{13}	
	R_{12}	R_{11}	R_{13}	R_{12}	R_{12}	R_{13}	R_{11}	R_{12}
$\Omega(High)$	1	0.6692	0.6606	0.3298	0.6702	0.3394	0.3308	0
$\Omega(\neg Low)$	0	0.3308	0.3394	0.6702	0.3298	0.6606	0.6692	1

FIGURE 5.9: Aggregated result for an accident scenario for OTOs

where:
$\Omega(High) = P($ Machine-related hazard $=$ Likely$|R_{13}, R_{12}, R_{11})$
$\Omega(\neg Low) = P($ Machine-related hazard $=$ Unlikely$|R_{13}, R_{12}, R_{11})$

Based on the Bayes chain rule, the marginal probabilities of likelihood of Machine-related hazard can be calculated as:

$P($ Machine-related hazard $=$ Likely$) = 0.5$
$P($ Machine-related hazard $=$ Unlikely$) = 0.5$

The total number amount of data that is needed to be imputed input into the CPT can be determined using equation (5) as $2^3, 2^4, 2^3, 2^4$ and 2^5 (i.e. 80 data). The above calculation is true for any number of parent nodes therefore if there is any uncertainty about the validity and invalidity of a child's parents, one should also remain uncertain about the validity and invalidity its child. However, one major use of BNs is in reviewing probability in the light of actual observation of events.

Once the structure and parameters have been determined in the CPT, the BN is ready to draw inferences. The obtained result from the experiment is presented in Fig 5.10, the extent of disruption obtained at the target node or goal is evaluated as: Goal = {(Yes = 0.2910 or 29.1%), (No = 0.7090 or 70.9%)}.

Assume that R_2, R_21 and R_42 are known with 100% certainty. These conditions haves an important effect on the occurrence probability of the overall effect on the accident scenarios. By using the Netica Software to simulate the effect of R_2, R_21 and R_42

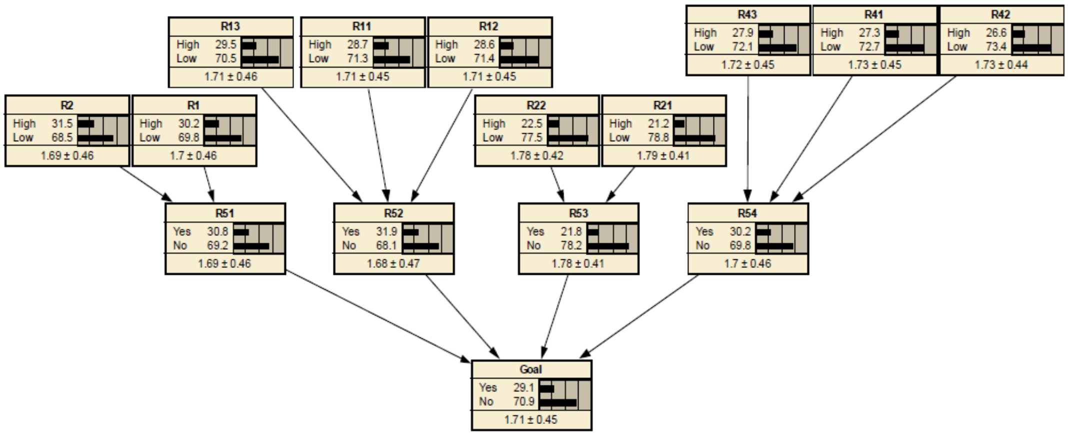


FIGURE 5.10: Aggregated result for an accident scenario for OTOs

on the model, the occurrence probabilities can be estimated.

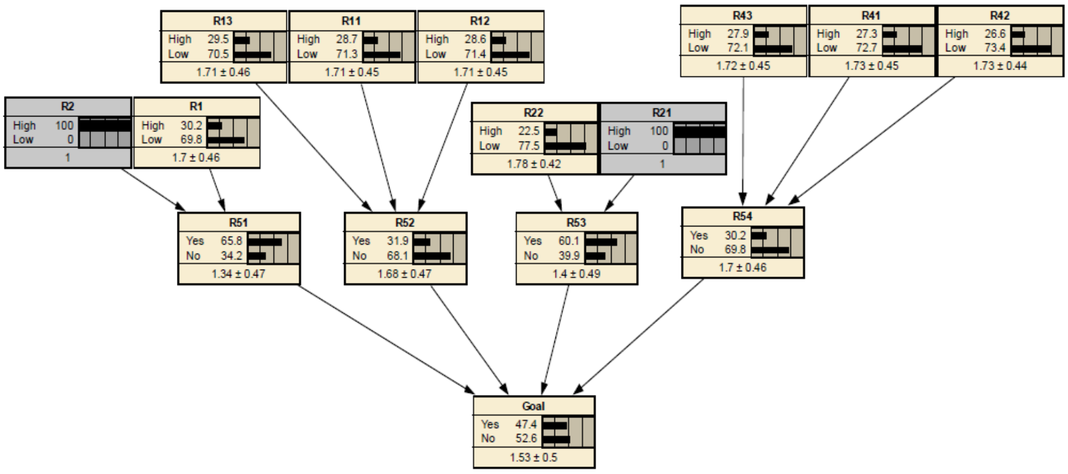


FIGURE 5.11: The effect of R_2 and R_{21} on the occurrence probability of an accident for OTOs

In the first scenario Fig 5.11, if R_2(Duty Holders Error) and R_21(Platform Communication Misinterpretation) are known with 100% certainty, it can be observed that the total likelihood of an accident occurrence increases to 0.4740 or 47.4%. However, based on the second scenario Fig 5.12, the values are different due to a new evidence R_42 (Atmospheric hazards) which tends to infer the likelihood to 0.5670 or 56.7% of an accident occurrence.

Prior to the instantiation of the state of a variable, the obtained results as presented yields a marginal probability. It is worth mentioning that whatever form of interference is exploited, the output for the probed variable is a probability distribution in each state.

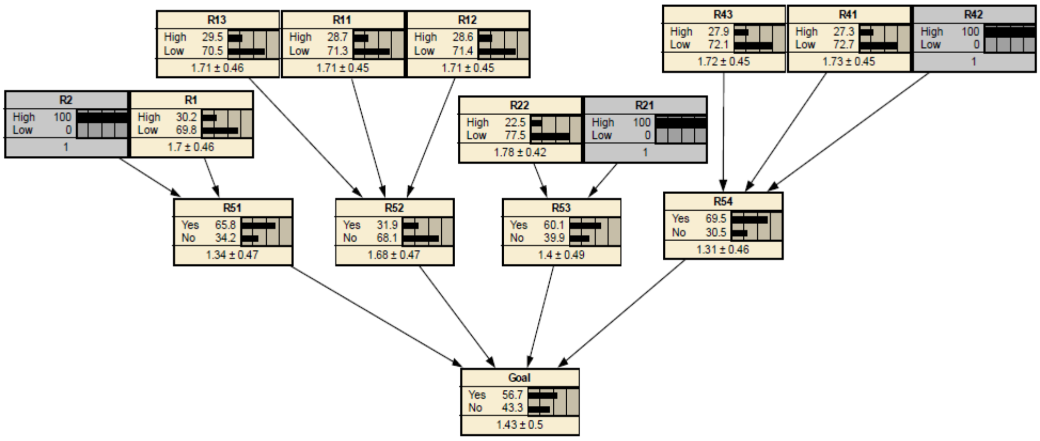


FIGURE 5.12: The effect of R_2, R_{21} and R_{42} on the occurrence probability of an accident scenario for OTOs

5.7.4 Sensitivity Analysis ($_+$BN – SAM)(Step 4)

The robustness of this BN model is demonstrated using a Sensitivity Analysis (SA). SA was used to logically identify the effects of inaccuracies and incompleteness of the variables influence of the model outputs on the decision node. The most logical way of conducting this analysis is to change the parameters data, based on the axiom discussed in Section 5.5.4. All the input variables (10 nodes) as shown in Tables 24 and 25 given a slight variation in probability values. An increase or decrease by 10%, 20% and 30% was done accordingly in respect to each node, and the results were obtained. It is noteworthy to mention that an increase to the nth lowest preference state of a parent variable β, simultaneously decreases the nth highest preference state of a parent variable β. This process continues for all other parameter variables.

For example, given that R_2 "Yes" was increased by 20% "DHE = increase", the probability occurrence of the model output (i.e. accident scenario outcome) is evaluated as "0.3203 or 32.03% Yes" and "0.6797 or 67.97% No". This implies that the initial outcome increases from "Yes = 29.1%" to "Yes = 32.03%". However, by increasing R_2 "No" by 20% "DHE= decreased", the probability occurrence of the model output decreases from "Yes = 29.1%" to "Yes = 26.32%". As shown in Tables 5.4 and 5.5, the results of all other parameter variables are presented. More so, while changing the value of a variable, all other input variables are left unchanged.

All obtained results are in harmony with Axioms 1 and 2. However, if the probability occurrence of the outcome is insensitive to a changed variable, the input variable is considered to be insignificant and to be removed.

Based on the obtained results in Table 5.4, the sensitivity of the model output to the increment variation of each individual parameter variable as illustrated in Fig 5.13 is assessed.

The correlation between the SA of an increment and decrement of the parameter variable output data shows the range of variation of each node on the system. Based

TABLE 5.4: Increment of parameter variable's likelihood

	Sensitivity Analysis at		
HF	**10%**	**20%**	**30%**
R_1	0.3051	0.3191	0.3323
R_2	0.3053	0.3203	0.3342
R_{11}	0.2963	0.3013	0.3062
R_{12}	0.2961	0.3011	0.3061
R_{13}	0.3054	0.3183	0.3324
R_{21}	0.3011	0.3112	0.3214
R_{22}	0.3021	0.3122	0.3234
R_{41}	0.2960	0.3000	0.3050
R_{42}	0.3042	0.3174	0.3300
R_{43}	0.2964	0.3014	0.3180

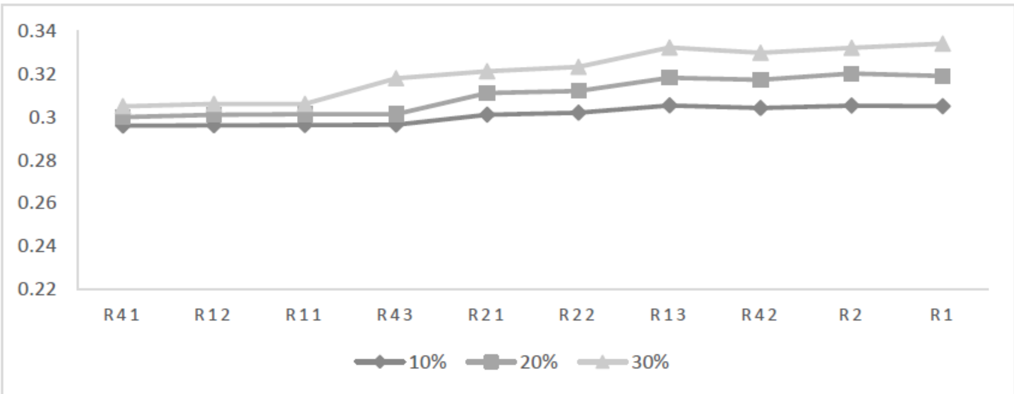


FIGURE 5.13: Sensitivity of the model output based on increment variation

on Fig 5.13, the behaviours of several inferences prior to changed values highlighted the most sensitive node that could trigger an accident on oil terminal platforms. The lines reveal the range value of the nodes and highlight a threshold for a significant action to be taken due to an increment in the likelihood of accident occurring or examining the effect of a decreased likelihood. As shown in Table 5.5, the results of all other nodes due to decrement are presented as follows:

Based on the obtained results in Tables 5.13 and 5.5, the sensitivity of the model output due to the increment/decrement variation of each individual parameter variable as illustrated in Fig 5.14 is assessed.

TABLE 5.5: Increment of parameter variable's likelihood

	Sensitivity Analysis at		
HF	**-10%**	**-20%**	**-30%**
R_1	0.2770	0.2632	0.2494
R_2	0.2762	0.2621	0.2472
$R_1$1	0.2861	0.2813	0.2763
$R_1$2	0.2860	0.2810	0.2762
$R_1$3	0.2771	0.2632	0.2500
$R_2$1	0.2810	0.2710	0.2614
$R_2$2	0.2800	0.2691	0.2670
$R_4$1 1	0.2860	0.2810	0.2780
$R_4$2	0.2782	0.2653	0.2564
$R_4$3	0.2864	0.2813	0.2770

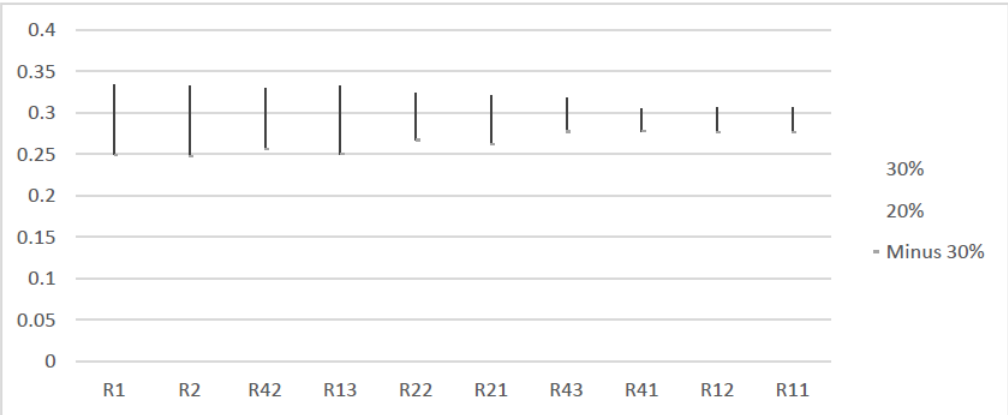


FIGURE 5.14: Sensitivity analysis results showing a range due to changes in the input data

5.8 Discussion and Conclusion

This chapter has demonstrated that BN model is an effective technique for dynamic hazard analysis of OTOs for resilience improvements. An empirical study was conducted on the HFs to establish the customised BN model tailored for OTOs. It was gathered from the analysis that such HFs play a significant role ion the build-up of an unexpected events with high operational disruptions. Given a particular case with known HFs, the occurrence probability of an accident for OTOs can be determined with a BN. In real practice, CMOs on oil terminal infrastructures under uncertainties can use BNs in such a way that they can add or drop any node or parameter variable based on the situation they faced. The implementation of the proposed BN process shows that, by mapping the data from $UtiSch_+$ model into BNs, the limitations of the $UtiSch_+$ model can be relaxed. Furthermore, it was envisaged to be an intelligent tool for analysing different variables in a dynamic environment.

The "Symmetrical model" was used to determine the CPT of the child node using weighted sum algorithm (See section 5.8). The reason why the weighted sum algorithm is more attractive to use is its kernel, a linear process. The weighted sum algorithm enables probability adapting; a second type of probability updating in which the conditional probability distribution are adapted using new evidence collected during a time interval. This allows oil terminal platform operators to employ a sound and coherent approach to exploit the customised BN model.

The results presented in this chapter provided an in-depth understanding in complementing the $UtiSch_+$ model, and also the relationships among the ten HFs with the most relative weights. Based on the input data and the results obtained for probability occurrence of the goal, it is evident that the variations and influence magnitude of each parameter variable is Goal = (Yes = 0.2910 or 29.1%) to occur. It is more interesting to know that the behaviours of several inferences i.e. (R_2, R_21) and $(R_2, R_21$ and $R_42)$, when analysed at 100% likelihood as shown in Fig 5.13 and 5.14 increased the likely occurrence probability of the goal/target node.

Apart from the above, like all other models, the sensitive analysis $({}_+BN - SAM)$ was used to determine the robustness of this BN model. Based on Tables 5.13 and 5.5, it can be concluded that the input data of all the 10 variables or nodes was increased by the same amount of 10%, 20% and 30% respectively. If the occurrence probability is not influenced by a parameter variable, it is considered insensitive and will be eliminated. It is evident that the model is more sensitive to R_2(Duty holders error). However, experience has shown that R_1 (Major accident hazards) on CMOs can be very demoraliszing, thereby wreaking severe havoc on operation with lasting consequences. Also, by decreasing the 10 variables by the same amount of 10%, 20% and 30% respectively, a correlation between the $({}_+BN - SAM)$ increment and decrement of the parameter variable shows a range of variation of each node on the system (Fig 5.14). This highlights a threshold for action to be taken due to an increment or examining the effect due to a decrement.

Subsequently, the developed BN forms part of a larger framework for assisting scientist and decision makers to understand CMOs in order to develop ideal strategies towards improving the resilience of their system. The BN provides a robust platform where both qualitative and quantitative datasets can be integrated. The proposed BN approach ensures that the computational analysis succumbs to the concept of d-separation and the results aggregation are easy to understand. The quantitative analysis of accident scenarios for OTOs using BN accounts for the occurrence of accidents in oil terminals, thus, crucial HFs can be taken into account to facilitate a resilient strategy for improving the resilience of OTOs.

Chapter 6

STRATEGIC DECISION SUPPORT FOR OTOS RESILIENCE STRATEGY SELECTION

Summary

The analysis of various alternatives that can be adopted to ensure OTOs resilience optimisation can be seen as a multi-attribute decision process. In view of this, this research aims to provide a logical approach in identification of important alternatives from the overall set of alternatives using Analytical Hierarchical Process and Prospect Theory (AHP-PT). The attributes and alternatives are represented on the hierarchical structure of the Plan Inspect Monitor and Manage (PIMMs) resilience investment strategy. An AHP model is used to determine the weight of the attribute, while PT provided the needed ranking and order of the PIMMs resilience strategy for OTOs resilience improvement.

6.1 Introduction

As a typical Multiple Attribute Decision Making (MADM) problem, the selection of an appropriate resilience investment strategy often requires the decision analyst to provide data in the form of a qualitative or quantitative assessment or both. As there are various ways to determine each alternative with respect to each of the attributes in question, the rationale in handling these data usually results in uncertain, indefinite or missing information that makes the decision-making process more complex and challenging (Yang and Xu, 2002; Kuo et al., 2007). In a decision-making process where subjective and imprecise data are represented, certain conditions have to be taken into consideration simultaneously in evaluating the suitability of alternative(s). A decision maker (DM) can use an existing or improved decision-making algorithm or develop a new decision algorithm in order to effectively make a decision among existing alternatives for a precise choice. Therefore, effective decisions can be made on the basis of consistent evaluation, which is simple in both concept and computation.

Many real-life complex socio-technical system problems have imprecise information about the required alternative strategies with respect to attributes for hazard prevention, control or mitigation. Numerous studies on complex systems require DMs to make strategic decisional judgements in order to handle the imprecision associated with the operation of these systems under uncertainty. DMs also have to reconcile group decisions by modifying incomplete evidence or information, to arrive at a final decision. In order to complete the predefined hazard-based model for resilience improvement, selecting the best strategic alternative feasible for accident scenarios for OTOs is an important priority. This can be achieved using an appropriate MADM tool.

Potential HFs affecting OTOs were identified and assessed in the previous chapters. A hazard-based model was developed and, in the later stage, the most significant HFs were analysed using a Bayesian Network (BN). There are no best or worst techniques for MADM, but some techniques are more suitable for a particular decision problem than others (Mergias et al., 2007). A facilitated process can also be developed and introduced for resilience management decision making to assist the DM to build resilience into a system in a way that it is easily understood by workers on oil terminal platforms when responding to crises.

Some of the essential problems faced in a decision-making process include: 1) the group setting, in which all participants do not have equal expertise about the problem domain, 2) the facilitation of systematic and objective decision making towards selection, alteration and additional designs, 3) whether to support or reject strategic resilience alternatives due to losses/gains, 4) whether decision making needs to be further informed by techniques fit for the retroactive change, and 5) how feasible is the application of these formal techniques.

To this end, this study proposes a simple yet effective novel modelling technique that can be used to solve these problems, and also enrich resilience strategic selection literature on OTOs in stochastic and deterministic terminal behaviour dynamics under uncertainty.

6.2 Decision Making Under Uncertainty

Decision making is a process of selecting a possible course of action from all available alternatives (Lai et al., 1994). The selection of an appropriate alternative for decision making has previously been a task for the decision analyst, to derive rational decisions involving risk and probabilities which are contained in different quantitative and qualitative forms. The PT concept is an essential process for selecting a suitable and applicable choice to provide a possible solution for Multiple attribute decision making (MADM) problems under uncertainty (Fan et al., 2013). A wide range of studies (see section 2.6) have been proposed to determine the selection of attributes and alternatives with respect to the overall goal of a realistic selection scenario. One of them is known to consider several strategies to support different conflicting criteria relating to a resilience investment selection problem for seaport operations (John et al., 2014b). MADM is an algorithm deployed to solve problems involving selection from a list of alternatives. It describes each alternative by using multiple attributes. For a given set of alternatives, MADM models try to choose the best alternative among them, rank the alternatives from the best to the worst or classify them into classes (OĞUZTİMUR, 2011). It specifies how criteria or attribute information can be processed in order to arrive at a choice suitable for investment (Lavasani et al., 2012). MADM methods generally require comparisons of attributes with respect to alternatives for efficient trade-off. In a MADM process, each decision table (also called a matrix) has four main parts, which are summarised as follows:

- Alternatives
- Criteria or Attributes
- Weight of experts or relative importance of each attribute
- Performance measure of alternatives with respect to criteria

Based on the analysis of MCDM methods, the basic information in a MADM model can be represented in the matrix presented below:

$$\begin{matrix} C_1\ C_2 \cdots C_m \\ (w_1\ w_2 \cdots w_m) \end{matrix}$$

$$Z = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{bmatrix} \begin{bmatrix} y_{1,1} & y_{1,2} & \cdots & y_{1,m} \\ y_{1,1} & y_{1,2} & \cdots & y_{1,m} \\ \vdots & \vdots & \ddots & \vdots \\ y_{n,1} & y_{n,2} & \cdots & y_{n,m} \end{bmatrix} \tag{6.1}$$

Where A_i $(i = 1, 2, 3, \ldots, n)$ is the i^{th} alternative; C_i $(i = 1, 2, 3, \ldots, m)$ is the i^{th} set of criteria with which each alternatives performance can be measured; $y_(i, j)(i = 1, 2, 3, \ldots, n), (j = 1, 2, 3, \ldots, m)$ is the measure of performance of the i^{th} alternative with respect to the m^{th} criterion; and w_j $(j = 1, 2, 3, \ldots, m)$ is the i^{th} criterion weight. It is essential to emphasise that all elements in the decision matrix must be normalised to the same units, so that all the possible attributes in the decision problem can be dealt with easily to eliminate any computational difficulty. As evidenced in Lavasani *et al.* (2012), there are four means of normalisation in a MADM problem; the two most popular methods are summarised as follows:

- Linear Normalisation: this approach divides the rating of n attribute by its maximum value. Usually, the normalised value $p_{i,j}$ can be obtained using:

$$p_{i,j} = \frac{y_{i,j}}{y_j^*}, 1, 2, 3, \ldots, n; j = 1, 2, 3, \ldots, m \tag{6.2}$$

- Vector Normalisation: this approach divides the rating of each attribute by its average, so that each normalised rating of $y_{i,j}$ can be obtained using:

$$p_{i,j} = \frac{y_{i,j}}{\sqrt{\sum i = 1^n y_{i.j}^2}}, 1, 2, 3, \ldots, n; j = 1, 2, 3, \ldots, m \tag{6.3}$$

Normally, an alternative in a MADM problem is often described using qualitative variables expressed by DMs. However, when no criteria evidence or information is available, the preferred approach is to use PT, which has the capability of handling such a situation under varying constraints.

6.3 Resilience Strategies for OTOs Systems

According to Liddell and Scott (1940) and Andrews and Roland (1987), a strategy is a high-level plan or method of action designed for obtaining a specific goal or result under conditions of uncertainty. Strategy is all about a pattern in a stream of decisions for gaining a position of advantage over evident operational scenarios or, at best, exploiting emerging possibilities. A strategy is more a set of strategic choices (options) an organisations adapts to than a fixed plan.

Based on the assessment of OTOs in Chapters 4 and 5, the two elements that need to be addressed in enhancing resilience are increasing their adaptive capacity and decreasing their vulnerability to hazards and uncertainty (Dekker et al., 2008; Aven, 2011). Therefore, reducing a systems vulnerability at the operational phase makes it less prone to disruptions, and increasing its adaptive capacity allows it to recognise/respond to shocks (Omer et al., 2012).

According to Mansouri et al. (2009), integrating resilience into the design and operation of complex systems can be potentially costly. However, experience has shown that a total loss of the whole system in the face of severe disruption could lead to long-term consequences. To this end, most DMs are faced with a high degree of strategic decisions that involve major resource implications regarding investment and uncertainty for an appropriate resilience strategies.

Strategic decisions involve different levels of many individual elements, and this interrelationship among choices has become a major source of decision complexity. Bolstering the effectiveness of operational decisions requires an in-depth and step-by-step analysis of the utilisation of a risk management algorithm, taking into account the complexities of operational uncertainty within a system. More importantly, the decision selection processes are challenging due to the fact that numerous events need to be modelled (Wang and Trbojevic, 2006). The conditions for attaining an ideal level of strategic decision making on resilience in CMOs involve an ample understanding of both the system and the attributes influencing its performance (Mostashari et al., 2011). Since the objective of a decision-making process is to obtain the best combination of attributes for rational decision making, effort needs to be tailored towards efficiently developing, structuring and assessing those attributes that influence alternative selection. It is significantly important to mention that the selection of the right alternative will enhance resilience of OTOs under high uncertainty.

Furthermore, the resilience strategies were suggested based on the uncertainties identified in the literature on oil terminal platforms, resilience conceptual framework review, and terminal failure mode analysis as discussed in the preceding chapters. Also, these chapters facilitated the selection procedure to identify an applicable strategy that can be implemented for CMOs under investigation. As a result, the exploration of different decision-making tools, algorithms, and approaches to propose a robust yet flexible decision-making approach based on a wide range of issues related to accidents, hazards, failures, planning and management will help to evaluate and rank operational efficiency for a given oil terminal platform (Rao and Davim, 2008).

The proposed strategies are tested against multiple scenarios, as presented in Subsection 6.3.1 and Table 1, to enhance a coherent decision-making process. This allows decision makers to share their strategic concerns and increase their understanding of the oil terminal operational systems, appreciating the potential impact of different alternatives before subsequently arriving at a strategic decision for resilience improvement and management of OTOs.

6.3.1 Assessment of OTOs for Strategic Resilience Improvement

Based on the analysis in sections 4.6 and 5.6, a critical aspect of a decision-making process lies in measuring and monitoring information about key attributes that facilitate disruptions to OTOs. Clearly, providing theoretical understanding of and empirical support for how significant hazards contribute to major disruptions and have enormous consequences has enabled real-time demand forecasting for monitoring, control and mitigation. In spite of the application of mathematical algorithms, utilising subjective judgement principles often make decisions imprecise for MADM problems.

It is important to emphasise that an early examination of the OTOs systems vulnerability to natural and subsequent related hazards was conducted and its failure modes were identified and modelled. Based on the obtained results presented in Figs 5.9, and the relative weight obtained using the novel $UtiSch_+$ model to establish the magnitude of uncertainty within oil terminal platforms/ship interface, a measured and evaluated study is required for strategic resilience decision. Thus, DMs need to suggest strategies for implementation that can adapt to, survive and recover from minor/major shocks or disruption to re-organise and resume functionality of operations under high uncertainty.

Following an intensive investigation into OTOs platforms, it is apparent that Man-, Machine- and Nature-related hazards have been fundamental in most accidents in complex maritime operations. Such an evaluation helps to measure the operational efficiency, robustness and flexibility of oil terminal platforms. Consequently, aided by a combination of qualitative and quantitative data, a single model framework was established to reduce the occurrence of accidents and system vulnerability; a set of strategies aligned with the evaluation of identified attributes may constitute a hierarchy (Yang and Sen, 1994). A similar concept has also been pointed out in John et al., (2014) for resilience investment strategy. It is noteworthy to mention that addressing the complexities of OTOs hazards/accidents requires the formidable task of understanding offshore and onshore oil terminal operations and thus (off)loading of crude oil, kerosene, diesel and petrol. Furthermore, using a proven methodology to investigate the acknowledged causes of hazards/accidents on OTOs establishes a group of dominant safety concerns for oil terminal platforms.

Following the investigation, ranking and analysis of hazards on OTOs, resilience strategies were identified based on a robust literature review and brainstorming sessions conducted with experts. These strategies were subsequently suggested to increase adaptive capacity, aid system recovery and reduce OTOs vulnerability. The identified strategies are summarised as follows (**?**Ronza et al., 2007; **?**; Madni and Sievers, 2014; Mansouri et al., 2010; Zhang and Lin, 2010; Aven, 2011; Berle et al., 2011; **?**; Dinh et al., 2012; Lavasani et al., 2012; Omer et al., 2012; John et al., 2014b):

- **Implement policies that manage the consequences of threats**
  - Policy changes for a resilient system: Safety first, security checks and monitoring.
  - Safe workplace and safe system of work: HSE (ISO 14001 and OHSAS 18001). Operate a hierarchical approach to risk. Provide information, instruction and a plan to prepare for seamless transition. Encourage employees to report unsafe activity and provide information on their duty of care, and responsibility for their own safety and that of any other(s) who may be affected by their acts or omission.
  - Commitment: Objective and target will be set annually to promote and communicate throughout the organisation the need for quality, safety and environ awareness. A fully integrated commitment management team should be adopted, independently verifying that integral operation is in accordance with requirements. There must be an absolute desire to reduce accident and work-related hazards.
  - State a clear code of responsibility: Operational responsibility should rest solely and absolutely with the master. Personnel to operate valves and to ensure safe and secure connection of all transfer apparatus to the ship manifold. All operation should be conducted in the spirit of mutual agreement for the completion of a safe and successful cargo-handling operation dependent upon effective cooperation, coordination and communication between all the parties involved.

  - Risk assessments audit: Revise and document where necessary a regularly inspected and tested automatic prevention system to ensure its proper operation. Ensure that the automatic prevention system follows Recognised And Generally Accepted Good Engineering Practice (RAGAGEP).

- **Creating modularity in systems:**
  - Setting up a terminal operation group: Responsible for creating operating expense synergies by sharing of personnel and resources, reducing safety risks due to a fully integrated, centrally coordinated operation, achieving capital investment cost saving by maximising the use of shared facilities. Aiming to reduce the overall investment on facilities (berths, tanks, etc.) in both capital and operational cost yet fits best with the shared facilities concept. Establishing a centre of excellence focused on OTOs. Making sure that the necessary resources, processes and support are available and employed effectively to achieve the target. Developing detailed implementation plans and schedules and where possible consolidating related recommendations into larger, project implementation with the plan to implement them as resources become available.
  - Replacement/repairing of primary and secondary well failure systems
  - Integral safety strategies: (a) Optimising transfer time: automatic path finding, automatic movement execution, optimised resources management of asset and people, (b) Marine time at berth: integrated order management, flexible jetty planning, alignment with additional services, (c) Marine movement: agile planning, comprehensive logistic movement, (d) Accuracy: precision measurement, custody transfer proof data, and (e) Clear operational records: integrated inventory management, track and trace in history.

- **Providing redundancy in systems**
  - Sweep arm system: Brought alongside vessels by means of thruster propulsion, with the aim of facilitating offshore loading and offloading operations. Sweep arm comprises a loading platform which will be positioned alongside midship manifolds, where the loading arm is winched towards the manifold. It is credible, practical and safe.
  - Proper allocation of resources to the various components of the system to enhance its operations.
  - Investing in weather-tracking technology with higher reliability and accuracy of operation.
  - Special platform built for the transfer of equipment.
  - Redundant-level monitoring system with independent high-level alarms that would trigger automated shut off/diversion system and monitor the history of incidents at the facilities, with or without consequence.

- **Robust enforcement and implementation of:**
  - International Safety Guide for Oil Tankers and Terminals (ISGOTT).
  - Enforcement and implementation of the International Maritime Dangerous Goods (IMDG) code.
  - Oil Company International Marine Forum (OCIMF)
- **Making Complex Marine Operations (CMOs) more cognitive:**
  - Prioritise training on complex terminal operation in order to increase knowledge, experience and flexibility for duty operators.
  - Staff training: Training of staff and simulations on the line of defence against disasters. Regular training on working knowledge for situation awareness and contingency procedures. Undergo a formal safety programme and/or safety skill certification training.
  - Strict operational protocol to ensure safe loading operations: Port standards and communication between ship and shore are key and paramount and are the difference between safety and disaster; following guidelines laid down by the Oil Company International Marine Forum (OCIMF), there should be key meetings between ship/shore interface so that everyone knows what they should do, that mooring is correct and safe, and there is an insinuator on-board ship for taking away hazardous vapours. Foreseeing problems before they occur is based on expertise and experience, continuous monitoring and improvement.
- **Hazard management and plant monitoring:**
  - Check proofing systems: Checklist methodology for inspection of safety equipment and installations at oil terminal platforms. This allows for systematic verification of safety standards for each inspected installation and a simple identification of deficiencies. A relevant checklist includes: storage and shipment, transhipment, sailing system and oil separator, fire and flood protection, hazard management and plant monitoring. The checklist should be further tested by different regional inspectors, and new inspectors should be trained in its application.
  - Third safety systems: Organisational measures and monitoring. This includes crisis management, aftercare management, operating data monitoring, capacity of operating resistance, mechanical resistance and resistance of facilities, mode of function of separators, internal emergency and danger prevention plans, technical measures to limit maximum pressure and efficiency of the safety equipment.
  - Establish a hazard analysis and mechanical integrity management system element to ensure that facilities are subject to RAGAGEP.

- Terminal internal monitoring: Terminal operators and duty holders at every change of shift should check the installation and joint proneness. Initiation of constant monitoring during usage and revision, and a repair plan should be used during maintenance work.
- Promote Plan Inspect Monitor and Manage (PIMMs) strategy for safety optimisation.

- **Defence plan in case of disaster:** Intervention teams that will operate under procedures and guidelines.
  - Berth emergency plan: Bring engine to standby. Inform all ships in the vicinity. Stand by to disconnect hoses or loading arms. Where corrective action is needed, terminal may not agree to operations or demand immediate cessation of operation until the situation is rectified. When safety is endangered, operation may be required to be stopped.
  - Facilities proneness: Installations, wagons and vessels connected to plugs, and grounding systems against electrostatic energy.
  - Emergency and intervention teams that will combat flooding, earthquakes, landslides, fires, etc., and operate under procedures and guidelines for intervention in case of natural disasters.
  - Emergency disconnect system (EDS): The activation of emergency release system results to sweep arm pulling away from vessel, then bow mooring is released and vessels leaves.
  - Internal alarm and hazard control monitoring: Consideration of impact, measures to limit the effects of accidents, measures by operators upon accidents.
  - Conduct a survey of randomly selected platforms and facilities at terminals in high-risk locations (facility response plan) to determine the nature of possible hazards due to uncertainty.
  - Promote structural integrity.

- **Handle the dynamic nature of the operation:** Regular client interaction and verification. Confirm, test and verify functionality.
  - Work procedures: Specific instruction and work procedure should be communicated by means of anti-explosion two-way radio transceivers. Communication should be monitored by the berth operator and advisor of hazardous goods, who can also allow time for additional safety measures to be implemented to ensure no occurrence or recurrence of the incident in the future.
  - Strict surveillance: Control plan to detect the basic responsibilities of terminal operators and duty holders (head of shifts) ignorance of which can lead to an accident or by an accident that has already occurred.

- Overflowing signalisation: Overflow signal to trigger an automatic shutdown of pumps, retention task equipped with tank park closing valves designed to limit the area affected by accidental spills, and protection wall against floods set up in certain areas.
- Visual signal: Monitoring sealing faces, lighting protection system, mobile detectors, control system for measuring levels of vapour and constant monitoring.
- High integrity prevention system which can be separated physically, electronically and independently.
- Safety integrity: Having realistic, reliable equipment, operating procedures and preventive maintenance, extent/rigour of operation monitoring, nature and intensity of facility operations. Engineer, operate and maintain automatic prevention system to achieve appropriate safety integrity level.

- **Handle the dynamic nature of the operation:** (1) Automatic movement control: automatic line up, avoid product contamination, lowest-cost operations, (2) Product blending: blend property control, automatic line up of multiple streams, (3) Additional service: line flushes, schedule and track additional service, and (4) Process safety control: keep process within safety limit, automatic pre- and post-processing.

  - Selection of material: Expected mechanical stress, tight and resistant.
  - Automation: Trans-loading technological installations such as automatic safety device and automatic detachment provided to interrupt the flow of substances in case of accident when loading and offloading is in progress.
  - Conduct a survey of randomly selected platforms and facilities at terminals in high-risk locations (facility response plan) to determine the nature of possible hazards due to uncertainty.
  - Minimising the days lost due to Lost Time Accident (LTA).
  - Additional safety measures to be implemented for breakdown of contractors safety system.

6.3.2 Strategies to Enhance Resilience Measures

Resilience has its exclusive distinctiveness. It different to safety, reliability and robustness (Zhang and Lin, 2010). The generic property of a resilient system is the recovery of system failure after damage. Thus, one of the most important aspects of a resilience strategy is the principles embedded within it. Zhang and Lin (2010) proposed five principles to design a preferred decision alternative based on four axioms learned from a biological system. Madni and Jackson (2009) proposed a conceptual framework for a resilience vision. It is important to note that resilience comes at a cost, as with all innovative engineering decision proposals. Thus, the rationale behind an enhanced resilience measure for MADM problems is to allow decision makers to focus on applying the most preferred decision alternative on impacting system attributes. To this end, five general principles that must be embedded in the alternative(s) as shown in Table 6.1.

- Principle I: A certain degree of functional redundancy. The more redundancy a system has, the higher the degree of resilience.
- Principle II: A certain degree of functional learning and redundancy management.
- Principle III: An ability to monitor the system's functions and performance, demands and the utilisation of system capacity.
- Principle IV: Emergent response to system's internal vulnerability and external mishap.
- Principle V: A physical entity to perform a new function for implementing changes in both cognitive and physical domains.

The identified resilience strategies as referred in Subsection (6.3.1) where then grouped into 6 alternatives, with all principles embedded in each alternative. The grouping of each alternative was based on literatures and brainstorming session with six judges, where a strategy which represent a principle was randomly chosen and allocated to an alternative (see Fig 6.5, Fig 6.6 and Fig 6.7 for grouping consistency). The procedure continued until all 6 alternatives was complete. Based on the numeric allocation of each principle, each strategy was allocated an identical numeration as represented in all alternatives. The output for the creation and grouping of all strategies and alternatives can be deduced in Table 6.1.

Table 6.1: Resilience strategy selection based on five general resilience principles

Alternatives	**Strategies**	**Strategic decision description**
	P1	Sweep arm system: Brought alongside vessels by means of thruster propulsion, with the aim to facilitate offshore loading and offloading operations. Sweep arm comprises of a loading platform which will be positioned alongside midship manifolds, where loading arm is winched towards manifold. It is credible, practical and safe.

	F1	Setting up a terminal operation group: Responsible for creating operating expense synergies by sharing of personnel and resources, reducing safety risks due to a fully integrated, centrally coordinated operation, achieving capital investment cost saving by maximising the use of shared facilities. Aiming to reduce the overall investment on facilities (berths, tanks etc.) in both capital and operational cost yet fits best with the shared facilities concept. Establishing a centre of excellence focused on OTOs. Making sure that the necessary resources, processes and support are available and employed effectively to achieve the target. Developing detailed implementation plans and schedules and where possible consolidate related recommendations into larger, project implementation with the plan to implement them as resources become available.
A_1	D3	Robust enforcement and implementation: International Safety Guide for Oil Tankers and Terminals (ISGOTT).
	T4	Emergency and intervention teams: that will combat flooding, earthquakes, landslides, fire etc. and operate under procedure and guidelines for intervention in case of natural disasters.
	S5	Policy changes for a resilient system: Safety first, security checks and monitoring.
	K2	Proper allocation of resources to the various components of the system to enhance its operations.
	J2	Safety integrity: Having realistic reliability equipment, operating procedures and preventive maintenance, extent/rigor of operation monitoring, nature and intensity of facility operations. Engineer, operate and maintain automatic prevention system to achieve appropriate safety integrity level.
A_2	V3	Robust enforcement and implementation: International Maritime Dangerous Goods (IMDG) code.

	Q4	Conduct a survey of random selected platforms and facilities at terminals in high-risk locations (facility response plan) to determine the nature of possible hazards due to uncertainty.
	W5	Safe workplace and safe system of work: HS & E (ISO 14001 and OHSAS 18001). Operate a hierarchical approach to risk. Provide information, instruction, and a plan to prepare for seamless transition. Encourage employees to report unsafe activity and provide information on their duty of care responsibility for their own safety and that of any other who may be affected by their acts or omission.
A_3	B3	Investing on weather tracking technology with higher reliability and accuracy of operation.
	E3	Integral safety strategies: (a) Optimising transfer time; automatic path finding, automatic movement execution, optimised resources management of asset and people, (b) Marine time at berth; integrated order management, flexible jetty planning, alignment with additional services, (c) Marine movement; agile planning, comprehensive logistic movement, (d) Accuracy; precision measurement, custody transfer proof data, and (e) Clear operational records; integrated inventory management, track and trace in history.
	L3	Robust enforcement and implementation: oil company international marine forum (OCIMF)
	R4	Emergency disconnect system (EDS): Activation of emergency release system, e.g. sweep arm pulls away from vessel, bow mooring is released and vessels leaves

	U5	Commitment: Objective and target will be set annually to promote and communicate throughout the organisation the need for quality, safety and environ awareness. A fully integrated commitment management team should be adopted, independently verifying integral operation is in accordance with requirements. An absolute desire to reduce accident and work-related hazards.
	C4	Redundant level monitoring system with independent high level alarms: that would trigger automated shut off/ diversion system and monitor the history of incidents at the facilities, with or without consequence.
	G4	Check proofing systems: Checklist methodology for inspection of safety equipment and installations at oil terminal platforms. This allows for systematic verification of safety standards of each inspected installation and a simple identification of deficiencies. Relevant checklist includes; storage and shipment, transhipment, sailing system and oil separator, fire and flood protection, hazard management and plant monitoring. Checklist should be further tested by different regional inspectors, and training of new inspectors.
A_4	Y3	Work procedures: Specific instruction and work procedure should be communicated by means of anti-explosion two-way radio transceivers. Communication should be monitored by the berth operator and advisor of hazardous goods whom can also allow time for additional safety measure to be implemented to ensure no occurrence or recurrence of incident in the future.

	X4	Third safety systems: Organisational measures and monitoring; crisis management, aftercare management, operating data monitoring, capacity of operating resistance, mechanical resistance and resistance of facilities, mode of function of separators, internal emergency and danger prevention plans, technical measures to limit maximum pressure and efficiency of the safety equipment.
	Z5	State a clear code of responsibility: Responsibility of operation should rest solely and absolutely with the master. Personnel to operate valves and to ensure safe and secure connection of all transfer apparatus to the ship manifold. All operation should be conducted in the spirit of mutual agreement for the completion of a safe and successful cargo handling operation dependent upon effective cooperation, coordination and communication between all the parties involved.
A_5	H5	Special platform built for the transfer of equipment.
	O5	Prioritise training on complex terminal operation in order to increase knowledge, experience and flexibility for duty operators.
	M3	Terminal internal monitoring: Terminal operators and duty holders at every change of shift check the installation and joint proneness. Initiation of constant monitoring during usage and revision and repair plan should be used during maintenance work.
	N4	Staff training: Training of staff and simulations on the line of defence against disasters. Regular training on working knowledge for situation awareness and contingency procedures. Undergo a formal safety programme and/or safety skill certification training.

	I5	Risk assessments audit: Revise and document where necessary regular inspected and tested automatic prevention system to ensure there proper operation. Ensure that automatic prevention system follows RAGAGEP
A_6	i	Additional safety measures to be implemented for breakdown on contractors safety system.
	ii	Hazard management and plant monitoring: Establish hazard analysis and mechanical integrity management system element to ensure that facilities are subject to Recognised and Generally Accepted Good Engineering Practices (RAGAGEP).
	iii	Strict surveillance: Control plan to detect the basic responsibilities of terminal operators and duty holders (head of shifts) which can lead to accident or can be caused by an accident that has already occurred.
	iv	Berth emergency plan: Bring engine to standby. Inform all ships in the vicinity. Stand by to disconnect hoses or loading arms. Where corrective action is needed, terminal may not agree to operations or demand immediate cessation of operation until the situation is rectified. When safety is endangered operation may be required to be stopped.
	v	Strict operational protocol to ensures safe loading operations: Ports standards and communication between ship and shore is key and paramount and it is the difference between safety and not. Key meetings between ship/shore interface knowing exactly what it should do, proper mooring in a safe standard, and insinuator for taking away hazardous vapours. Foresing problems before they occur based on expertise and experience, continuous monitoring and improvement.

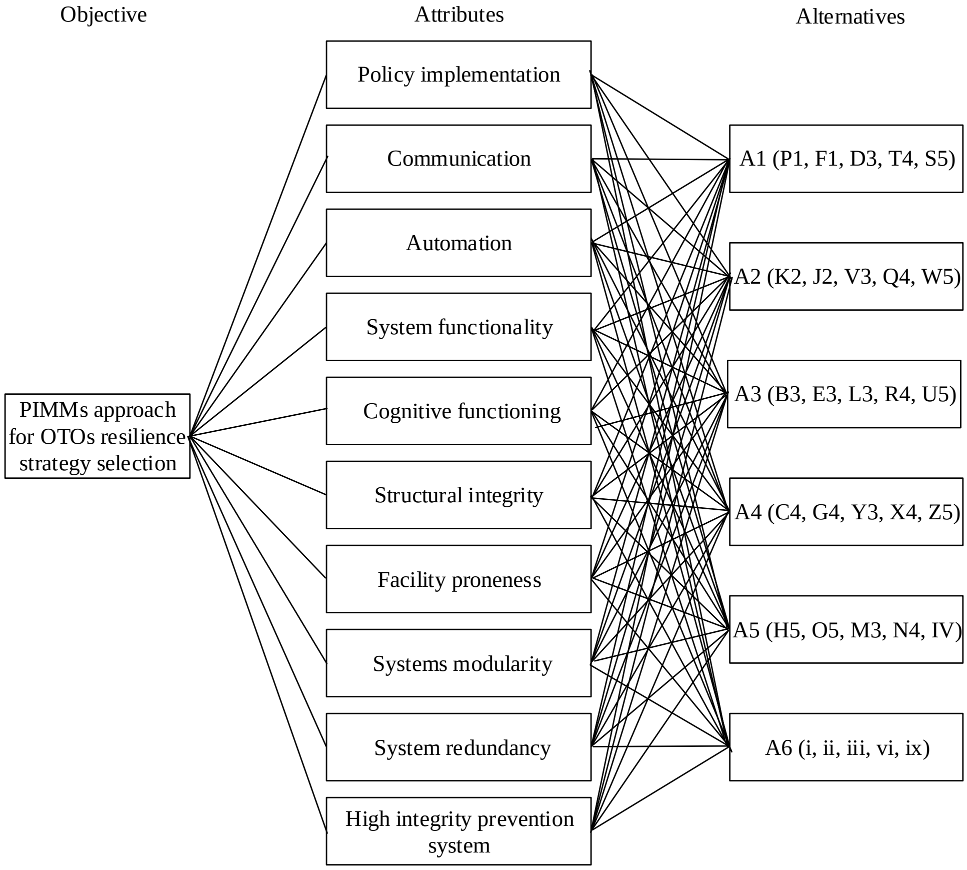


Figure 6.1: Hierarchical structure for Plan Inspect Monitor and Manage (PIMMs) resilience investment strategy.

6.4 Modelling using Prospect Theory (PT)

PT has been demonstrated to be a robust tool for handling complex and real-life problems for decision-making processes in an uncertain environment. PT uses complex mathematical algorithms for analysis, hence this chapter proposes a simplified strategic decision-support system using a PT approach for resilience strategy selection. The PT approach will also significantly optimise performance effectiveness on oil terminal platforms when subjected to stochastic terminal behaviours operational constraints. In addition, it is important to mention that the capability and efficiency of PT in handling complex engineering solutions, its flexibility in computational analysis, and its ability to simultaneously consider a positive or negative ideal solutions, as well as its systematic and logical results' evaluation, necessitate the use of PT as a tool for resilience strategy selection. For further information on PT, refer to section 2.6 and Tversky and Kahneman (1979, 1992).

PT relies on subjects' behaviour and it shows that preferences are non-liner. An increase in the Probability Weighting Function (PWF) p_1 to be gained from prospect

x_1 from 0.99 to 1.0 has more impact on a subject than an increase in PWF p_2 to gain from a prospect x_2 from 0.10 to 0.11. More so, subjects are more sensitive to losses from a given prospect than gains of the same magnitude. However, subjects tend to be risk averse over moderate probability gains, i.e. they typically prefer a certain gain on a prospect to a 50% chance of a better prospect, and are risk seeking over losses, i.e. subjects tend to prefer a 50% chance of a negative prospect to a certain negative prospect. Subject' behavioural sensitivity on gains and losses is represented by the value function (VF) v over a prospect x, thus $v(x)$. This motivates concave up over a positive prospect $v(+x_1)$ and concave down (convex shape) over a negative prospect $v(-x_1)$.

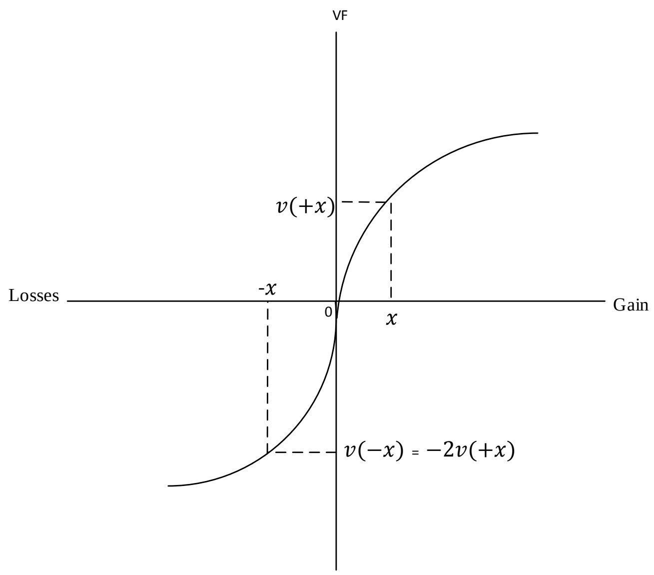


FIGURE 6.2: An S-shaped value function as adapted from Tversky and Kahneman (1979)

Tversky and Kahneman (1979, 1992) demonstrated the importance of the value function (VF), which represents the reference point, to explain why subjects tend to be risk seeking in the realm of loss. The reference point is created by different circumstances (e.g. framing effect) and can be manipulated. It serves as a boundary that distinguishes gains from losses (Tversky and Kahneman, 1992), but from what point can a subject estimate positive and negative prospects? The reference point is the subject's neutral point "0" and it is based on psychology; it is the subject's present decisions, wealth or something else. Equivalent to risk aversion on gain and risk seeking on losses, Fig 6.2 shows a common S-shaped curve, concave above the reference point ($v^+(x) \leq 0, x \geq 0$) and convex with a steeper curve (a kink) on the negative prospect (losses) below the reference point ($v^-(x) \geq 0, x \leq 0$). Empirically, the difference between the negative and the positive prospect is often a factor of 2, i.e. a steeper one means two losses happen together. When a subject is offered a positive probability of not having a negative prospect for certain, the subject makes a choice and accepts the decision. Thus, given the curve is steeper by a factor of 2 in Fig 6.2, the value of a negative prospect $v(-x) \cong -2x$value of a positive prospect of $x(v^{+}(x) < v^{-}(-x) textfor x \geq 0)$, i.e. the marginal value of a negative prospect is always halved by 2.

Following the outcomes as expressed in PT as positive or negative deviations from a neutral reference point, if $x_i \geq r_p 0$ it denotes a gain and if $x_i < r_p 0$ it denotes a loss. The emphasis is on the VF and PWF specification by a number of authors (Kahneman and Tversky, 1979; Tversky and Kahneman, 1986, 1992; Gonzálvez-Gallego et al., 2015; Fan et al., 2013; Zhou et al., 2014). The reflective form of the VF is given by:

$$v(x) = \begin{cases} f(s_i)^{\alpha} & if x_i \geq r_p 0 \\ -\lambda[-f(s_i)^{\beta} & if x_i < r_p 0 \end{cases} \tag{6.4}$$

Where α and β measure the concavity and convexity of the value function for positive (gains) and negative (losses) prospects respectively, and $0 \leq \alpha, \beta \leq 1$. λ is the coefficient of loss aversion with much larger values of $\lambda > 1$.

The properties of the probability weighting function was defined by Kahneman and Tversky (1979) included that subjects tend to psychologically overweight small probabilities (i.e. if a probability is small enough, subjects round it up to 0) and underweight large probabilities (i.e.) especially depending on the context as shown in Fig 46. Thus, the PWF observes nonlinear voilation near the endpoint 0 and 1 (where $[w(p_1) + w(1 - p_2) < 1]$) due to psycological weight. PT uses decision weight . The decision weight multiplies the value for a higher prospect outcome $w(p)$ and $1 - w(p)$ for a lower prospect outcome. They are much as subjective probabilities inferred from choices between prospects. However, they are not probabilities and as such they do not obey the probability axioms (Kahneman and Tversky, 1979), but how does it corresponds to objective probabilities?

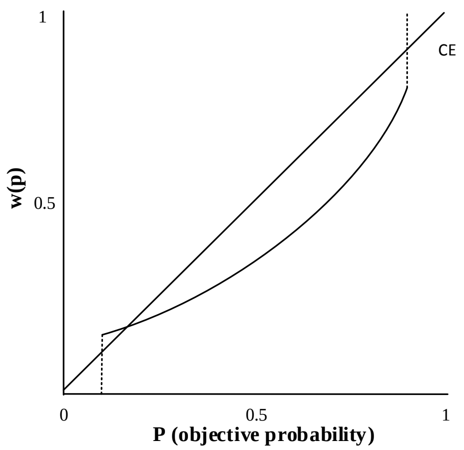


FIGURE 6.3: Probability Weighting Function (PWF) adapted from Tversky and Kahneman (1979)

If subjects are rational enough, the mapping from objective probability to decision weight will be the 45 degree line. Given an overweighting phenomenon of a really small probability, subjects psychologically round it up to 0. If a probability is small enough yet significant and large enough that it cannot be ignored, subjects tend to overweight it. We tend to overweight above the 45 degrees line and underweight below the 45 degree line. Kahneman and Tversky (1979) argued that a hypothetical shape develops, i.e. the overweighting at the beginning (0-0.5) has to be cancelled out to some degree by underweighting $(0.5 - 1.0)$. Technically, if we have to introduce a certainty effect into a graph, by the time we get to the probability of 1.0, we have another discontinuity towards the top because we are overweighting the probability of 1.

The additivity of decision weight means the probabilities have to add to $1(P_1 + P_2 = 1)$ i.e. if we have just two prospect outcomes, the probabilities of those outcomes have to add up to 1. However, due to uncertainty about decision weights, we can no longer make the assumption that, just because the probabilities add up to 1, the sum of the decision weight on these probabilities must also add up to 1, i.e. $w(P_1) + w(P_2) = 1$. Therefore, unless there is a very specific probability, decision weights are generally $w(P_1)+w(P_2) < 1$ and this is referred to as the sub-additivity of decision weight. It is important to keep this point about decision weight in mind, because it becomes somewhat of a psychological distinction which describes behaviours. For example, there are two different ways of getting something wrong: 1) overweight: one could literary think that the chances of being in a plane crash are larger than they are, or 2) underweight: one could also objectively know the risk of being in a plane crash and just psychologically decide that the probability is more important than it actually is. Thus, having a certainty effect on a risk but psychologically deciding that the probability is more important than it actually is. Either way (overweighting or underweighting) will definitely make the subject achieve the goal but for different reason.

It is important to be clear that subjects aren't actually overestimating the probabilities of outcomes, they are just subjectively overweighting or underweighting them in their decision-making processes. Subjects tend to sometimes overestimate probabilities as well, i.e. not perceiving them in an objective way but rather in a subjective way, even though the objective probabilities are known. It is important to note that subjects can make these errors at the same time and this compounds the deviation irrationally. A subject's perception of probabilities changes over time and, as such, the respective PWS for the gains and losses domains are:

$$w^+(P) = \frac{(p_{xi})^{r+}}{(p_{xi})^{r+} + (1 - p_{xi})^{r+})^{\frac{1}{r+}}} \tag{6.5}$$

$$w^-(P) = \frac{(p_{xi})^{r-}}{(p_{xi})^{r-} + (1 - p_{xi})^{r-})^{\frac{1}{r-}}} \tag{6.6}$$

Decision weight measures the impact of events on the desirability of prospects, and not merely the perceived likelihood of these events. The decision weight associated with an outcome can be interpreted as the marginal contribution of the respective event, defined in terms of the capacities W^+ and W^- i.e. i.e. for a positive prospect outcome, π_i^+ is the difference between the capacities of the events "the outcome is at least as good x_i " and "the outcome is strictly better than x_i", whereas, for negative prospect outcomes, π_i^- is the difference between the capacities of the events "the outcome is at least as bad as x_i and "the outcome is strictly worse than x_i. If each W is additive and hence a probability measure, then π_i is simply the probability of A_i. It follows readily from the definitions of π and W that, for both positive and negative prospects, the decision weights add to 1. However, for mixed prospects, decision weights for gains and losses are defined by separate capacities and, as such, the sum can be either smaller or greater than 1.

The prospect value is calculated with the combination of the VF and PWF. Let S be a finite set of states of nature; subsets of S are called events. It is assumed that exactly one state obtains, which is unknown to the decision maker. Let X be a set of consequences, also called outcomes. We assume that X includes a neutral outcome denoted by 0, and we interpret all other elements of X as gains or losses, denoted by x_i^+ or x_i^- consequences, respectively. An uncertain prospect f is a function from S into X that assigns to each state $s\varepsilon S$, such that a consequence $f(s) = x$ in X. A prospect f is then represented as a sequence of pairs (x_i, A_i) which yields x_i if A_i occurs, where $x_i > x_j$ iff $i > j$, and A_i (probability) is a partition of S. We use positive and negative subscripts to denote positive and negative outcomes, then 0 to index the neutral outcome. A prospect is called strictly positive or positive, respectively, if its outcomes are all positive or non-negative, and strictly negative and non-positive prospects are defined similarly; all other prospects are called mixed. The positive part of f, denoted f^+, is obtained by letting $f^+(s) = f(s)$ iff $f(s) > 0$, and $f^+(s) = 0$ iff $f(s) \leq 0$. The negative part of f, denoted f^-, is defined similarly. We assign to each prospect f a number $V(f)$ such that f is preferred to or indifferent to f_i iff $V(f) \geq V(f_i)$. Therefore the prospect $U(R)$ is given as:

$$U(R) = \sum_{i=0}^{n} (p_{xi})v(x_i) + \sum_{n}^{i=0} w^-(p_{xi})v(x_i) \tag{6.7}$$

$$U(R) = \sum_{i=0}^{n} w^*(p_{xi})v(x_i) \tag{6.8}$$

$$u(x_i) = \sum_{i=1}^{n} v[f(s_i)]w(p_{xi}) \tag{6.9}$$

PT outlines a framework and provides a menu of the different ways that subjects' use mental heuristics or how they perceive prospects based on gains and losses to come up with a unifying theory for decision making under risk

6.5 PT Process

The resolve procedure of PT for a MADM problem in this study is based on the format of a DMs attribute aspirations (Lotfi et al., 1992; Nowak, 2006; Brown et al., 2012; Fan et al., 2013). It is assumed that DMS determine their level of aspiration for different attributes that describe each alternative. Fan et al. (2013) presented a method to solve MADM problems with three formats of attribute aspirations to obtain an overall prospect value. This value helps to determine the ranking of an alternative from a set of alternatives. In addition, the motivation for the use of attribute aspiration in a PT process is that it plays an important role in the decision process. More so, it provides a simple model that can be related to and used in a generic oil terminal platforms.

It is acknowledged that PT (Kahneman and Tversky, 1979) needs a resilient condition for gain-loss separability (Brown et al., 2012) because it has shown a systematic violation in experimental studies Wu and Markle (2008). But Brown et al. (2012) demonstrated that there is sufficient empirical evidence that suggests that attribute aspiration provides a satisfactory approach resolution for gain-loss systematic violation. Attribute aspirations are expressed in multiple formats by DMs, but formally in the following ways: (1) "would better not be over an nth term", (2) "would better be over an nth term" and (3) "would better be between kth and nth term" (Lotfi et al., 1992; Kulak, 2005; Kulak and Kahraman, 2005; Nowak, 2006; Fan et al., 2013). On the other hand, some practical examples have shown that the aspiration level of a DM could be regarded as his/her reference point. A decision analyst is critical on the deviation of the attribute value (gain-loss), where in some cases it is over/under the reference point or indifferent within.

According to Fan et al. (2013), based on the objective or subjective measure of achievement for each attribute that describe each alternative from a set of alternatives, Let $A = 1, 2, \ldots, a and N = 1, 2, , n$. Let $M = M_1, M_2, \ldots, M_a$ be a finite alternative set, where M_i denotes the i^{th} alternative, $i \in A; C = C_1, C_2, \ldots, C_n$ be a finite attribute set, where C_j denotes the j^{th} attribute, $j \in N$. Let $w = (w_1, w_2, \ldots, w_n)^T$ be an attribute weight vector, where w_j denotes the weight or the importance degree of attribute C_j, such that $\sum_{j=1}^{n} w_j = 1 and 0 \leq w_j \leq 1, j \in N$. Let $k = [k_{ij}]_{a \times n}$ be a decision matrix, where K_{ij} is an attribute value, i.e., the consequence for alternative M_i with respect to attribute $C_j, i \in M, j \in N$. We consider that K_{ij} is a crisp value, and the attribute aspirations provided by a DM are represented as following:

- *Aspiration format I* : The attribute value K_{ij} would better not be over $b_j^{\wr}$, where $b_j^{\wr}$ is the aspiration level of attribute C_j provided by the DM, and it is a crisp number. For example, when an oil company needs to select a piece of equipment based on reliability, the DM wants the price of the equipment to be no more than £50,000.

- *Aspiration format II* : The attribute value K_{ij} would better be over b_j^*, whereb_j^* is a crisp number. For example, when selecting operation equipment, the DM wants the quality of the equipment to be over 6 (0: the worst; 10: the best).

- *Aspiration format III* : The attribute value K_{ij} would better be in the range of $[b_j^c, b_j^f], b_j^f > b_j^c$, and any possible value in the range is equally acceptable to the DM. For example, the DM requires the load capacity of the equipment to be in the range of 2 to 2.5t.

where $K_{ij} \geq 0, b_j^{l} \geq 0, b_j^* \geq 0 and b_j^c \geq 0$.

According to different attributes corresponding with the above three attribute aspiration formats, attribute set $C = \{C_1, C_2, \ldots, C_n\}$ can be divided into three subsets: C^I, C^{II} and $C^{III} C^I \bigcup C^{II} \bigcup C^{III} = C$, where $C^I = \{C_1, C_2, \ldots, C_{l_1}\}, C^{II} = \{C_{l_{1+1}}, C_{l_{1+2}}, \ldots, C_{l_2}\}$, and $C^{III} = \{C_{l_2}, C_{l_{1+2}}, \ldots, C_n\}$ are the attribute sets with regard to aspiration formats I, II and III, respectively. Then, subscripts of these three subsets can be denoted as $N^I = \{1, 2, \ldots, l_1\}, N^{II} = \{l_1 + 1, l_1 + 2, \ldots, l_2\}$, and $N^{III} = \{l_2 + 1, l_2 + 2, \ldots, n\}$ respectively. Obviously, $N^I \bigcup N^{II} \bigcup N^{III} = N, N^I \cap N^{II} = \phi, N^{II} \cap N^{III} = \phi, N^I \cap N^I II = \phi$. If the psychological behaviour of the DM reflects the aforementioned attribute aspiration formats, then the ranking of the most desirable alternative(s) from the finite set M using decision matrix K and attribute weight vector w can be determined. Thus, the processes involved for solving an MADM problem with multiple formats of attribute aspirations was mostly done by manual calculations, and are given as follows:

- Determine the decision weight of attributes by aggregation, according to experts' preference judgements.
- Determine reference points according to DM's attribute aspirations.
- Construct gainloss matrix.
- Construct prospect value matrix.
- Construct normalized matrix.
- Calculate the overall prospect value of each alternative.
- Determine the ranking of alternatives according to the obtained overall prospect values.

6.6 Application of PT for the selection of a strategic resilience alternative for OTOs

6.6.1 Step 1: Determine the Decision Weight Obtained by Aggregation, according to Experts' Preference Judgements

The Analytical Hierarchy Process (AHP) has been an exciting research subject in many different fields (logistics, finance, refineries, operations, transportation, marketing, etc.) due to its wide range of application (OĞUZTİMUR, 2011). Introduced by Saaty (1977, 1980), AHP involves aggregation of various comparisons to obtain a rational vector that reflects the decisions revealed by preference data provided by DMs judgements on the different attributes. Additionally, it is suited for complex decisions that involve comparison of decision elements (Kabir and Hasin, 2011; Benítez et al., 2012). The basis of AHP as a tool for decision making is its ability to determine relative weights to rank decision attributes in any application. Also, it helps to model subjective decision-making processes based on multiple attributes in a hierarchical system. AHP provides pairwise comparisons amongst attributes.

The process involved in AHP is based on a matrix of pairwise comparisons between attributes (Cao et al., 2008). In summary, AHP has three main steps: (1) structuring the hierarchy, (2) pairwise comparisons (determining the weights) and (3) decision phase (selection of the best alternative among the others) (**?**Kabir and Hasin, 2011; John et al., 2014b).

Let m be a decision point number assigned to a defined decision-making problem, and n be a number assigned to attributes (denoted by $a_1, a_2, \ldots, a_n$) that are affecting these decision points. It is very important to correctly determine the number of attributes that will affect the result in order to perform consistent and rational pairwise comparisons. *Forming a Comparison Matrix between attributes*: For $n \times n$ pairwise comparison, a dimensional square matrix between attributes formed. When $i = j$, the components on the diagonal of the comparison matrix take a value of 1 value because related attributes compare within themselves in such situations. The comparison matrix is shown below.

$$A = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{1,1} & a_{2,2} & \cdots & a_{2,n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ . & . & \cdots & . \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} \end{bmatrix} \tag{6.10}$$

When comparing attributes to each other, it is done on one-to-one and reciprocally in accordance to their importance value. This comparison could be performed using the importance scale as shown in Table 6.2.

If a DM deems i to be more important than j (i.e. i = 1,$j = 3$), then the comparison matrix takes 3 as a value. Otherwise, the comparison takes a 1/3 value if the more important option is used for j, such that $i = 3$, $j = 1$. In the same comparison for i and j, if the attributes have equal importance, then the component will take 1 as a value. Therefore, comparisons are performed when attribute are not equally important. Suppose there are m DMs with equal weights, the components in the row and column pairwise comparison matrix can be determined using the following formula for all values of i and j:

$$a_{ij} = \frac{1}{a_{ij}} \tag{6.11}$$

Table 6.2: Importance Scale

Numbers (a_{ij})	**Value**	**Description**
1	Equal	i and j are equally important (E)
3	Moderately more important	i is moderately more important than j (MI)
5	Strongly important	i is strongly important than j (ST)
7	Very strongly more important	i is strongly more important than j (SV)
9	Absolutely important	i is absolutely important than j (AI)
2,4,6,8	Intermediate values	Used when a comparison is needed (iNa, iNb, iNc, iNd)

$$\text{Where } a_{ij} \text{ is the relative importance by comparing attributes } i \text{ and } j \\ i = 1, 2, 3, \ldots, n \text{and} j = 1, 2, 3, \ldots, n \tag{6.12}$$

$$A = a_{ij} = \begin{bmatrix} 1 & a_{1,2} & \cdots & a_{1,n} \\ 1/a_{2,n} & 1 & \cdots & a_{2,n} \\ . & . & \cdots & . \\ 1/a_{n,1} & a_{n,2} & \cdots & 1 \end{bmatrix} \tag{6.13}$$

Determine the percentage Importance Distributions of Attributes: This refers to the weights of these attributes in total; a column vectors w with a set of numerical weight denoted by $w_1, w_2, \ldots, w_n$ which constitute the comparison matrix and, a vector W_k which constitute the weight matrix. It is noteworthy to mention that, in realistic situations, w_i/w_j is usually not known. Therefore, the weight vector is given as:

$$W_k = \begin{bmatrix} W_{1,1} \\ W_{2,1} \\ . \\ . \\ \cdots \\ W_{n,1} \end{bmatrix} \tag{6.14}$$

In general, weights $w_1, w_2, \ldots, w_n$ can be determined using the following equation (Pillary and Wang, 2003):

$$W_k = \frac{1}{n} \sum_{j=1}^{n} (\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}})(k = 1, 2, 3, \ldots, n) \tag{6.15}$$

Where a_ij stands for the entry of row i and column j in a comparison matrix of order n.

Ensure consistency in attributes comparisons pairwise judgement: Naturally, the authenticity of the results will depend on the consistency of the decision maker's pairwise comparisons between attributes. For consistency, $a_{ij} = k$ implies that $a_{ij} = 1/k$. Thus, AHP provides a process to measure the consistency of these pairwise comparisons by computing a Consistency Ratio (CR). The essence of the CR calculation is such that, if the value is more than 0.10, either there could be a calculation error or it indicates an inconsistency in the pairwise comparisons of the DMs' judgements; thus, the pairwise judgements need to be reviewed. But, when the calculated CR value is 0.10 or less, the pairwise comparisons made by the DMs are consistent and considered reasonable, and the computation of the weight vectors holds. The CR is obtained according to the following equations Eq. (6.16), Eq. (6.17) and Eq. (6.18)

$$CR = \frac{CI}{RI} \tag{6.16}$$

$$CR = \frac{\lambda_{max}^{-n}}{n-1} \tag{6.17}$$

$$\lambda_{max} = \sum_{j=1}^{n} \frac{\frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \tag{6.18}$$

Where CI is the consistency index, RI represents the average random index as shown in Table 6.5, "n" is the matrix order, and λ_{max} stands for maximum weight value of the "$(n \times n)$" comparison matrix A. For example, the RI value of three criteria comparisons will be 0.58 as shown in Table 6.3.

Table 6.3: RI Values for Comparisons

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

6.6.2 Step 2: Determine the Reference Points according to DM's Attribute Aspirations

As proposed by Kahneman and Tversky (1979, 1992), a DM is often apprehensive about the deviations of attribute values from attribute aspirations. Therefore according to prospect theory, a DM's attribute aspirations can be regarded as reference points (Fan et al., 2013) If r_p0 denotes the reference point concerning attribute $C_j, j \in N$, then as proposed by Fen et al. (2013) the following ways can be used to determine the reference points for aspiration formats I, II and III, respectively (Fan et al., 2013).

- Aspiration format I: For $C_j \in C^I, b^l_j$ can be regarded as the reference point r_p0, i.e. $r_p0 = b^l_j$, $j \in N^I$. If K_{ij} is over the reference point b^*_j, such that $K_{ij} > b^l_j$, the surplus can be deemed as the DM's 'loss'; but if K_{ij} underachieves, such that $K_{ij} < b^l_j$, the deficient can be deemed as the DM's 'gain'.

- Aspiration format II: For $C_j \in C^{II}, b^*_j$ can be regarded as the reference point r_p0 , i.e., $r_p0 = b^*_j, j \in N^{II}$. For this case, a slight difference can be observed from (1). If K_{ij} is over the reference point b^*_j, i.e., $K_{ij} > b^*_j$, the surplus can be deemed as the DM's 'gain'; if K_{ij} is under b^*_j , i.e.,$K_{ij} < b^*_j$, the lacking part can be regarded as the DM's 'loss'

- Aspiration format III: For $C_j \in C^{III}, [b^c_j, b^f_j]$ can be regarded as the reference point r_p0, i.e., $r_p0 = [b^c_j, b^f_j], j \in N^{III}$. For this case, if K_{ij} is in the range of $[b^c_j, b^f_j]$, i.e., $b^f_j \leq K_{ij} \leq b^c_j$, there is neither a 'gain' nor a 'loss' for the DM; if K_{ij} is not in the range of $[b^c_j, b^f_j]$, i.e., $K_{ij} < b^f_j$ or $K_{ij} > b^c_j$, the deviation of K_{ij} and $[b^c_j, b^f_j]$, can be deemed as the DM's 'loss'.

where:
K_{ij} is the attribute value
b^l_j, b^*_j, and $[b^c_j, b^f_j]$are the aspiration level for different conditions i.e.
"would better not be over", "would better be over" and "would better be in the range of" respectively
r_p0 represents the reference point

In summary, the reference points for aspiration formats I, II and III are $b^l_j, j \in N^I, b^*_j, j \in N^{II}$ and $[b^c_j, b^f_j], j \in N^{III}$ respectively.

6.6.3 Step 3: Construct a Gain –Loss Matrix

To calculate the gain and loss matrix, we consider the aspiration formats I, II and III respectively, which are described as follows (Fan et al., 2013):

1) Aspiration-format I: we know that $r_p0 = b^l_j, j \in N^I$, but if $K_{ij} > b^l_j$, i.e., the consequence for alternative M_i concerning attribute C_j fails to meet the DM's aspiration, then the DM will be unsatisfied; if $K_{ij} < b^l_j$, i.e., the consequence for alternative M_i concerning attribute C_j exceeds the DM's aspiration, then the DM will be satisfied. The deviation of K_{ij} from b^l_j can be regarded as the DM's gain/loss. Thus, a gain-loss function is created for aspiration format I, represented as,

$$S(k) = b^l_j - k, j \in N^I \tag{6.19}$$

where:
k denotes a variable about the attribute value
b_j^l denotes the reference point,
$S(k)$ denotes the gain or loss

i.e., for alternative M_i the DM's gain/loss concerning attribute C_j is given using Eq. (6.19), as shown in Eq. (6.20):

$$S_{ij} = b_j^l - k_{ij}, i \in A, j \in N^I \tag{6.20}$$

Therefore, if $K_{ij} > b_j^l$, S_{ij} can be deemed as the DM's loss; if $K_{ij} < b_j^l, S_{ij}$ can be deemed as the DM's gain.

2) Aspiration-format II: we know $r_p0 = b_j^*, j \in N^{II}$; If $K_{ij} > b_j^*$, the DM will be satisfied; if $K_{ij} < b_j^*$, the DM will be unsatisfied. Thus, a gain-loss function is created for aspiration format II, represented as,

$$Sk = k - b_j^*, j \in N^{II} \tag{6.21}$$

i.e., for alternative M_i the DM's gain/loss concerning attribute C_j is given using Eq.(6.21), as shown in (6.22):

$$S_{ij} = k_{ij} - b_j^*, i \in A, j \in N^{II} \tag{6.22}$$

Therefore, if $K_{ij} > b_j^*$, S_{ij} can be deemed as the DM's gain; if $K_{ij} < b_j^*$, S_ij can be deemed as the DM's loss.

3) Aspiration format III: Since r_p0 is an interval number, i.e., $r_p0 = [b_j^c, b_j^f], j \in N^{III}$, there are three possible position relationships between K_{ij} and r_p0 , i.e., (1) $K_{ij} < b_j^f$, (2) $b_j^f \leq K_{ij} \leq b_j^c$, and (3) $K_{ij} > b_j^c$. The gain-loss functions for the three positional forms are created for aspiration format III.

   I. For the first possible position, let y be an arbitrary value in interval $[b_j^c, b_j^f]$, and k be a variable about attribute value, then the perceived difference between k and y can be expressed by:

$$d(ky) = d(k, b_j^f) + d(b_j^f, y), i \in A, j \in N^{III} \tag{6.23}$$

   Where $d(k, b_j^f)$ is the perceived difference between k and b_j^f, and $d(b_j^f, y)$ is that between b_j^f and y. While $d(b_j^f, y) = 0, d(k, b_j^f)$ can be expressed by the deviation of k from b_j^f, i.e.:

$$d(k, b_j^f) = \gamma_j(k - b_j^f), i \in A, j \in N^{III} \tag{6.24}$$

$$d(ky) = \gamma_j(k - b_j^f), i \in A, j \in N^{III} \tag{6.25}$$

where γ_j is the parameter reflecting the sensitivity of the DM to the deviation, $\gamma_j > 0$. If $0 < \gamma < 1$, it means that the perceived difference between k and b_j^f is smaller than the absolute equivalent deviation between them, but if $\gamma_j > 1$ it means that the perceived difference is greater than the absolute equivalent deviation. Therefore Eq.(6.24) can be changed to Eq.(6.25). Apparently, $d(k, y)$ is also the perceived difference between k and $[b_j^c, b_j^f]$ because of the randomness of y i.e. $d(k, r_p0) = \gamma_j(k - b_j^f)$. Therefore, the gain-loss function for the first possible position is:

$$S(k) = \gamma_j(k - b_j^f), i \in A, j \in N^{III} \tag{6.26}$$

II. For the second possible position, i.e. $b_j^f \le K_{ij} \le b_j^c$ there is no perceived difference between k and r_p0 to the DM because k is in the range of $[b_j^c, b_j^f]$. Therefore, the gain-loss function for the second possible position is:

$$S(k) = 0, i \in A, j \in N^{III} \tag{6.27}$$

III. For the third possible position, i.e. $K_{ij} > b_j^c$, the gain-loss function can be built, i.e.

$$S(k) = \eta_j(b_j^c - k), i \in A, j \in N^{III} \tag{6.28}$$

Where η_j is the parameter reflecting the sensitivity of the DM to the deviation between k and $b_j^c, \eta_j > 0$. If $0 < \eta_j < 1$, it means that the perceived difference between k and b_j^c is smaller than the absolute equivalent deviation between them, but if $\eta_j > 1$, it means that the perceived difference is greater than the absolute equivalent deviation. In summary, the gain-loss function is created for aspiration format III, and is expressed by:

$$s(k) = \begin{cases} \gamma_j(k_{ij} - b_j^f) & k < b_j^f \\ 0, & b_j^f \le k \le b_j^c, i \in A, j \in N^{III} \\ \eta(b_j^c - k_{ij}) & k > b_j^c \end{cases} \tag{6.29}$$

Obviously, the DM's gain/loss for alternative M_i concerning attribute C_j is given using Eq. (6.29)

$$s_{ij} = \begin{cases} \gamma_j(k_{ij} - b_j^f) & k < b_j^f \\ 0, & b_j^f \leq k_{ij} \leq b_j^c, i \in A, j \in N^{III} \\ \eta(b_j^c - k_{ij}) & k_{ij} > b_j^c \end{cases} \tag{6.30}$$

Hence, if $K_{ij} < b_j^f$ or $K_{ij} > b_j^c$, then Sij can be deemed to be the DM's loss; if $b_j^f \leq K_{ij} \leq b_j^c$, then $S_{ij} = 0$, the DM is indifferent.

The concept in Eqs.(6.29) and (6.30) suggest that parameters γ_j and η_j reflect the DM's attitudes for the deficient ($\gamma_j > \eta_j$) and surplus ($\gamma_j > \eta_j$) parts, relative to the reference point, respectively; for the former, the DM is more sensitive to a deficiency than a surplus if $\gamma_j > \eta_j$, and for the later, the DM is more sensitive to a surplus than a deficiency if $\gamma_j > \eta_j$.

Therefore, to construct the gain-loss matrix for all alternatives concerning attributes ($C_j, j \in N$), a combination of Eqs. (6.20), (6.22) and (6.30) can be utilized:

$$M_{gl} = [S_{ij}]_{a \times n} \tag{6.31}$$

6.6.4 Construct Prospect Value Matrix

In practical MADM problems, DMs have different psychological views of gains and losses (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992; Gonzalez and Wu, 1999; Fan et al., 2013). As such, according to prospect theory each alternative's gain/loss is transformed into a prospect value. The prospect value of alternative M_i concerning attribute C_j is given in Eq. (6.32):

$$V_{ij} = \begin{cases} f(s_{ij})^{\alpha} & \text{if } s_{ij} \geq r_p 0 \\ -\lambda[-f(s_{ij}]^{\beta} & \text{if } s_{ij} < r_p 0 \end{cases} \quad i \in A, j \in N^{III} \tag{6.32}$$

Where α and β measure the concavity and convexity of the value function for positive (gains) and negative (losses) prospects respectively,$0 \leq \alpha, \beta \leq 1$. λ is the coefficient of loss aversion, $\lambda > 1$. Based on the experimental data given by Tversky and Kahneman (1992), the the coefficients of α, β and λ are $\alpha = \beta = 0.88$ and $\lambda = 2.25$, a prospect value matrix (M_v) can be constructed using Eq. (6.33).

$$M_v = [V_{ij}]_{a \times n} \tag{6.33}$$

6.6.5 Step 5: Construct Normalised Matrix

Since prospect values concerning different attributes are generally vague, the prospect value matrix (M_v) needs to be normalized (n^*) in order to transform the prospect values into the comparable values. This is achieved by normalising every element in matrix M_v into a corresponding element M_v^* as shown in Eq. (6.34). Such that:

$$n^* = M_v^* = [V_{ij}^*] \left\{ \; V_{ij})^* = \frac{v_{ij}}{v_j^{max}}, \; i \in A, j \in N^{III} \right. \tag{6.34}$$

where V_j^{max} denotes $max_{i \in A}\{|V_ij|\}, j \in N$.

6.6.6 Step 6: Calculate the Overall Prospect Value of each Alternative

Then, using the simple additive weighting method (Tzeng and Huang, 2011) the overall prospect value of alternative M_i, can be calculated using Eq. (6.35):

$$U(R) = \sum_{j=1}^{n} [f(V_{ij}^*)] w_(p_{ij}), i \in A \tag{6.35}$$

6.6.7 Step 7: Determine the Ranking of Alternatives according to the Obtained Overall Prospect Values

Based on the results and according to Fan et al. (2013), considering the obtained overall prospect values of all alternatives, the greater the $U(R)$ from the set of alternatives, the better an alternative M_i will be. Therefore, in an ascending or descending order of the overall prospect values of all alternatives, we can select the desirable alternative(s) from the alternative set M.

6.7 Empirical Study

As discussed in section 6.3, a survey was conducted to facilitate a general understanding and knowledge of the significance of the developed resilience strategic decision to investigate the relationships between alternatives and attributes and whether alternatives have a positive or negative prospect effect on attributes. This study was conducted in four phases: (1) questionnaire formulation and pilot study, (2) choosing the right experts (3) survey data collection and description, and (4) case study. We discuss each of the phases below.

6.7.1 Questionnaire formulation and Pilot Study

Prior to actual data collection and, to eliminate content ambiguity in the questions, a pilot study was instigated to validate the questionnaire. First, a draft version of the questionnaire and cover letter was developed. The questionnaire was examined by an academician and five specialists to comment on the appropriateness of the questions and whether any were unclear. Based on their feedback, the questionnaire was redrafted for the pilot study. The pilot study was conducted by asking randomly selected "judges" drawn from the maritime domain and an oil terminal focus group to pre-asses the questionnaire's effectiveness, accuracy and unambiguous communication with targeted respondents. A total of six "judges" were selected. The questions were measured on a four-point Likert-type scale with response options ranging from 1 (unsatisfied and negative prospect) to 4 (satisfied and positive prospect). The ratio of judges' correct agreement was considered good and the discriminant validity feedback from the pilot study was eliminated. Ethical approval was also obtained to further validate questionnaire contents and participant consent. The questionnaire as represented at the end of the pilot study was used for data collection (see Apendix 6C for final questionnaire).

6.7.2 Choosing the Right Experts (DMs) for OTOs

A cross-section of experts or decision makers (DMs) was considered to participate in the survey. Consultants and experts with relative (onshore/offshore oil fields) and vast (academic, maritime domain, oil and gas refineries) experience related to this research were selected at random. Experts service times and academic qualifications were used as thresholds (John et al., 2014b).For more information, see Chapter 3.

6.7.3 Survey Data Collection and Description

The questionnaire was web-based and a link was e-mailed to targeted expert participants. A cover letter was offered to respondents prior to the main question page (see Appendix 6C). After a follow-up process, data were collected via the internet, using eSurvey. 25 respondent participated in the survey out of which 9 were completed, 10 were uncompleted and 6 with no response. Out of the 9 respondent, 5 were part of the senior management team while the remaining 4 were below the criteria as stated by the research sampling frame (see Subsection 3.3.1). In all, five valid responses were obtained, yielding a final response rate of around 20%. This response rate is comparable to other studies conducted in the literature (Mokhtari et al., 2012; Hammitt and Zhang, 2013; Alyami et al., 2014; John et al., 2016). The following are the background of the five experts assigned to participate in the survey:

- A Senior operation manager who has been involved with oil terminal operational services for more than 20 years.
- A Junior marine operation manager who has been involved with (off) loading operations on offshore/onshore oil terminal platforms for more than 12 years.
- A Consultant on oil terminal operational risk assessment, with a vast amount of experience in marine operation, who has been involved in port management and applicability of modelling tools for OTOs for more than 20 years.
- A Senior maritime safety engineer with a PhD who has been involved with QHSE on offshore oil installation and port safety for more than 20 years.
- A Doctor of maritime technology who has been involved in the marine industry for more than 20 years, having both academic and onshore/offshore industrial experience in the field of oil terminal management and marine operations.

When these experts made their judgements, they assigned values to each question. Table 6.4 shows the evaluation for each question.

As shown in Fig **??** the empirical study revealed that the attributes proposed for OTOs resilience strategy for decision making have over a 50% positive influence and will have a significant impact on achieving system resilience. More so, the arithmetic mean for all alternatives spans across unsatisfied but positive prospect to satisfied and positive prospect, as seen in Fig 6.5, Fig 6.6 and Fig 6.7 based on Table 6.4 and Table 6.5. Therefore, the evaluation of the attribute and alternative prospects reveal the industry experts level of acceptance, general understanding and knowledge of the significance of these proposed resilience strategies.

According to the experts judgement, all the attributes will significantly improve OTOs resilience when combined with the alternative(s) for positive prospects; therefore, selecting the best alternative(s) for OTOs resilience optimisation is key.

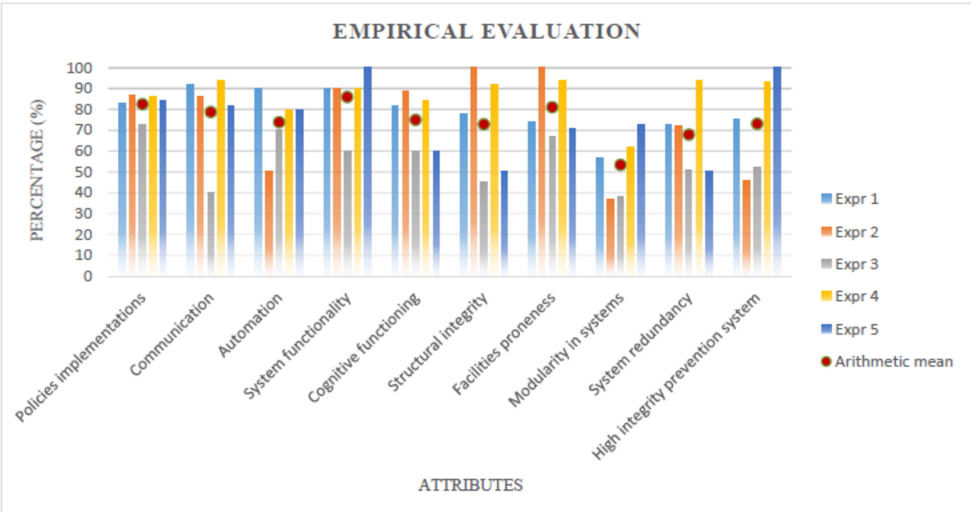


FIGURE 6.4: Consistency of prospect attributes for OTOs based on expert judgements

6.8 Case Study

The case study was conducted at the BAP offshore and onshore oil terminal group of companies, in Kaohsiung, Taiwan. It is a large terminal platform built with state-of-the-art engineering facilities and has been in operation since 1998. BAP is responsible for the supply of crude oil, refined crude, oil exploration, maintenance and modification work. The personnel working on the terminal platform are proud of the facilities and feel a strong ownership of their working environment. The BAP oil terminal has a good reputation with regard to safety.

Although BAPs statistics on occupational accidents are low compared to other industries, the frequency of unexpected events, such as near miss/incidents/accidents, has

Table 6.4: Consistency of prospects based on empirical study for resilience strategy selection

Alternatives	Prospects	Arithmetic mean	Attributes	Arithmetic mean
A1	P1	5.00	Policy implementations	82.6%
	F1	3.80	Communication	78.8%
	D3	4.20		
	T4	3.00		
	S5	4.20		
A2	k2	4.60	Automation	74%
	J2	4.60	System functionality	86%
	V3	5.00		
	Q4	5.00		
	W5	4.20		
A3	B3	5.00	Cognitive functioning	75%
	E3	4.60	Structural integrity	73%
	L3	3.80		
	R4	3.60		
	U5	5.00		
A4	C4	4.00	Facility proneness	81.2%
	G4	4.20	System modularity	53.4%
	Y3	4.00		
	X4	4.60		
	Z5	5.00		
A5	H5	4.20	System redundancy	68%
	O5	5.00	High integrity prevention system	73.2%
	M3	4.20		
	N4	5.00		
	I5	5.00		
A6	i	4.20		
	ii	4.30		
	iii	3.80		
	vi	3.40		
	ix	4.20		

Table 6.5: Alternatives linguistic terms assessment for OTOs

Prospect linguistic terms	Values
Satisfied and positive prospect	4.5 – 5
Satisfied but negative prospect	3.5 – 4.49
Unsatisfied but positive prospect	2.4 – 3.49
Unsatisfied and negative prospect	0 – 2.39

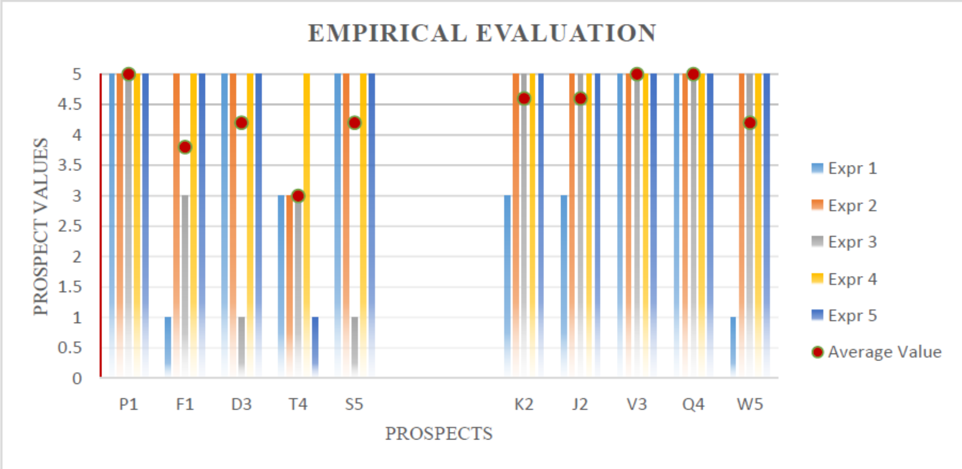


FIGURE 6.5: Experts judgements on the consistency of A_1 and A_2 prospect alternatives for OTOs strategic decision.

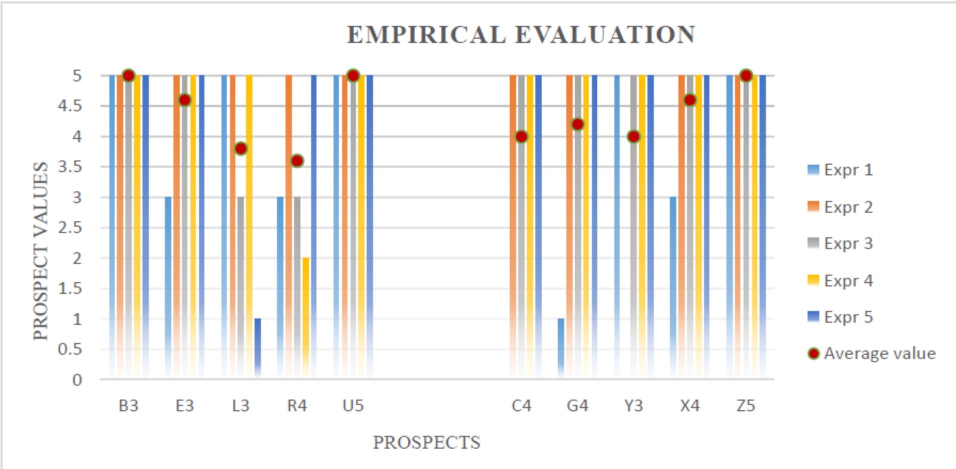


FIGURE 6.6: Experts judgements on the consistency of A_3 and A_4 prospect alternatives for OTOs strategic decision.

increased during the last year. There may be a number of reasons for this. The management of BAP by mutual reflection upon how to strengthen certain operational qualities that could make all oil terminal platforms more resilient. Their approach was to choose a recommended alternative for resilience optimisation. Five expert were invited to form a committee, and the committee was tasked with developing a list of alternatives and to determine the attributes. After thorough investigation, the committee presented six alternatives $(A_1, A_2, \ldots, A_6)$. The committee also finalised the attributes after a thorough evaluation. Ten attributes were considered, which were:

- RS_1: Policy implementation
- RS_2: Communication
- RS_3: Automation.

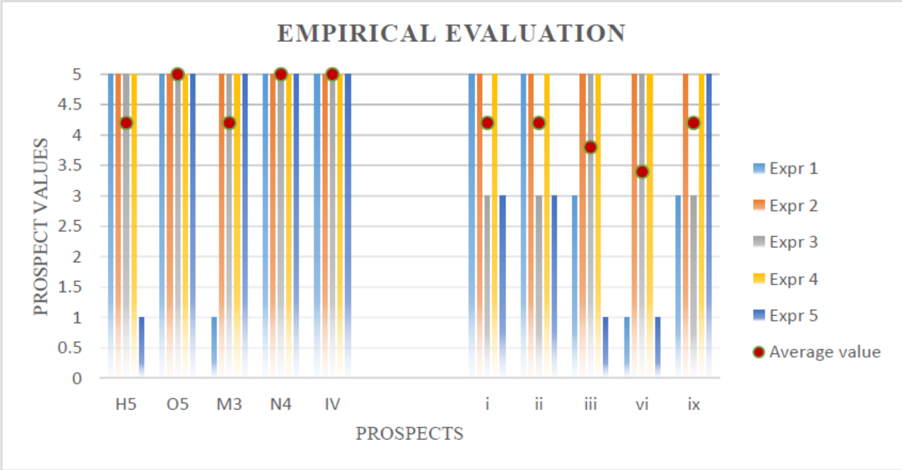


FIGURE 6.7: Experts judgements on the consistency of A_5 and A_6 prospect alternatives for OTOs strategic decision.

- RS_4: System functionality
- RS_5: Cognitive functioning
- RS_6: Structural integrity
- RS_7: Facilities proneness
- RS_8: System modularity
- RS_9: System redundancy
- RS_10: High integrity prevention system

The data concerning the 10 attributes were obtained from the committees evaluation using a qualitative and quantitative data collection method. According to historical data from a resilience engineering perspective, BAP provided the objective for each attribute, i.e. this was based on the committee that had been set up and attribute aspirations were proposed as shown in Table 6.6. The decision matrix for the five participants is presented in Table 6.7; for the overall obtained results to be used for the computation of the decision matrix for all attributes and alternatives, see Appendix 6B. A PT process was used to select the anticipated strategic alternative for BAPs offshore and onshore OTOs resilience optimisation.

6.9 Results Analysis

Step 1: A rational pairwise comparison was conducted for all attributes in order to determine the weights. Fig 6.8 shows the aggregated numerical values of all five experts, and was developed using a comparison matrix, and calculated manually (see Appendix 6A).

Table 6.6: The DM's attribute aspirations

Attributes	**Aspirations**
RS_1	Policy implementation would better be over 63%
RS_2	Communication would better not be under 64%
RS_3	Automation would better be over 60%
RS_4	System functionality would better be over 70%
RS_5	Cognitive functioning would better be over 60%
RS_6	Structural integrity would better be over 60%
RS_7	Facilities proneness rate would better be in the range of $[1, \ldots, 10]$%
RS_8	System modularity would better be in the range of $[21, \ldots, 30]$%
RS_9	System redundancy would better be in the range of $[21, \ldots, 30]$%
RS_10	High integrity prevention system would better not be over 65%

Table 6.7: DMs assessment of an attribute with respect to alternatives

	Alternatives						
Attribute	A_1	A_2	A_3	A_4	A_5	A_6	
	52	75	87	50	63	63	*expr 1*
	44	81	14	80	6	24	*expr 2*
Policy implementation	75	75	82	75	86	74	*expr 3*
	80	44	80	68	46	64	*expr 4*
	32	11	47	56	80	47	*expr 5*
$M = \sum x \frac{1}{n}$	56.6	57.2	62	65.8	56.2	47.8	

For RS_1 pairwise comparison with RS_2 for all experts, the Geomean is thus calculated based on experts judgements (see Appendix 6C), the following values were obtained for the pairwise comparison: $expr$ expr $1 = \frac{1}{2},$ expr $2 = 1,$ expr $3 = 3,$ expr $4 = \frac{1}{2},$ expr $5 = 1$

$Geomean = \sqrt[5]{\frac{1}{2} \times 1 \times 3 \times \frac{1}{2} \times 1} = 0.9440875$

Fig 6.9 was determined using equation 6.13, where the weights (i.e. $w_1, w_2, \ldots, w_10$) were calculated using Fig 6.8.

For RS_2, the sum of the column as seen in the weight matrix (6.12) is determined in Fig 6.9, where $w_{n,2} = 9.9093$. Thus $\frac{0.9440875}{9.9093} = 0.0953$

FIGURE 6.8: Results for the pairwise comparisons

	RS_1	RS_2	RS_3	RS_4	RS_5	RS_6	RS_7	RS_8	RS_9	RS_{10}
RS_1	1.0000	0.9440875	1.3195079	1	1.4309691	0.8705506	1.0238363	2.6307169	1.933182	1.0844718
RS_2	1.0592238	1.0000	1.1486984	0.6083643	1.1486984	0.8027416	0.8218759	2.1117858	1.5518456	1
RS_3	0.7578583	0.8705506	1.0000	0.6988271	1.1486984	0.7578583	0.8913012	2.352158	1.35096	0.7154845
RS_4	1	1.6437518	1.4309691	1.0000	1.3195079	0.9440875	1.3025855	2.7663237	2.2679332	1.2457309
RS_5	0.6988271	0.8705506	0.8705506	0.7578583	1.0000	0.5743492	0.9440875	1.933182	1.5157166	0.8705506
RS_6	1.1486984	1.2457309	1.3195079	1.0592238	1.7411011	1.0000	1.1486984	2.352158	1.7826025	1.1075663
RS_7	0.9767187	1.2167287	1.1219551	0.7677039	1.0592238	0.8705506	1.0000	2.1689435	1.2457309	0.8705506
RS_8	0.3801245	0.4735329	0.4251415	0.3614906	0.5172819	0.4251415	0.461054	1.0000	0.6988271	0.3539529
RS_9	0.5172819	0.644394	0.7402143	0.4409301	0.659754	0.5609776	0.8027416	1.4309691	1.0000	0.7860031
RS_{10}	0.9221079	1	1.3976542	0.8027416	1.1486984	0.9028805	1.1486984	2.8252345	1.2722596	1.0000

FIGURE 6.9: Percentage importance distribution of attributes for all experts

Attributes											Weight
RS_1	0.1182	0.0953	0.1225	0.1334	0.1281	0.1129	0.1073	0.1220	0.1322	0.1200	0.1192
RS_2	0.1252	0.1009	0.1066	0.0811	0.1028	0.1041	0.0861	0.0979	0.1062	0.1107	0.1022
RS_3	0.0896	0.0879	0.0928	0.0932	0.1028	0.0983	0.0934	0.1090	0.0924	0.0792	0.0939
RS_4	0.1182	0.1659	0.1328	0.1334	0.1181	0.1225	0.1365	0.1282	0.1551	0.1379	0.1349
RS_5	0.0826	0.0879	0.0808	0.1011	0.0895	0.0745	0.0989	0.0896	0.1037	0.0964	0.0905
RS_6	0.1358	0.1257	0.1225	0.1413	0.1558	0.1297	0.1203	0.1090	0.1219	0.1226	0.1285
RS_7	0.1154	0.1228	0.1041	0.1024	0.0948	0.1129	0.1048	0.1005	0.0852	0.0964	0.1039
RS_8	0.0449	0.0478	0.0395	0.0482	0.0463	0.0551	0.0483	0.0464	0.0478	0.0392	0.0463
RS_9	0.0611	0.0650	0.0687	0.0588	0.0590	0.0728	0.0841	0.0663	0.0684	0.0870	0.0691
RS_{10}	0.1090	0.1009	0.1297	0.1071	0.1028	0.1171	0.1203	0.1310	0.0870	0.1107	0.1116

The weight w_1(for RS_1)is $= (\frac{1.0000}{8.4608} + \frac{0.9440875}{9.9093} +, \ldots, \ldots, \frac{1.0844718}{9.0343}) = 0.1192$. This procedure is repeated for $w_2, \ldots, w_{10}$. Table 6.9 represents the weight of $RS_1, RS_2, \ldots, \ldots, RS_{10}$ relative to their importance value.

To ensure the consistency in all attributes pairwise comparisons, a multiplicative computation of attribute weight with each numerical value rating in the columns in Fig 6.9 was performed. Fig 6.10 and Table 6.9 describes the process for obtaining numerical value and the results obtained, respectively.

FIGURE 6.10: Multiplicative computation of Attributes weights to determine the consistency ratio

	PI		COMM		AUTO		SF		CF		FP		SI		MS		SR		HIP
	1.0000		0.9441		1.3195		1.0000		1.4310		0.8706		1.0238		2.6307		1.9332		1.0845
	1.0592		1.0000		1.1487		0.6084		1.1487		0.8027		0.8219		2.1118		1.5518		1.0000
	0.7579		0.8706		1.0000		0.6988		1.1487		0.7579		0.8913		2.3522		1.3510		0.7155
	1.0000		1.6438		1.4310		1.0000		1.3195		0.9441		1.3026		2.7663		2.2679		1.2457
0.1192	0.6988	0.1022	0.8706	0.0939	0.8706	0.1349	0.7579	0.0905	1.0000	0.1285	0.5743	0.1039	0.9441	0.0463	1.9332	0.0691	1.5157	0.1116	0.8706
	1.1487		1.2457		1.3195		1.0592		1.7411		1.0000		1.1487		2.3522		1.7826		1.1076
	0.9767		1.2167		1.1220		0.7677		1.0592		0.8706		1.0000		2.1689		1.2457		0.8706
	0.3801		0.4735		0.4251		0.3615		0.5173		0.4251		0.4611		1.0000		0.6988		0.3540
	0.5173		0.6444		0.7402		0.4409		0.6598		0.5610		0.8027		1.4310		1.0000		0.7860
	0.9221		1.0000		1.3977		0.8027		1.1487		0.9029		1.1487		2.8252		1.2723		1.0000

Table 6.8: The weights of all attributes

No	Attribute	Weights
1	Policy implementation	0.1192
2	Communication	0.1022
3	Automation	0.0939
4	System functionality	0.1349
5	Cognitive functioning	0.0905
6	Facilities proneness	0.1285
7	Structural Integrity	0.1039
8	System modularity	0.0463
9	System redundancy	0.0691
10	High integrity prevention system	0.1116

Table 6.9: Results of multiplicative computation

Attributes											**Total**
RS_1	0.1192	0.0965	0.1295	0.1349	0.1295	0.1119	0.1064	0.1218	0.1336	0.1210	0.1986
RS_2	0.1263	0.1022	0.1079	0.0821	0.1040	0.1032	0.0854	0.0978	0.1072	0.1116	0.0275
RS_3	0.0903	0.0890	0.0939	0.0943	0.1040	0.0974	0.0926	0.1089	0.0934	0.0789	0.9435
RS_4	0.1192	0.1680	0.1344	0.1349	0.1194	0.1213	0.1353	0.1281	0.1567	0.1390	0.3563
RS_5	0.0833	0.0890	0.0817	0.1022	0.0905	0.0738	0.0981	0.0895	0.1047	0.0972	0.9100
RS_6	0.1369	0.1273	0.1239	0.1429	0.1576	0.1285	0.1193	0.1089	0.1232	0.1236	0.2921
RS_7	0.1164	0.1243	0.1054	0.1036	0.0959	0.1119	0.1039	0.1004	0.0861	0.0972	0.0450
RS_8	0.0453	0.0484	0.0399	0.0488	0.0468	0.0546	0.0479	0.0463	0.0483	0.0395	0.4658
RS_9	0.0617	0.0659	0.0695	0.0595	0.0597	0.0721	0.0834	0.0663	0.0691	0.0877	0.6948
RS_{10}	0.1099	0.1022	0.1312	0.1083	0.1040	0.1160	0.1193	0.1308	0.0879	0.1116	0.1213

CR is defined in Eq.(6.16) but when calculating the CR value, the consistency index (CI) has to be determined. Eq. (6.17) is used to calculate the value for CI as follows:

$$CI = \frac{\lambda^{-n}}{n-1} \tag{6.36}$$

where λ_{max} stands for maximum weight value and is given as:

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \tag{6.37}$$

This implies that, using Table 6.9, λ_{max} for $RS_1 = \frac{1.1986}{0.1192} = 10.0554$

Thus , $\lambda_{max} = \frac{10.0554+10.0538+10.0479+10.0541+10.0552+10.0553+10.0577+10.0605+10.0549+10.0474}{10}$

$\lambda_{max} = 10.0542$ Therefore, $CI = \frac{10.0542-10}{10-1} = 0.0060$

Table 6.10: The weights of all attributes

No	**Attribute**	λ_{max} **values**
1	RS_1	10.0554
2	RS_2	10.0538
3	RS_3	10.0479
4	RS_4	10.0541
5	RS_5	10.0552
6	RS_6	10.0553
7	RS_7	10.0577
8	RS_8	10.0605
9	RS_9	10.0549
10	RS_{10}	10.0474

The CR value will then be calculated using Eq. (6.16) and Table 6.5. The RI value represents the average random index as shown in Table 6.5. Since there is 10 attributes, the RI value will be 1.49; thus, the estimation of the CR value is shown below: $CR = \frac{CI}{RI} = \frac{0.0060}{1.49} = 0.004$

Step 2: According to prospect theory, the DMs' attribute aspirations can be used to determine reference points; thus, Table 6.6 provides the reference points, i.e. $r_p1 = 63, r_p2 = 64, r_p3 = 60, r_p4 = 70, r_p5 = 60, r_p6 = 60, r_p7 = [1, ..10], r_p8 = [21, \ldots, 30], r_p9 = [21, \ldots, 30]$ and $r_p10 = 65$. These reference points are based on BAP's given objective. The decision data for all five expert participants are shown in the decision matrix, Table 6.11.

Table 6.11: The Decision Matrix

	Attributes									
Alternatives	RS_1	RS_2	RS_3	RS_4	RS_5	RS_6	RS_7	RS_8	RS_9	RS_{10}
A_1	56.6	68.6	69.6	82.6	65.2	71.6	8.00	18.0	28.0	60.2
A_2	57.2	60.8	67.6	68.2	63.4	59.8	3.00	38.0	18.0	66.0
A_3	62.0	83.6	66.2	78.4	74.4	80.2	13.0	57.0	23.0	64.4
A_4	65.8	78.8	62.2	60.4	60.4	64.0	18.0	13.0	13.0	65.8
A_5	56.2	42.4	44.2	73.4	54.4	72.0	23.0	23.0	39.0	58.2
A_6	47.8	57.6	56.8	83.4	54.4	50.2	8.00	3.00	28.0	65.2

Step 3: Using Eqs. (6.20), (6.22) and (6.30) and as shown in Fig 6.1, according to Fan et al. (2013) the gain-loss matrix was calculated manually, and can be constructed

TABLE 6.12: The Gain-Loss Matrix

$$M_{gl} = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{bmatrix} \begin{bmatrix} -6.4 & 4 & 9.6 & 12.6 & 5.2 & 11.6 & 0 & -9.6 & 0 & -4.8 \\ -5.8 & -3.2 & 7.6 & -1.8 & 3.4 & -0.2 & 0 & -12 & -9.6 & 1 \\ -1 & 19.6 & 6.2 & 8.4 & 14.4 & 20.2 & -4.5 & -40.5 & 0 & -0.6 \\ 2.8 & 14.8 & 2.2 & -9.6 & 0.4 & 4 & -12 & -13.6 & -13.6 & 0.8 \\ -6.8 & -21.6 & -15.8 & 3.4 & -5.6 & 12 & -19.5 & 0 & -13.5 & -6.8 \\ -15.2 & -6.4 & -3.2 & 13.4 & -5.6 & -9.6 & 0 & -21.6 & 0 & 0.2 \end{bmatrix}$$

TABLE 6.13: Prospect Value Matrix

$$M_v = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{bmatrix} \begin{bmatrix} -11.5 & 3.39 & 7.32 & 9.29 & 4.27 & 8.64 & 0 & -16.47 & 0 & -8.95 \\ -10.57 & -6.26 & 5.96 & -3.77 & 2.94 & -0.55 & 0 & -20.04 & -16.47 & 1 \\ -2.25 & 13.71 & 4.98 & 6.51 & 10.46 & 14.08 & -8.45 & -58.44 & 0 & -1.44 \\ 2.47 & 10.71 & 2 & -16.47 & 0.45 & 3.39 & -20.04 & -22.37 & -22.37 & 0.82 \\ -12.16 & -33.61 & -25.53 & 2.94 & -10.25 & 8.91 & -30.72 & 0 & -22.37 & -12.16 \\ -24.67 & -11.52 & -6.26 & 9.81 & -10.25 & -16.77 & 0 & -33.61 & 0 & 0.24 \end{bmatrix}$$

using Eq. (6.31), as shown in Table 6.12.

for $RS_1 \in A_1, \ldots, A_6$, using the equation $S_{ij} = b_j^{\wr} - K_{ij}$ where $K_{ij} = 56.6, b_j^{\wr} = r_p 1 = 63$

therefore, $S_{ij} = 56.6 - 63 = -6.4$

Where for attributes RS_7, RS_8, RS_9, we take $_j = 0.8 and_j = 1.5$ in Eq. (6.30) (Fan et al., 2013), thus for $RS_7 \in A_1, \ldots, A_6$, using Eq. (6.30) where $b_j^c = 10, K_{ij} = 18$. This implies that $K_{ij} > b_j^c$ and, as such, Eq. (6.28) applies.

therefore, $1.5(10 - 18) = -12$

Step 4: To construct the prospect value matrix (M_v), we take the coefficients, α, β and γ based on the estimate given by Tversky and Kahnemans (1992) experimental data, i.e. $\alpha = \beta = 0.88$ and $\lambda = 2.25$. Then, using Table 6.12 and by applying Eq. (6.32), M_v can be constructed as shown in Table 6.13, i.e., done by manual calculation:

for $RS_1 \in A_1$, using the equation $-\lambda[-f(S_{ij})]^{\beta}$, if $S_{ij} < 0, S_{ij} = -6.4$,

therefore, $V_{ij} = -2.25[-6.4]^{0.88} = -11.52$

for $RS_1 \in A_4$, if $S_{ij} \geq 0$ such that $S_{ij} = 2.8$, the Eq. $f(S_ij)^{\alpha}$ applies:

therefore, $V_{ij} = [2.8]^{0.88} = 2.47$

Step 5: The normalised values (n^*) for Table 6.13 can be constructed using Eq. (6.34). This can be determined as shown in Table 6.14, and as follows:

for $RS_3 \in A_1, \ldots, A_6$, using the equation $V_{ij}^* = \frac{V_{ij}}{V_j^{max}}$, where $V_j^{max} = 25.53, V_{ij} = 7.32$

therefore, $V_{ij}^* = \frac{7.32}{25.53} = 0.29$

Table 6.14: Normalised Matrix

$$n^* = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{bmatrix} \begin{bmatrix} -0.47 & 0.1 & 0.29 & 0.56 & 0.41 & 0.52 & 0 & -0.28 & 0 & -0.74 \\ -0.43 & -0.19 & 0.23 & -0.23 & 0.28 & -0.03 & 0 & -0.34 & -0.74 & 0.08 \\ -0.09 & 0.41 & 0.19 & 0.4 & 1 & 0.84 & -0.28 & -1 & 0 & -0.12 \\ 0.1 & 0.32 & 0.08 & -1 & 0.04 & 0.2 & -0.65 & -0.38 & -1 & 0.07 \\ -0.49 & -1 & -1 & 0.18 & -0.98 & 0.53 & -1 & 0 & -0.99 & -1 \\ -1 & 0.34 & -0.19 & 0.59 & -0.98 & -1 & 0 & -0.58 & 0 & 0.02 \end{bmatrix}$$

Table 6.15: Overall Prospect Value using the Simple Additive Weighting Method

$$U(R) = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ Weight \end{bmatrix} \begin{bmatrix} -0.47 & 0.1 & 0.29 & 0.56 & 0.41 & 0.52 & 0 & -0.28 & 0 & -0.74 \\ -0.43 & -0.19 & 0.23 & -0.23 & 0.28 & -0.03 & 0 & -0.34 & -0.74 & 0.08 \\ -0.09 & 0.41 & 0.19 & 0.4 & 1 & 0.84 & -0.28 & -1 & 0 & -0.12 \\ 0.1 & 0.32 & 0.08 & -1 & 0.04 & 0.2 & -0.65 & -0.38 & -1 & 0.07 \\ -0.49 & -1 & -1 & 0.18 & -0.98 & 0.53 & -1 & 0 & -0.99 & -1 \\ -1 & 0.34 & -0.19 & 0.59 & -0.98 & -1 & 0 & -0.58 & 0 & 0.02 \\ 0.1192 & 0.1022 & 0.0939 & 0.1349 & 0.0905 & 0.1285 & 0.1039 & 0.0463 & 0.0691 & 0.1116 \end{bmatrix}$$

Step 6: The overall prospect value $[U(R)]$ can be obtained by manual calculation, using Eq. (6.35), i.e. as shown in Table 6.15

$$\begin{aligned} \text{U(R)} \ = A_1 = & -0.47 \times 0.1192 + 0.1 \times 0.1022 + 0.29 \times 0.0939 + 0.56 \times 0.1349 + 0.41 \times 0.0905 + \\ & 0.52 \times 0.1285 + 0 \times 0.1039 - 0.28 \times 0.0463 + 00.0691 - 0.74 \times 0.1116 = 0.0653 \end{aligned}$$

Table 6.16: Overall Prospect Value results and Ranking Order of resilience

Alternatives	**Prospect Values** $[U(R)]$	**Ranking**
A_1	0.0653	2
A_2	-0.1166	3
A_3	0.2126	1
A_4	-0.1999	4
A_5	-0.3979	6
A_6	-0.2645	5

Step 7: The ranking of the six alternatives as shown in Table 6.16 for a strategic decision making for resilience improvement is in the order $A_3 > A_1 > A_2 > A_4 > A_6 > A_5$. Evidently, the result revealed that A_1, and A_2 produce different values, which corresponds to a better resilience strategy compared to A_4, A_5 and A_6. It is noteworthy to mention that A_3 is regarded as the best strategy for resilience improvement compared to the remaining alternatives. As outlined in the proposed resilience conceptual framework, A_3, A_1 and A_2 seem reasonable and appropriate for investment by the oil terminal under investigation to improve OTOs resilience in order to monitor, control

and mitigate incident/hazards or risk. These strategies have overall prospect values of $0.2121, 0.0653$ and -0.1166 respectively. Therefore, the proposed method contributes to using PT as a proposed additional safety choice in method for resilience optimisation of oil terminal infrastructures.

6.10 Discussion and Conclusion

6.10.1 Discussion

Choosing the right alternative for improvement to a resilience strategy seems to be an important paradigm in mitigating CMO failures due to man-, machine-, nature-, coordination- and correspondence-related hazards. Such failures can have a catastrophic impact on onshore/offshore oil terminal platforms if the right resilience investment strategy is not adopted. An empirical study was conducted to investigate all six identified alternative strategies (A_1, A_2, A_3, A_4, A_5 and A_6) in relation to 10 attributes (policy implementation, communication, automation, system functionality, cognitive functioning, structural integrity, facility proneness, modularity of system, system redundancy and high integrity prevention system) in the real world. A PT-based methodology was employed to choose the right alternative strategy. The advantage of the proposed PT model is that it enables aggregation of both qualitative and quantitative data. The AHP method was used to investigate the weight values of all attributes considered for all the alternatives. The mechanism of the PT model was used to analyse five expert's subjective judgements. Based on the result obtained, the resilience of the oil terminal under investigation can be improved by implementing alternative $A_3(B3, E3, L3, R4$ and $U5)$, i.e. Investing in weather-tracking technology with higher reliability and accuracy of operation; Integral safety strategies: (a) Optimising transfer time, automatic path finding, automatic movement execution, optimised resources management of assets and people, (b) Marine time at berth: integrated order management, flexible jetty planning, alignment with additional services, (c) Marine movement: agile planning, comprehensive logistic movement, (d) Accuracy: precision measurement, custody transfer proof data, and (e) Clear operational records: integrated inventory management, track and trace in history; Robust enforcement and implementation of OCIMF; Emergency disconnect system: Activation of emergency release system; and Commitment: Objective and target will be set annually to promote and communicate throughout the organisation the need for quality, safety and environ awareness. A fully integrated, committed management team should be put in place, able to independently verify that integral operation is in accordance with requirements. This management team should have an absolute desire to reduce accidents and work-related hazards. However, by implementing additional layers of barrier in the form of alternative $A_1(P1, F1, D3, T4, S5)$ and $A_2(K2, J2, V3, Q4, W5)$ respectively, parallel system resilience will be enhanced to further help optimise a resilient OTOs system under high uncertainty (A_1, i.e. Sweep arm system, setting up a terminal operation group, enforcement and implementation of ISGOTT, emergency and intervention teams, policy changes for a resilient system; and A_2, i.e. Proper allocation of resources to the various components of the system to enhance its operations, safety integrity, enforcement and implementation of the IMDG code, conduct a survey of random selected platforms and facilities at terminals, and ensure a safe workplace and safe system of work).

6.10.2 Conclusion

This chapter has presented a strategic decision-support, multiple-attribute, decision-making method based on aspiration level that can be implemented for resilience strategy selection for OTOs. The method has been tested in a logical, succinct and transparent manner against multiple scenarios where information available is subjective and imprecise. The strength of this strategic decision-making approach is in the fact that both heterogeneous and homogeneous groups of experts can be utilised and their subjective opinions can be aggregated in a simplified manner even if there is only partial or incomplete information available. In the evaluation process, the AHP is applied to determine the weights of the influencing attributes, and a PT algorithm is implemented to rank the resilience strategies or alternatives in a flexible and straightforward manner. To support a strategic decision on resilience strategy selection, PT needs to be utilised to handle multiple organisational objectives, complex decision making and long-term consequences of disruption to oil terminal platforms in an uncertain environment. The proposed approach can be applied to situations where both qualitative and quantitative data have to be integrated and synthesised for evaluation processes during complex and multiple decision making involving CMOs. Since the result of the calculation is sensitive to attribute weights, these should be carefully chosen by oil terminal management and safety analysts to avoid misrepresentation and information loss during ship and terminal interface.

Chapter 7

Conclusion

Summary

This chapter highlights the developed conceptual framework and models with an attempt to integrate them in a logical relationship. The chapter discusses and summarises the importance of the integrated model, the basis for the development of the conceptual framework as an advanced risk assessment technique for OTOs and the need to select the right strategic resilience decision for OTOs optimisation. It also explains the thesis limitations as well as proposed possible opportunities for future research to improve on the developed methodologies and system resilience framework.

7.1 Introduction

The impact of various operational hazards on oil terminal infrastructures could likely be catastrophic disruption with major consequences. The effectiveness of oil terminal operational systems depends on their degree of soundness and resilient effectuation under high uncertainties. Therefore, evaluation, analysis and multi-attribute decision making methods have become inevitable for OTOs. Thus, a conceptual resilience framework and novel models tailored to optimise the resilience optimisation of OTOs in offshore/onshore oil terminals have been developed in this study. The validation of these proposed hazard/risk-based models has also been demonstrated. It is now appropriate to reflect on the previous chapters detailing of this research.

7.2 Research Summary

This research aimed at investigating the uncertainties for OTOs in order to monitor, control and mitigate its operational risk. The research aim was achieved as follows:

- The literature review conducted revealed that OTOs are continually exposed to diverse risks because they usually operate in a dynamic environment in which accident barriers are sometimes surpassed, leading to the disruption of operations due to high uncertainties. Uncertainties and the unpredictability of events during OTOs can lead to system disruption with potential to cause major fire outbreaks, explosion and transit accidents; damaging infrastructure, the environment and loss of life with high consequences. Previous literature also provided an insight into the modelling of past accident scenarios of CMOs in order to reveal their vulnerabilities. The common operational hazards that have become an issue within the risk management as reviewed in the literature on oil terminals and OTOs can be categorised into: (a) Man-related hazards, (b) Machine-related hazards, (c) Communication- and Correspondence-related hazards, (d) Management-related hazards and (e) Nature-related hazards. A dynamic Hierarchical structure for resilience improvement was also developed based on the categorised identified uncertainties.

- A novel resilience framework was developed to proactive improve OTOs in controlling losses from operational hazards. Applying a novel resilience framework to offshore/onshore oil terminal installations, where different hazardous materials such as crude oil, petrol, kerosene and diesel are being transported remains a more realistic way of improving the ability of an operational system to avoid, adapt and recover to a stable state as well as to improve its defence capabilities. A Resilience framework also provide a flexible yet robust model for OTOs to address disruption particularly as new hazards are constantly evolving.

- Models were also developed to support the proposed novel resilience framework, such as:

  - An innovative approach towards integrating Utility Theory and Swiss Cheese Model into oil terminal risk assessment has been presented. The ($UtiSch_{+}$) model was used to determine the relative weight of the identified HFs.
  - A BN tailored to fit into the framework to construct a causal relationship model for OTOs. Ten HFs with the most relative weights served as input for the developed BN model. By evaluating the BNs, overall probability that a specific hazard is present were calculated. The robustness of the BN model was demonstrated using a Sensitivity Analysis (SA) to test its validity. The result demonstrated that the BN model is an effective technique for dynamic hazard probability evaluation of OTOs for resilience improvements.
  - To select the appropriate strategy aimed at improving the resilience of OTOs, it is necessary to rank these strategies in an order of importance. This study proposed a strategic Analytical Hierarchical Process (AHP)-Prospect Theory (PT) approach to demonstrate such an important strategy selection process. An AHP technique was used to determine the weights of the influencing attributes and a PT algorithm was implemented to rank the resilience strategies

in a flexible and straightforward manner. The result revealed seems reasonable and appropriate to support strategic decisions on resilience strategy selection for OTOs resilience improvement.

- Empirical study was conducted to justify the proposed models. The empirical study for chapter 4 was independent from that of Chapter 6. Empirical evaluations shows the consistencies of all HFs, significant HFs and proposed resilience strategies fro OTOs improvement with participant responses in the real-world (see Fig 4.8, 5.7, 6.4, 6.5, 6.6 and 6.7).

- A case study was conducted to validate the ($UtiSch_+$) model (see Section 4.8) and a test case was also conducted to justify the selection process of all identified resilience strategies (see Section 6.8). The results indicate that this model tackles complex decision problems on oil terminal platforms in a simple and efficient manner.

7.2.1 Discussion

The resilience optimisation of OTOs has become an area of interest in the 21st century. It has become the best possible option by which to tackle uncertainties in the real world. The resilience of OTOs in this study is based on the resilience engineering perspective of operational studies. It provides system flexibility, robustness and the ability to cope with incident/hazard/accident when and after they occur. In this study, a resilience conceptual framework has been developed for OTOs. The hazard identification phase in the framework analyses system attributes such as OTOs facilities, complexities and functionality as well as other principal causes of safety problems with the potential to cause major disruption; the assessment phase evaluates the resilience level of the system and then analyses the uncertainty within the system; while the mitigation phase proffers strategic resilience decision solutions for proactive hazard/risk management. OTOs resilience depends on tools and techniques to ensure the operation can cope with unforeseen situations, anticipate failure, resist destruction and restore the operation to as close to its original state as possible. This study proposes some traditional modelling techniques suited to tackle uncertainties which are in turn tailored for OTOs resilience improvement in onshore/offshore oil terminals.

Additionally, the result established that human factors, technical failure and nature are the major sources of uncertainties in oil terminal infrastructures. It is crucial to identify the hazards within oil terminal operational infrastructures in order to address them and the uncertainty they create, and improve the resilience of the infrastructures.

The applicability of the innovative model in the real world can assist the oil industry in achieving robust and resilient CMOs under high uncertainty. The resilience conceptual framework and model has been tested and validated to be dynamic with the addition of any new evidence. In addition, a more profound implication of the results of this study is that they empirically show that there is a wide spread of uncertainty variables in the oil industry. However, a more interesting outcome of this study is the fact that the oil industry is taking extensive measures to prevent, control and mitigate hazard/risk during operations.

The selection of a strategic decision for OTOs resilience improvement has become a critical aspect of the decision-making process in the real world. Making a strategic resilience decision enables a real-time forecast for OTOs resilience. Following the investigation, ranking and evaluation of hazards in OTOs, tailored resilience strategies were identified based on a robust literature review, accident reports, workshop seminar reports and a brainstorming session conducted with relevant specialists. A Plan Inspect Monitor and Manage (PIMMs) approach was proposed as a resilience strategy for OTOs. The PIMMs strategy consists of multiple attributes and this makes it a MADM problem. As outlined in the proposed resilience conceptual framework and models, the MADM problem was solved based on AHP-PT, thus improving on the traditional decision-making approaches for maritime safety.

In all, this research has demonstrated that the developed framework and models have the potential to prevent, control and mitigate hazard/risk. In other words, feasible answers to system vulnerability, adaptability, survival and recovery issues are possible. The importance of this finding is that it enables the major oil firms to be sustainable, increases a companys reputation for safety and risk management, and enables it to continue to be an economically attractive asset for positive revenue impacts. More importantly, no previous research has studied the impact of high uncertainty and a resilience strategic optimisation for OTOs.

7.2.2 Main Conclusion

There is a need for a proactive, robust yet flexible approach to the resolution of uncertainties in OTOs. A resilience strategy is an advanced-level plan of action which should be adopted to address the adaptive capacity and increased vulnerability of a system due to hazards. Resilience optimisation requires an in-depth and step-by-step hazard/risk analysis to attain an ideal level of system scrutiny. As such, proven methodologies to investigate and evaluate hazards/accident on oil terminal facilities, facilitate the process of achieving a resilient system. A novel resilience framework was proposed in this study, tailored for OTOs. Models were developed to support the proposed framework, methodologies were proposed that provided a platform where OTOs can be assessed effectively and efficiently, and the empirical study results which are fundamental to forming logical and valid conclusions have demonstrated the significance of the study.

It is noteworthy to mention that all the important research questions such as: Will the proposed research framework and models affect operations at oil terminals? What are the risks involved in oil terminal operations? What are the values of the proposed novel risk models to oil terminal operations? How do we implement the proposed research framework and models in case studies? Should operators attribute loss to normal errors in measuring hazards, other than improved techniques to rectify measuring of errors? have been answered in this study. The selection of the right resilience strategic alternatives for decision making investment will enhance the resilient properties of OTOs under high uncertainty.

7.3 Research Contribution to Knowledge

The main contribution of the research is the creation of the generic resilience conceptual framework and analytical model, capable of performing advanced risk assessment. The proposed holistic framework comprises relevant tools and techniques for structuring, assessing, analysing, managing and mitigating hazard factors that affect OTOs. A key aspect of this study is the integration of the Utility Theory and the Swiss Cheese Model as well as the use of AHP-PT, which are based on decision makers' behavioural psychology, to facilitate decision-making processes for OTOs resilience improvement. The robustness of the developed models can be tailored to practical applications, enabling oil terminal industrial risk management professionals such as terminal risk managers and auditors to deal with safety and risk problems. More so, it will help to guide oil terminal risk analysts through a series of well-defined structured phases and steps necessary to improve resilient effectuation, especially in situations where a high level of uncertainty exists. The implemented framework provides a logical and organised procedure, and benefits can be gained from using the defined resilience conceptual framework. The goal of the study was focused on resilience as a strategy to achieve a high level of safety and continuity of operations, it became a basis for improving managerial decision making and enhanced procedures for OTOs. The deficiency of risk assessment literature for OTOs and uncertainty treatment within the marine industry highlights the importance of the subject matter; thus, the research will enrich the knowledge base for OTOs. The resilience conceptual framework adopted means that there is a shift in thinking, from probability estimation to uncertainty assessment. Resilience is recommended as a suitable strategy to cope with shocks and safety-related issues and, as such, the discussion of the results in the light of the theories and practical applications has enabled the resolve of the research to the body of knowledge.

7.4 Research Limitation

The study has not investigated accidents scenarios as a result of storage tank farms, mooring operations and manoeuvring for berthing and unberthing operations leading to disruption, due to time constraints for the analysis of OTOs in the real world. In relation to risk assessment and resilience improvements in oil terminals, it has not been possible to find any proven benchmark result to fully validate the research outcomes. Given such difficulty and due to lack of data, a possible method of partial validation of the models can be achieved through conducting more industrial case studies, as demonstrated in the BN and PT sensitivity analysis performed in Chapters 5 and 6 respectively. Experts' relative experience and vast knowledge prowess are vital in the application of the novel framework to real industrial case studies as described in this research; thus, the criteria for choosing these experts is crucial. Finally, the confidential nature of oil terminals when conducting an empirical study highlights the difficulty of gathering secondary data for the identified hazard factors.

7.5 Recommendation and Future Research

The research has attempted to provide a structure that links risk and resilience, as well as to formulate a conceptual framework for resilience improvement of OTOs. Avenues to further enhance the implementation of the developed framework and models in a different context have been identified to include:

- A Formal Resilience Assessment (FRA) with an holistic framework as a primary method for uncertainty assessment is recommended for future research. This will be suggested to container terminals, storage tank farms and other process industries, as a standard for resilience improvement. This will encourage other researchers to apply the assessment method to other areas of interest.

- The application of the developed novel framework and models to other high reliability industries such as construction, petrochemical and gas plants, will be useful for future research. This could give rise to interesting findings and will boost the confidence of the obtained thesis result. Other multi-attribute decision-making techniques such as TOPSIS, VIKOR and, fuzzy set can be employed in testing how sound the decision model is, and may further enrich the deficient literature on resilience modelling in complex marine operations.

- The proposed risk-based model could be extended to incorporate other categories of hazard-related factors such as political risk and security risk that were not included in the present study. Furthermore, when extending the certainty equivalent status quo to a 4x4 matrix to determine the utility context of a DM, the Utility Swiss Cheese algorithm will be much more reliable to obtain an optimal value for the considered DM.

- Due to the complexity of the analytical results obtained under conditions of scarce data, the application of computer simulation and analysis-related software with inputs from secondary/historic data is recommended to evaluate and facilitate the process of data compilation at the operational phase. This will further improve the resilience of OTOs due to unforeseen events.

- The combination of expert judgement and historical data in a fuzzy environment to evaluate hazard and risk factors capable of dealing with uncertainty will help in firming up the structures for resilience improvement. The use of diverse but powerful intelligent tools and algorithms from other fields and concepts will open promising new pathways for developing and optimising OTOs resilience under uncertainty.

- From within the participants, five experts were selected at random to participate in the risk assessment process for OTOs. However, it is recommended to increase the number of experts for more collaborative modelling and compare the obtained results with this study to reassure other researchers about the effectiveness of the original results. This will further validate and reinforce the applicability of the hazard/risk-based models for use in other industry.

Appendix A

Appendices for Chapter 4

A.1 Appendix 4A: DMs decision on risk attributes and attributes for Utility assessment

where: $(Expr)$ = expert, and(HF) = Hazard factor

where: (UCC) = Utility context of comparison,(YOE) = years of experience, (RM) = response mood,(IP) = individual perspective, and(RO) = recurrence

Table A.1: DMs' decision on hazard attributes

HF	Experts				
	Expr 1	**Expr 2**	**Expr 3**	**Expr 4**	**Expr 5**
MAHs (R_1)	2	5	3	6	6
DHE (R_2)	2	5	6	5	6
PI (R_3)	1	6	5	5	5
S (R_4)	1	5	2	5	5
ICF (R_5)	1	5	5	3	5
MEHs (R_{11})	2	6	5	3	3
EF (R_{12})	2	5	2	5	5
WCSF (R_{13})	2	5	3	5	5
PCM (R_{21})	3	5	5	5	6
SA (R_{22})	2	5	5	5	5
PCI (R_{23})	2	6	5	5	3
HRE (R_{31})	2	5	3	6	4
JSSR (R_{32})	1	6	2	5	5
LE (R_{33})	2	6	2	6	4
DE (R_{34})	2	5	2	3	6
BR (R_{35})	2	6	2	2	6
HH (R_{41})	3	4	3	2	5
SH (R_{42})	3	3	3	2	5
AH (R_{43})	3	5	3	2	5
EH (R_{44})	3	5	3	2	5

Table A.2: DMs' Utility assessments

UCC	Experts				
	Expr 1	**Expr 2**	**Expr 3**	**Expr 4**	**Expr 5**
YOE	20 yrs	20 yrs	12 yrs	20 yrs	21 yrs
RM	7	5	3	6	6
IP	7	5	3	4	6
RO	1	5	1	3	5

A.2 Appendix 4B: Extent of failure of barriers for each risk factor in the proposed model

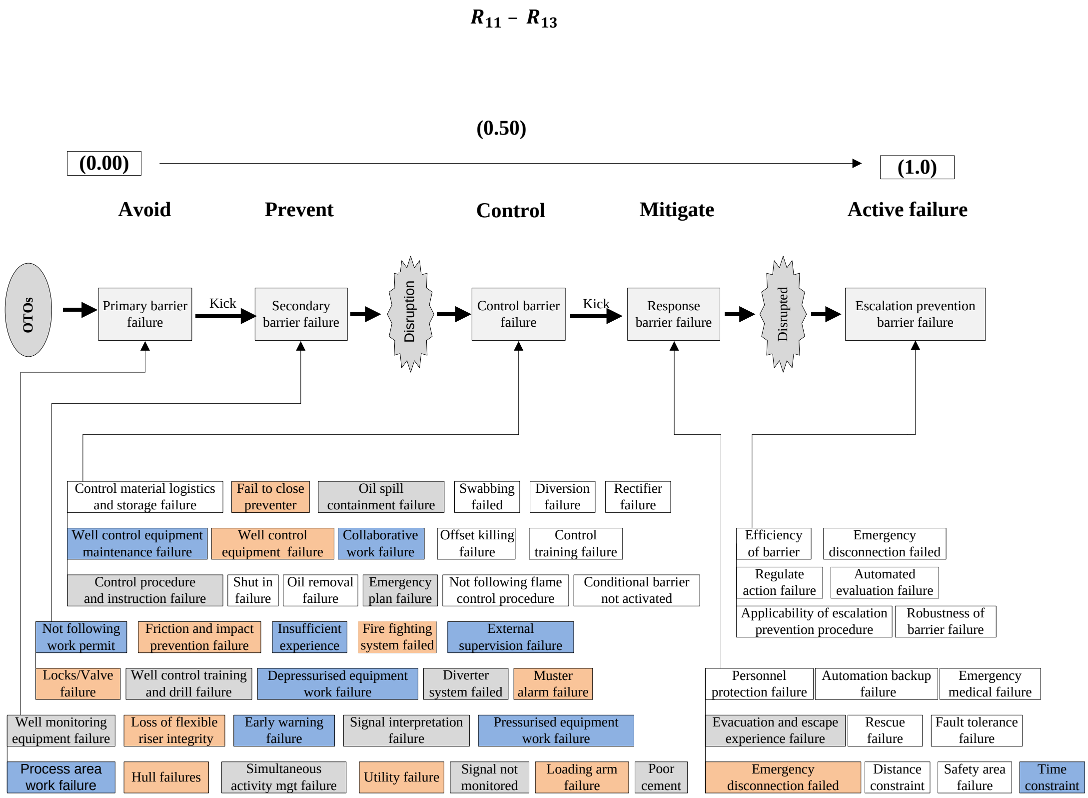


FIGURE A.1: Extent of barriers failure for each HFs in the proposed model

TABLE A.3: Experts assessments using the $UtiSch_{+}$ model (R11-R13)

Expr 1(C)					Expr 2(B)			
HFs	**u(x)**	**$\mathbf{UtiSch_{+}}$**	**W**	**R**	**u(x)**	**$\mathbf{UtiSch_{+}}$**	**W**	**R**
R_{11}	0.4197	$c_1 < 0.75$	0.2361	1	0.9368	$c_1 < 0.75$	0.3513	1
R_{12}	0.4197	$c_2 < 0.75$	0.2361	1	0.8671	$c_2 < 0.75$	0.3250	2
R_{13}	0.4197	$c_3 < 0.75$	0.2361	3	0.8671	$c_3 < 0.50$	0.3250	3

Expr 3(D)					Expr 4(Q)			
HFs	**u(x)**	**$\mathbf{UtiSch_{+}}$**	**W**	**R**	**u(x)**	**$\mathbf{UtiSch_{+}}$**	**W**	**R**
R_{11}	0.8671	$c_1 < 0.75$	0.3250	1	0.6984	$c_1 < 0.75$	0.2619	3
R_{12}	0.5882	$c_2 < 0.75$	0.2206	3	0.8671	$c_2 < 0.75$	0.3250	1
R_{13}	0.6984	$c_3 < 0.75$	0.2619	2	0.8671	$c_3 < 0.50$	0.3250	1

Expr 5(W)				
HFs	**u(x)**	**$\mathbf{UtiSch_{+}}$**	**W**	**R**
R_{11}	0.6984	$c_1 < 0.75$	0.2619	3
R_{12}	0.8671	$c_2 < 0.75$	0.3250	1
R_{13}	0.8671	$c_3 < 0.75$	0.3250	1

$\boldsymbol{R_{21} - R_{23}}$

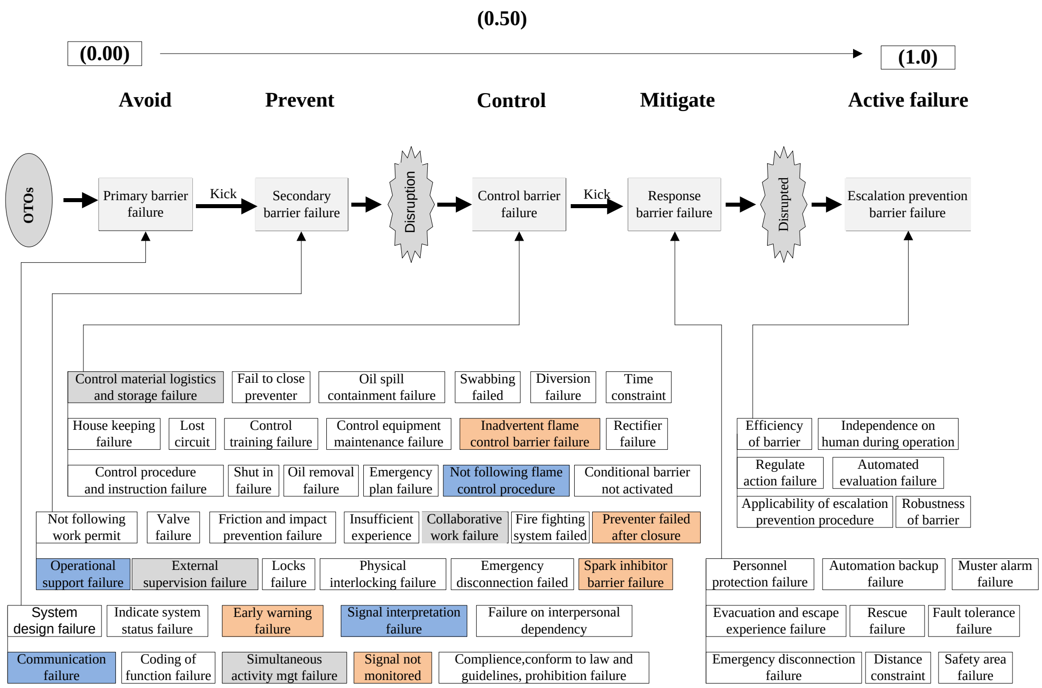


FIGURE A.2

TABLE A.4: $R21 - R23$

	Expr 1(C)				Expr 2(B)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_{21}	0.6984	$c_1 < 0.75$	0.1746	1	0.8671	$c_1 < 0.50$	0.2168	2
R_{22}	0.5882	$c_2 < 0.75$	0.1471	2	0.8671	$c_2 < 0.50$	0.2168	2
R_{23}	0.5882	$c_3 < 0.75$	0.1471	2	0.8671	$c_3 < 0.50$	0.2342	1

	Expr 3(D)				Expr 4(Q)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_{21}	0.8671	$c_1 < 0.75$	0.2168	1	0.6984	$c_1 < 0.50$	0.2168	1
R_{22}	0.8671	$c_2 < 0.75$	0.2168	1	0.8671	$c_2 < 0.50$	0.2168	1
R_{23}	0.8671	$c_3 < 0.75$	0.2168	1	0.8671	$c_3 < 0.50$	0.3250	1

	Expr 5(W)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_{21}	0.9368	$c_1 < 0.50$	0.2342	1
R_{22}	0.8671	$c_2 < 0.50$	0.2168	2
R_{23}	0.8671	$c_3 < 0.50$	0.1746	3

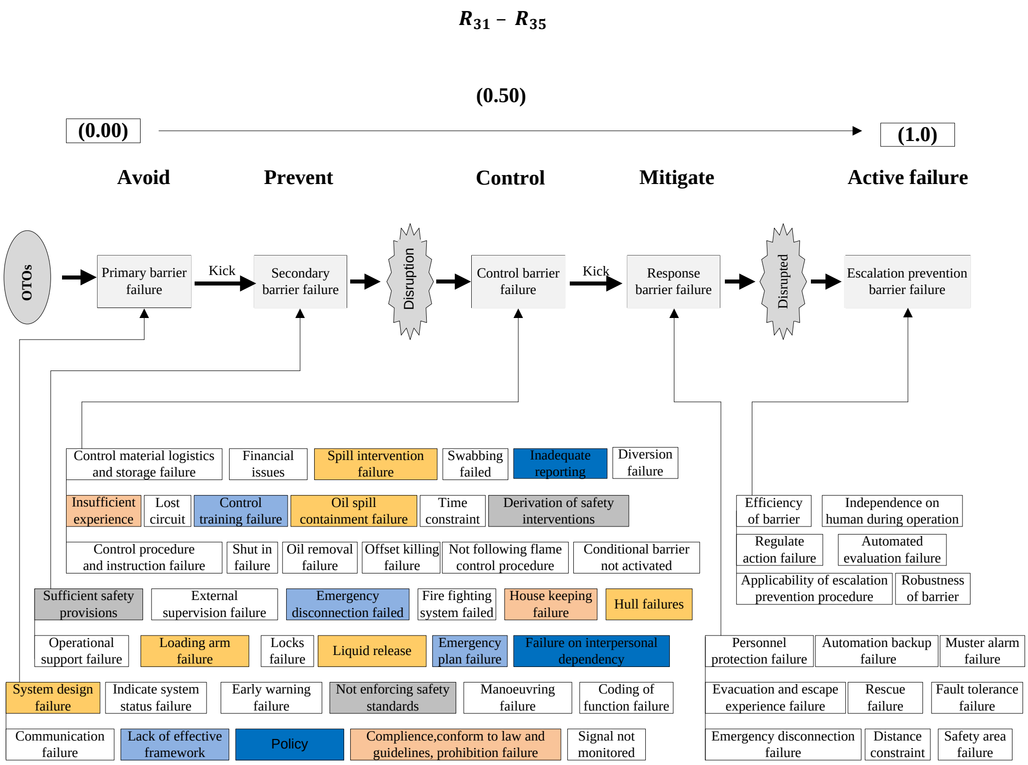


FIGURE A.3

Table A.5: $R31 - R35$

	Expr 1(C)				Expr 2(B)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_{31}	0.5882	$c_1 < 0.50$	0.1471	1	0.8671	$c_1 < 0.75$	0.2168	4
R_{32}	0.4385	$c_2 < 0.50$	0.2206	5	0.9368	$c_2 < 0.75$	0.2342	1
R_{33}	0.5882	$c_3 < 0.50$	0.1471	1	0.9368	$c_3 < 0.50$	0.2342	1
R_{34}	0.5882	$c_4 < 0.50$	0.1471	1	0.8671	$c_4 < 0.50$	0.2168	4
R_{35}	0.5882	$c_5 < 0.50$	0.1471	1	0.9368	$c_5 < 0.50$	0.2342	1

	Expr 3(D)				Expr 4(Q)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_{31}	0.6984	$c_1 < 0.75$	0.1746	1	0.9368	$c_1 < 0.75$	0.2342	1
R_{32}	0.5882	$c_2 < 0.75$	0.1471	2	0.8671	$c_2 < 0.75$	0.2168	3
R_{33}	0.5882	$c_3 < 0.50$	0.1471	2	0.9368	$c_3 < 0.50$	0.2342	1
R_{34}	0.5882	$c_4 < 0.50$	0.1471	2	0.8671	$c_4 < 0.50$	0.6984	4
R_{35}	0.5882	$c_5 < 0.50$	0.1471	2	0.6984	$c_5 < 0.50$	0.5882	5

	Expr 5(W)			
HFs	**u(x)**	**UtiSch$_+$**	**W**	**R**
R_{31}	0.7889	$c_1 < 0.50$	0.1973	4
R_{32}	0.8671	$c_2 < 0.50$	0.2168	3
R_{33}	0.7889	$c_3 < 0.50$	0.1973	4
R_{34}	0.9368	$c_4 < 0.50$	0.2342	1
R_{35}	0.9368	$c_5 < 0.50$	0.2342	1

A.3 Appendix 4C: Final Questionnaire and feedbacks for $UtiSch_+$ Model (Fig A.6 - A.20)

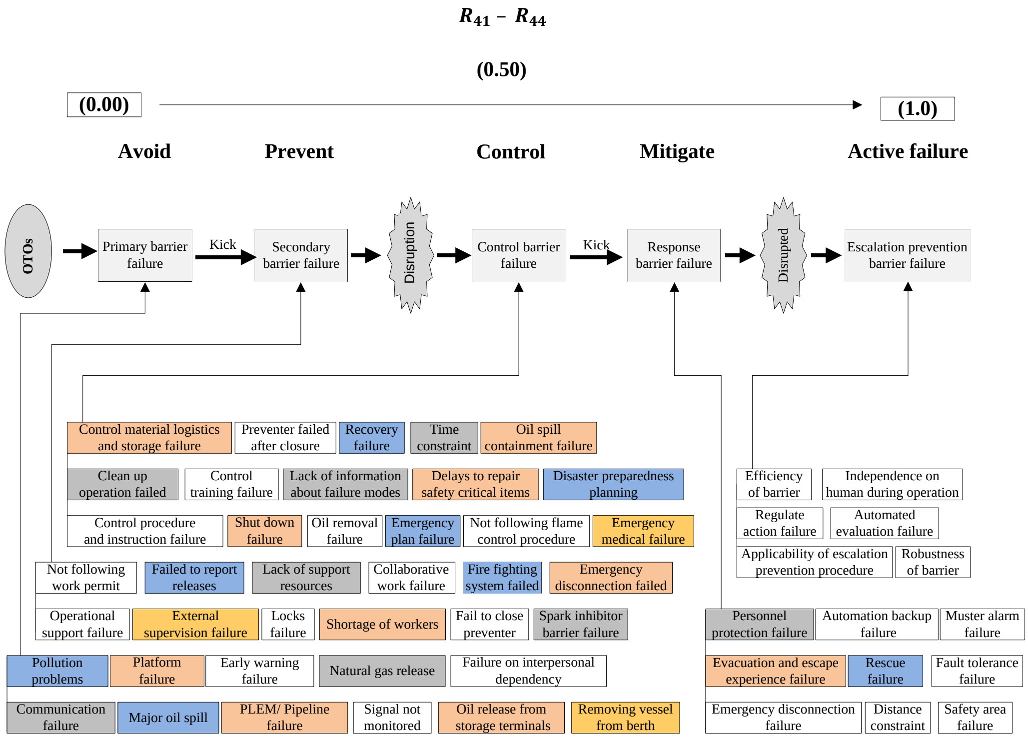


FIGURE A.4

A.4 Appendix 4D: Ethical Approval (Fig A.21)

A Resilience Modelling Approach on Oil Terminal Operations under High Uncertainty

Page 1

My name is Ambisire Y. Usman, I am carrying out a research project at Liverpool Logistics, Offshore and Marine (LOOM) Research Institute. You are being selected to take part in a research study. Before you decide it is important that you understand why the research is being done and what it involves. Please take time to read the following information. Ask us if there is anything that is not clear or if you would like more information. Take time to decide if you want to take part or not.

1. What is the purpose of the study?

The aim of the above research topic is to investigate the uncertainties of oil terminals operations in order to monitor, mitigate and control the operational risks. The analysis of these risks are capable of helping decision makers and stakeholders in oil terminal operations to critically evaluate risk attributes in order to rank them according to the outcome(s) leading to a disruption.The scope of this questionnaire considers as far as reasonable practicable offshore and onshore oil terminals operations platforms with satisfactory and very good safety standards. This research is student led, and in order to improve the quality and relevance of the research, the researcher would greatly appreciate your views by completing the provided questionnaire.

2.Do I have to take part?

No. It is up to you to decide whether or not to take part. If you do, you have consented to be part of this study. You are still free to withdraw at any time and without giving a reason. A decision to withdraw will not affect your rights/any future treatment/service you receive.

3.What will happen to me if I take part?

The questionnaires takes a maximum of 20 minutes of your time, however it is vital to the research development. Within the next 4 weeks, the researcher hopes to have collected significant data. The duration of this research is 36 months, although a significant amount of time have elapsed.

4.Are there any risks / benefits involved? No risk involved

5.Will my taking part in the study be kept confidential?

The information provided will be treated with confidentiality.

A tooltip is provided for further information to provide more clarity about the meaning of each question. Thank you for taking time to read through this introduction.

Page 2

Please indicate likelihood occurrence of hazard event: Man Related Hazards

	Very unlikely	Moderately unlikely	somewhat unlikely	Not sure	Somewhat likely	Moderately likely	Very likely
Major Accident Hazards (MAHs)	○	○	○	○	○	○	○
Duty Holders Error (DHE)	○	○	○	○	○	○	○
Personnel Issues (PI)	○	○	○	○	○	○	○
Sabotage	○	○	○	○	○	○	○
Indirect Contributing Factors (ICF)	○	○	○	○	○	○	○

Please indicate likelihood occurrence of hazard event: Machine Related Hazards

	Very Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat Likely	Moderately Likely	Very Likely
Maintenance Event Hazards (MEHs)	○	○	○	○	○	○	○
Equipment Failure (EF)	○	○	○	○	○	○	○
Well Control System Failure (WCSF)	○	○	○	○	○	○	○

FIGURE A.5

Please indicate likelihood occurrence of hazard event: Coordination and Correspondence Related Hazards

	Very Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat Likely	Moderately Likely	Very Likely
Platform Communication Misinterpretation (PCM)	○	○	○	○	○	○	○
Situation Awareness (SA)	○	○	○	○	○	○	○
Lack of proper Crew Interaction (PCI)	○	○	○	○	○	○	○

Please indicate likelihood occurrence of hazard event: Management Related Hazards

	Very Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat likely	Moderately likely	Very Likely
Human Resources Error (HRE)	○	○	○	○	○	○	○
Job Safety Rules and Regulation (JSRR)	○	○	○	○	○	○	○
Latent Error (LE)	○	○	○	○	○	○	○
Design Error	○	○	○	○	○	○	○
Business Risk (BR)	○	○	○	○	○	○	○

Please indicate likelihood occurrence of hazard event: Nature Related Hazards

	Very Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat Likely	Moderately Likely	Very Likely
Hydrologic (HH)	○	○	○	○	○	○	○
Seismic (SH)	○	○	○	○	○	○	○
Atmospheric (AH)	○	○	○	○	○	○	○
Epidemic	○	○	○	○	○	○	○

Please indicate the likelihood that you would engage in the described behaviour if you were to find yourself in that situation. Provide a rating in the questions below:

	Extremely Sad	--	-	+	++	+++	Excellent
Response mood (RM)	○	○	○	○	○	○	○

Please indicate the likelihood that you would engage in the described behaviour if you were to find yourself in that situation. Provide a rating in the questions below:

	Not Satisfied	--	-	+	++	+++	Satisfactory
Individual preference (IP)	○	○	○	○	○	○	○

Please indicate the likelihood that all the hazards may occur. Provide a rating in the questions below:

	Seldom Occur	--	-	+	++	+++	More Likely to Occur
Recurrent (RO)	○	○	○	○	○	○	○

Year(s) of experience on current job?

Figure A.6

TABLE A.6: $R_{41} - R_{44}$

Expr 1(C)

HFs	u(x)	UtiSch$_+$	W	R
R_{41}	0.6984	$c_1 < 0.75$	0.26191	1
R_{42}	0.6984	$c_2 < 0.75$	0.2619	1
R_{43}	0.6984	$c_3 < 0.75$	0.2619	1
R_{44}	0.6984	$c_4 < 0.50$	0.1746	4

Expr 2(B)

HFs	u(x)	UtiSch$_+$	W	R
R_{41}	0.7889	$c_1 < 0.75$	0.2958	2
R_{42}	0.6984	$c_2 < 0.75$	0.2619	3
R_{43}	0.8671	$c_3 < 0.75$	0.3250	1
R_{44}	0.8671	$c_4 < 0.50$	0.2168	4

Expr 3(D)

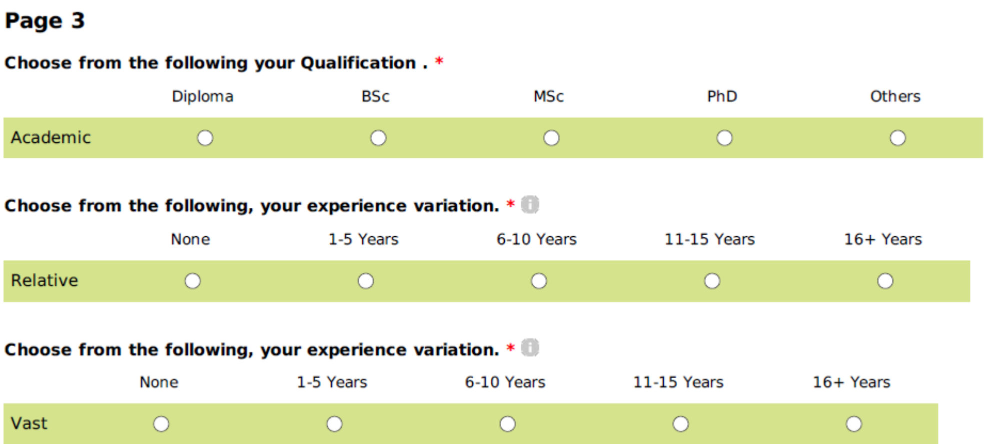
HFs	u(x)	UtiSch$_+$	W	R
R_{41}	0.6984	$c_1 < 0.75$	0.2619	1
R_{42}	0.6984	$c_2 < 0.75$	0.2619	1
R_{43}	0.6984	$c_3 < 0.75$	0.2619	1
R_{44}	0.6984	$c_4 < 0.50$	0.1746	4

Expr 4(Q)

HFs	u(x)	UtiSch$_+$	W	R
R_{41}	0.5882	$c_1 < 0.75$	0.2206	1
R_{42}	0.5882	$c_2 < 0.75$	0.2206	1
R_{43}	0.5882	$c_3 < 0.75$	0.2206	1
R_{44}	0.5882	$c_4 < 0.50$	0.1471	4

Expr 5(W)

HFs	u(x)	UtiSch$_+$	W	R
R_{41}	0.8671	$c_1 < 0.75$	0.3250	1
R_{42}	0.8671	$c_2 < 0.75$	0.3250	1
R_{43}	0.8671	$c_3 < 0.75$	0.3250	1
R_{44}	0.8671	$c_4 < 0.50$	0.2168	4


Page 3

Choose from the following your Qualification . *

	Diploma	BSc	MSc	PhD	Others
Academic	○	○	○	○	○

Choose from the following, your experience variation. *

	None	1-5 Years	6-10 Years	11-15 Years	16+ Years
Relative	○	○	○	○	○

Choose from the following, your experience variation. *

	None	1-5 Years	6-10 Years	11-15 Years	16+ Years
Vast	○	○	○	○	○

FIGURE A.7

A Resilience Modelling Approach on Oil Terminal Operations under High Uncertainty

1. Please indicate likelihood occurrence of hazard event: Man Related Hazards

Number of participants: 11

	Very unlikely (1)		Moderately unlikely (2)		somewhat unlikely (3)		Not sure (4)		Somewhat likely (5)		Moderately likely (6)		Very likely (7)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Major Accident Hazards (...	1x	10.00	2x	20.00	1x	10.00	-	-	3x	30.00	2x	20.00	1x	10.00	4.20	2.04
Duty Holders Error (DHE)	-	-	2x	20.00	1x	10.00	-	-	4x	40.00	2x	20.00	1x	10.00	4.60	1.71
Personnel Issues (PI)	1x	11.11	1x	11.11	1x	11.11	-	-	4x	44.44	1x	11.11	1x	11.11	4.33	1.94
Sabotage	2x	18.18	1x	9.09	-	-	1x	9.09	5x	45.45	-	-	2x	18.18	4.27	2.10
Indirect Contributing Fact...	1x	10.00	2x	20.00	1x	10.00	-	-	5x	50.00	-	-	1x	10.00	4.00	1.89

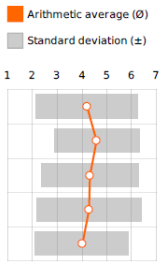


Figure A.8

2. Please indicate likelihood occurrence of hazard event: Machine Related Hazards

Number of participants: 10

	Very Unlikely (1)		Moderately Unlikely (2)		Somewhat Unlikely (3)		Not Sure (4)		Somewhat Likely (5)		Moderately Likely (6)		Very Likely (7)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Maintenance Event Hazar...	-	-	2x	20.00	2x	20.00	-	-	3x	30.00	2x	20.00	1x	10.00	4.40	1.78
Equipment Failure (EF)	-	-	3x	30.00	-	-	-	-	4x	40.00	1x	10.00	2x	20.00	4.60	1.96
Well Control System Failu...	-	-	3x	30.00	1x	10.00	1x	10.00	4x	40.00	1x	10.00	-	-	3.90	1.52

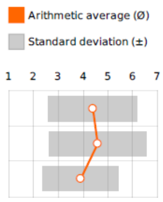


Figure A.9

3. Please indicate likelihood occurrence of hazard event: Coordination and Correspondence Related Hazards

Number of participants: 10

	Very Unlikely (1)		Moderately Unlikely (2)		Somewhat Unlikely (3)		Not Sure (4)		Somewhat Likely (5)		Moderately Likely (6)		Very Likely (7)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Platform Communication ...	-	-	-	-	2x	20.00	-	-	5x	50.00	2x	20.00	1x	10.00	5.00	1.25
Situation Awareness (SA)	-	-	1x	10.00	1x	10.00	-	-	6x	60.00	1x	10.00	1x	10.00	4.80	1.40
Lack of proper Crew Inter...	1x	10.00	2x	20.00	1x	10.00	-	-	4x	40.00	1x	10.00	1x	10.00	4.10	1.97

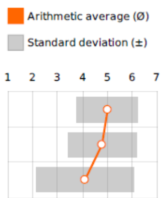


Figure A.10

4. Please indicate likelihood occurrence of hazard event: Management Related Hazards

Number of participants: 10

	Very Unlikely (1)		Moderately Unlikely (2)		Somewhat Unlikely (3)		Not Sure (4)		Somewhat likely (5)		Moderately likely (6)		Very Likely (7)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Human Resources Error (H...	1x	10.00	1x	10.00	1x	10.00	1x	10.00	3x	30.00	2x	20.00	1x	10.00	4.40	1.90
Job Safety Rules and Reg...	1x	10.00	2x	20.00	-	-	-	-	4x	40.00	2x	20.00	1x	10.00	4.40	2.01
Latent Error (LE)	-	-	3x	30.00	1x	10.00	1x	10.00	1x	10.00	3x	30.00	1x	10.00	4.30	1.95
Design Error	1x	10.00	2x	20.00	1x	10.00	1x	10.00	3x	30.00	1x	10.00	1x	10.00	4.00	1.94
Business Risk (BR)	1x	10.00	3x	30.00	-	-	-	-	2x	20.00	3x	30.00	1x	10.00	4.20	2.20

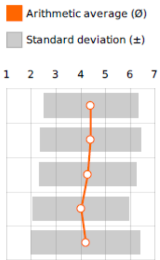


FIGURE A.11

5. Please indicate likelihood occurrence of hazard event: Nature Related Hazards

Number of participants: 10

	Very Unlikely (1)		Moderately Unlikely (2)		Somewhat Unlikely (3)		Not Sure (4)		Somewhat Likely (5)		Moderately Likely (6)		Very Likely (7)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Hydrologic (HH)	1x	10.00	1x	10.00	3x	30.00	1x	10.00	2x	20.00	1x	10.00	1x	10.00	3.90	1.85
Seismic (SH)	1x	10.00	1x	10.00	5x	50.00	-	-	2x	20.00	1x	10.00	-	-	3.40	1.51
Atmospheric (AH)	-	-	2x	20.00	3x	30.00	-	-	3x	30.00	2x	20.00	-	-	4.00	1.56
Epidemic	1x	10.00	1x	10.00	3x	30.00	1x	10.00	3x	30.00	1x	10.00	-	-	3.70	1.57

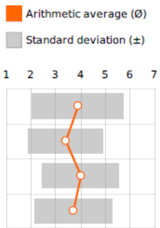


FIGURE A.12

6. Please indicate the likelihood that you would engage in the described behaviour if you were to find yourself in that situation. Provide a rating in the questions below:

Number of participants: 10

	Extremely Sad (1)		-- (2)		- (3)		+ (4)		++ (5)		+++ (6)		Excellent (7)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Response mood (RM)	-	-	1x	10.00	1x	10.00	2x	20.00	2x	20.00	2x	20.00	2x	20.00	4.90	1.66

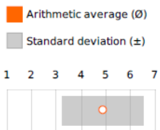


FIGURE A.13

7. Please indicate the likelihood that you would engage in the described behaviour if you were to find yourself in that situation. Provide a rating in the questions below:

Number of participants: 10

	Not Satisfied (1)		-- (2)		- (3)		+ (4)		++ (5)		+++ (6)		Satisfactory (7)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Individual preference (IP)	-	-	1x	10.00	1x	10.00	4x	40.00	2x	20.00	1x	10.00	1x	10.00	4.40	1.43

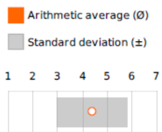


FIGURE A.14

8. Please indicate the likelihood that all the hazards may occur. Provide a rating in the questions below:

Number of participants: 10

	Seldom Occur (1)		-- (2)		- (3)		+ (4)		++ (5)		+++ (6)		More Likely to Occur (7)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Recurrent (RO)	2x	20.00	2x	20.00	1x	10.00	2x	20.00	3x	30.00	-	-	-	-	3.20	1.62

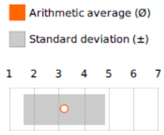


FIGURE A.15

9. Year(s) of experience on current job?

Number of participants: 10

- 20 years
- 10
- 11 years
- 12
- 20
- 15
- 20
- 20
- 21
- 11

FIGURE A.16

10. Choose from the following your Qualification . *

Number of participants: 10

	Diploma (1)		BSc (2)		MSc (3)		PhD (4)		Others (5)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Academic	3x	30.00	-	-	3x	30.00	4x	40.00	-	-	2.80	1.32

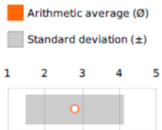


FIGURE A.17

11. Choose from the following, your experience variation. *

Number of participants: 10

	None (1)		1-5 Years (2)		6-10 Years (3)		11-15 Years (4)		16+ Years (5)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Relative	2x	20.00	1x	10.00	2x	20.00	2x	20.00	3x	30.00	3.30	1.57

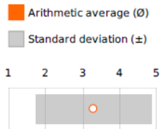


FIGURE A.18

12. Choose from the following, your experience variation. *

Number of participants: 10

	None (1)		1-5 Years (2)		6-10 Years (3)		11-15 Years (4)		16+ Years (5)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Vast	-	-	1x	10.00	1x	10.00	3x	30.00	5x	50.00	4.20	1.03

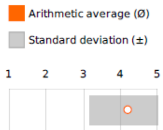


FIGURE A.19

Dear Ambisire,

With reference to your application for Ethical approval.

15/ENR/001 – Ambisire Usman, PGR - A resilience modelling approach on oil terminal operations under high uncertainties (Jun Ren)

Liverpool John Moores University Research Ethics Committee (REC) has reviewed the above application and I am pleased to inform you that ethical approval has been granted and the study can now commence.

Approval is given on the understanding that:

- any adverse reactions/events which take place during the course of the project are reported to the Committee immediately;
- any unforeseen ethical issues arising during the course of the project will be reported to the Committee immediately;
- the LJMU logo is used for all documentation relating to participant recruitment and participation eg poster, information sheets, consent forms, questionnaires. The LJMU logo can be accessed at http://www.ljmu.ac.uk/corporatecommunications/60486.htm

Where any substantive amendments are proposed to the protocol or study procedures further ethical approval must be sought.

Applicants should note that where relevant appropriate gatekeeper / management permission must be obtained prior to the study commencing at the study site concerned.

For details on how to report adverse events or request ethical approval of major amendments please refer to the information provided at http://www.ljmu.ac.uk/RGSO/RGSO_Docs/EC8Adverse.pdf

Please note that ethical approval is given for a period of five years from the date granted and therefore the expiry date for this project will be February 2020. An application for extension of approval must be submitted if the project continues after this date.

LIVERPOOL JOHN MOORES UNIVERSITY

Mandy Williams, Research Support Officer

(Research Ethics and Governance)
Research and Innovation Services
Kingsway House, Hatton Garden, Liverpool L3 2AJ
t: 01519046467 e: a.f.williams@ljmu.ac.uk

Figure A.20

Appendix B

Appendices for Chapter 5

B.1 Appendix 5A: BN Sensitivity Analysis (SA) results for Increment and Decrement of Parameter Variable Likelihood

	R1	R2	R11	R12	R13	R21	R22	R41	R42	R43
30%	0.3342	0.3323	0.3062	0.3061	0.3324	0.3214	0.3234	0.305	0.33	0.318
	0.2494	0.2472	0.2763	0.2762	0.25	0.2614	0.267	0.278	0.2564	0.277
20%	0.3191	0.3203	0.3013	0.3011	0.3183	0.3112	0.3122	0.3	0.3174	0.3014
	0.2632	0.2621	0.2813	0.281	0.2632	0.271	0.2691	0.281	0.2653	0.2813
10%	0.3051	0.3053	0.2963	0.2961	0.3054	0.3011	0.3021	0.296	0.3042	0.2964
	0.277	0.2762	0.2861	0.286	0.2771	0.281	0.28	0.286	0.2782	0.2864

B.2 Appendix 5B: The correlation between the SA of an increment and decrement parameter

	R1	R2	R42	R13	R22	R21	R43	R41	R12	R11
30%	0.3342	0.3323	0.33	0.3324	0.3234	0.3214	0.318	0.305	0.3061	0.3062
20%	0.2632	0.2621	0.2653	0.2632	0.2691	0.271	0.2813	0.281	0.281	0.2813
Minus 30%	0.2494	0.2472	0.2564	0.25	0.267	0.2614	0.277	0.278	0.2762	0.2763

B.3 Appendix 5C: Final Questionnaire for BN

Probability distribution over child nodes for compatibility parental configuration

Page 1

My name is Ambisire Y. Usman, I am carrying out a research project at Liverpool Logistics, Offshore and Marine (LOOM) Research Institute. I have contacted you before now, but I wish to obtain more information that is important for the success of this research. Please take time to read the following information. Ask us if there is anything that is not clear or if you would like more information. Take time to decide if you want to take part or not.

1. What is the purpose of the study?

The aim of the above research topic is to investigate the uncertainties of oil terminals operations in order to monitor, mitigate and control the operational risks. The analysis of these risks are capable of helping decision makers and stakeholders in oil terminal operations to critically evaluate risk attributes in order to rank them according to the outcome(s) leading to a disruption.The scope of this questionnaire considers as far as reasonable practicable offshore and onshore oil terminals operations platforms with satisfactory and very good safety standards. This research is student led, and in order to improve the quality and relevance of the research, the researcher would greatly appreciate your views by completing the provided questionnaire.

2.Do I have to take part?

No. It is up to you to decide whether or not to take part. If you do, you have consented to be part of this study. You are still free to withdraw at any time and without giving a reason. A decision to withdraw will not affect your rights/any future treatment/service you receive.

3.What will happen to me if I take part?

The questionnaires takes a maximum of 20 minutes of your time, however it is vital to the research development. Within the next 4 weeks, the researcher hopes to have collected significant data. The duration of this research is 36 months, although a significant amount of time have elapsed.

4.Are there any risks / benefits involved? No risk involved

5.Will my taking part in the study be kept confidential?

The information provided will be treated with confidentiality.

Thank you for taking time to read through this introduction.

FIGURE B.1

Page 2

Please indicate the likelihood occurrence for R1 and R2 required to populate the CPT for Coordination and correspondence related Hazard.

States : (a) High and (b) Low

R1 { Major Accident Hazards(MAHs)}
R2 { Duty Holders Error (DHE)}
CPT(Conditional Probability Table)

	Very Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat Likely	Moderately Likely	Very Likely
R1	○	○	○	○	○	○	○
R2	○	○	○	○	○	○	○

Page 3

Please indicate the likelihood occurrence for R11, R12 and R13 required to populate the CPT for Coordination and correspondence related Hazard.

States : (a) High and (b) Low

R21 { Maintenance Event Hazards(MEHs)}
R22 { Equipment failure (EF)}
R13 {Well control system failure(WCSF) }
CPT(Conditional Probability Table)

	Very Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat likely	Moderately Likely	Very Likely
R11	○	○	○	○	○	○	○
R12	○	○	○	○	○	○	○
R13	○	○	○	○	○	○	○

Figure B.2

Page 4

Please indicate the likelihood occurrence for R21, 22 and R23 required to populate the CPT for Coordination and correspondence related Hazard.

States : (a) High and (b) Low

R21 { Platform Communication Misunderstanding(PCM)}
R22 { Situation Awareness (SA)}
CPT(Conditional Probability Table)

	Very Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat likely	Moderately Likely	Very Likely
R21	○	○	○	○	○	○	○
R22	○	○	○	○	○	○	○

Page 5

Please indicate the likelihood occurrence for R41, R42, and R43 required to populate the CPT for Coordination and correspondence related Hazard.

States : (a) High and (b) Low

R41 { Hydrologic Hazard(HH)}
R42 { Atmospheric Hazard(AH)}
R43 {Seismic Hazard (SAI) }
CPT(Conditional Probability Table)

	Very Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat likely	Moderately Likely	Very Likely
R41	○	○	○	○	○	○	○
R42	○	○	○	○	○	○	○
R43	○	○	○	○	○	○	○

FIGURE B.3

Appendix C

Appendices for Chapter 6

C.1 Appendix 6A: Pairwise Comparison for all Attributes

TABLE C.1

Academic + Industrial (21+)

	RS_1	RS_2	RS_3	RS_4	RS_5	RS_6	RS_7	RS_8	RS_9	RS_{10}
RS_1	1	1/2	1	1	1	1	1/2	1	2	1/2
RS_2	2	1	1/2	1/2	1	1	1/2	1	2	1
RS_3	1	2	1	1	1	1	1/2	1	2	1/2
RS_4	1	2	1	1	1	1	1/2	1	2	1/2
RS_5	1	1	1	1	1	1	1/2	1	2	1
RS_6	1	1	1	1	1	1	1/2	1	1	1/2
RS_7	2	2	2	2	2	2	1	2	2	1
RS_8	1	1	1	1	1	1	1/2	1	2	1/2
RS_9	1/2	1/2	1/2	1/2	1/2	1	1/2	1/2	1	1/2
RS_{10}	2	1	2	2	1	2	1	2	2	1

TABLE C.2

Senior Manager (16-20)

	RS_1	RS_2	RS_3	RS_4	RS_5	RS_6	RS_7	RS_8	RS_9	RS_{10}
RS_1	1	1	4	1	1	1/2	1/2	7	3	4
RS_2	1	1	4	1	1	1/2	1/2	7	3	4
RS_3	1/4	1/4	1	1/3	1/3	1/4	1/4	4	1/2	1/2
RS_4	1	1	3	1	1	1/2	1/2	6	3	3
RS_5	1	1	3	1	1	1/2	1/2	6	2	2
RS_6	2	2	4	2	2	1	1	8	3	5
RS_7	2	2	4	2	2	1	1	8	3	5
RS_8	1/7	1/7	1/4	1/6	1/6	1/8	1/8	1	1/4	1/5
RS_9	1/3	1/3	2	1/3	1/2	1/3	1/3	4	1	3
RS_{10}	1/4	1/4	2	1/3	1/2	1/5	1/5	5	1/3	1

Table C.3

Senior Safety Manager (16-20)

	RS_1	RS_2	RS_3	RS_4	RS_5	RS_6	RS_7	RS_8	RS_9	RS_{10}
RS_1	1	3	1	2	2	1	3	3	3	3
RS_2	1/3	1	1/2	1/3	1/3	1/3	1/2	1	1/2	1/2
RS_3	1	2	1	2	2	1	3	3	3	3
RS_4	1/2	3	1/2	1	1	1/2	3	3	2	2
RS_5	1/2	3	1/2	1	1	1/2	3	3	2	2
RS_6	1	3	1	2	2	1	2	3	2	2
RS_7	1/3	2	1/3	1/3	1/3	1/2	1	2	1/2	1/2
RS_8	1/3	1	1/3	1/3	1/3	1/3	1/2	1	1/2	1/2
RS_9	1/3	2	1/3	1/2	1/2	1/2	2	2	1	1
RS_{10}	1/3	2	1/3	1/2	1/2	1/2	2	2	1	1

Table C.4

Junior Manager (11-15)

	RS_1	RS_2	RS_3	RS_4	RS_5	RS_6	RS_7	RS_8	RS_9	RS_{10}
RS_1	1	1/2	1	1	1	1/2	1/2	3	1/2	1/2
RS_2	2	1	2	1	2	1	1	3	1	1
RS_3	1	1/2	1	1/2	1	1/2	1/2	3	1/2	1/2
RS_4	1	1	2	1	1	1	1	3	1	1
RS_5	1	1/2	1	1	1	1/2	1/2	3	1/2	1/2
RS_6	2	1	2	1	2	1	1	3	1	1
RS_7	2	1	2	1	2	1	1	3	1	1
RS_8	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1	1/3	1/3
RS_9	2	1	2	1	2	1	1	3	1	1
RS_{10}	2	1	2	1	2	1	1	3	1	1

Table C.5

Consultant (20+)

	RS_1	RS_2	RS_3	RS_4	RS_5	RS_6	RS_7	RS_8	RS_9	RS_{10}
RS_1	1	1	1	1/2	3	2	3	2	3	1/2
RS_2	1	1	1	1/2	3	2	3	2	3	1/2
RS_3	1	1	1	1/2	3	2	3	2	3	1/2
RS_4	2	2	2	1	4	3	5	3	5	1
RS_5	1/3	1/3	1/3	1/4	1	1/2	2	1/2	2	1/4
RS_6	1/2	1/2	1/2	1/3	2	1	2	1	3	1/3
RS_7	1/3	1/3	1/3	1/5	1/2	1/2	1	1/2	1	1/5
RS_8	1/2	1/2	1/2	1/3	2	1	2	1	2	1/3
RS_9	1/3	1/3	1/3	1/5	1/2	1/3	1	1/2	1	1/5
RS_{10}	2	2	2	1	4	3	5	3	5	1

C.2 Appendix 6B: DMs Assessment of Attribute with respect to Alternatives

Table C.6

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	75	79	88	89	60	87	*expr 1*
	60	81	74	67	44	60	*expr 2*
Communication	77	75	83	86	47	56	*expr 3*
	81	45	80	93	50	53	*expr 4*
	50	24	93	59	11	32	*expr 5*
$M = \sum x \frac{1}{n}$	68.6	60.8	83.6	78.8	42.4	57.6	

Table C.7

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	75	77	79	65	30	74	*expr 1*
	71	82	78	62	43	62	*expr 2*
Automation	70	75	79	82	57	75	*expr 3*
	81	74	82	57	84	64	*expr 4*
	51	30	13	45	7	9	*expr 5*
$M = \sum x \frac{1}{n}$	69.6	67.6	66.2	62.2	44.2	56.8	

Table C.8

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	85	84	75	57	82	92	*expr 1*
	79	81	80	56	63	89	*expr 2*
System Functionality	86	78	79	45	68	73	*expr 3*
	70	23	81	59	93	82	*expr 4*
	51	30	13	45	7	9	*expr 5*
$M = \sum x \frac{1}{n}$	65.2	63.4	74.4	60.4	54.4	54.4	

Table C.9

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	74	77	78	60	22	85	*expr 1*
	93	94	62	51	61	21	*expr 2*
Cognitive Functioning	18	15	85	77	75	65	*expr 3*
	76	77	84	52	83	9	*expr 4*
	65	54	63	62	31	92	*expr 5*
$M = \sum x \frac{1}{n}$	65.2	63.4	74.4	60.4	54.4	54.4	

Table C.10

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	82	77	80	54	89	49	*expr 1*
	94	95	96	76	44	53	*expr 2*
Structural Integrity	18	12	77	47	83	60	*expr 3*
	79	77	76	49	64	69	*expr 4*
	85	38	72	94	80	20	*expr 5*
$M = \sum x \frac{1}{n}$	71.6	59.8	80.2	64	72	50.2	

Table C.11

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	11 btw 15	16 btw 20	16 btw 20	16 btw 20	1 btw 5	6 btw 10	*expr 1*
	6 btw 10	26 btw 30	21 btw 25	16 btw 20	26 btw 30	16 btw 20	*expr 2*
Facilities Proneness	6 btw 10	1 btw 5	11 btw 15	16 btw 20	21 btw 25	1 btw 5	*expr 3*
	6 btw 10	1 btw 5	11 btw 15	16 btw 20	6 btw 10	6 btw 10	*expr 4*
	6 btw 10	1 btw 5	11 btw 15	16 btw 20	6 btw 10	6 btw 10	*expr 5*
$M = \sum x \frac{1}{n}$	8	3	13	18	23	8	

Table C.12

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	11 btw 15	16 btw 20	21 btw 25	16 btw 20	11 btw 15	1 btw 5	*expr 1*
	16 btw 20	21 btw 25	41 btw 59	31 btw 40	21 btw 25	16 btw 20	*expr 2*
Modularity in Systems	16 btw 20	31 btw 40	16 btw 20	11 btw 15	21 btw 25	1 btw 5	*expr 3*
	16 btw 20	31 btw 40	41 btw 59	11 btw 15	16 btw 20	6 btw 10	*expr 4*
	16 btw 20	31 btw 40	41 btw 59	11 btw 15	21 btw 25	31 btw 40	*expr 5*
$M = \sum x \frac{1}{n}$	18	38	57	13	23	3	

Table C.13

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	26 btw 30	11 btw 15	31 btw 40	21 btw 25	16 btw 20	26 btw 30	*expr 1*
	26 btw 30	16 btw 20	21 btw 25	26 btw 30	31 btw 40	11 btw 15	*expr 2*
System Redundancy	31 btw 40	26 btw 30	11 btw 15	11 btw 15	31 btw 40	26 btw 30	*expr 3*
	26 btw 30	16 btw 20	21 btw 25	11 btw 15	11 btw 15	26 btw 30	*expr 4*
	26 btw 30	16 btw 20	21 btw 25	11 btw 15	31 btw 40	21 btw 25	*expr 5*
$M = \sum x \frac{1}{n}$	28	18	23	13	39	28	

Table C.14

Attribute	Alternatives						
	A_1	A_2	A_3	A_4	A_5	A_6	
	70	76	80	59	85	82	*expr 1*
	23	83	76	84	22	70	*expr 2*
High integrity Prevention	73	70	21	55	65	85	*expr 3*
	83	84	62	52	60	58	*expr 4*
	52	17	83	79	59	31	*expr 5*
$M = \sum x \frac{1}{n}$	60.2	66	64.4	65.8	58.2	65.2	

C.3 Appendix 6C:Final Questionnaire and Feedbacks for PT Assessment

Strategic Decision Support for Oil Terminal Operations (OTOs) Resilience Strategy Selection

Page 1

Dear Sir/Madam,

My name is Ambisire Y. Usman, a PhD student at Liverpool John Moores University. I have contacted you before now, but I wish to obtain more information that is important for the success of this research. Please take time to read the following information. Ask us if there is anything that is not clear or if you would like more information, see tooltip or rather please contact Tel: 07787053481, Email: A.Y.Usman@2012.ljmu.ac.uk

Strategic decision making is a vital aspect of my research project in order to monitor, mitigate and control operational hazards (i.e. Man, machine, Natural and Communication and correspondence related hazards during loading/ offloading operation at ship/terminal interference). The results of this study will be used to help decision makers and stakeholders in oil terminal operational platforms to rank the right alternative for a resilient system, capable of adapting, surviving and recovering from Complex marine operational accident, hazards or a major disruption. Because you are an expert, I am inviting you to participate in this research study by completing this survey.

The following questionnaire will takes a maximum of 20 minutes of your time. There is no compensation for responding nor is there any risk. In order to ensure that all information will remain confidential, please do not include your name. If you choose to participate in this project, please answer all questions as honestly as possible. Your participation in this project is entirely voluntary and you can withdraw from the study at any time.

1. The survey?

The questionnaire considers as far as reasonable practicable offshore and onshore oil terminals operations platforms with satisfactory and very good safety standards. This research is student led, and in order to improve the quality and relevance of the research, the researcher would greatly appreciate your views by completing the provided questionnaire.

2.Do I have to take part?

No. It is up to you to decide whether or not to take part. If you do, you have consented to be part of this study. You are still free to withdraw at any time and without giving a reason. A decision to withdraw will not affect your rights/any future treatment/service you receive.

3.What will happen to me if I take part?

The questionnaires takes a maximum of 20 minutes of your time, however it is vital to the research development. Within the next 2 weeks, the researcher hopes to have collected significant data. The duration of this project is 36 months, although I wish to complete this study in the next few months.

4.Are there any risks / benefits involved?

No risk involved

5.Will my taking part in the study be kept confidential?

The information provided will be treated with confidentiality.

Thank you for taking time to read through this introduction.

FIGURE C.1

Page 2

Give an appropriate percentage to each attribute to reflect its importance: Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

Policies Implementation

click on the provided intervals and drag where necessary.

(0) (100)

Communication

(0) (100)

Automation

(0) (100)

Systems' functionality

(0) (100)

Cognitive functioning

(0) (100)

Facilities Proneness

(0) (100)

Structural Integrity

(0) (100)

Modularity in Systems

(0) (100)

FIGURE C.2

System Redundancy

(0) [ ] (100)

High Integrity Prevention System

(0) [ ] (100)

Page 3

The following strategies should be adopted for resilience strategic decisions for these Alternatives: A1, A2, A3, A4, A5, A6 respectively.

A1 (see tooltip please)

	Satisfied and a Positive Prospect	Satisfied but a Nagetive prospect	Unsatisfied but a Positive Prospect	Unsatisfied and a Nagative Prospect
P1	○	○	○	○
F1	○	○	○	○
D3	○	○	○	○
T4	○	○	○	○
S5	○	○	○	○

A2 (see tooltip please)

	Satisfied and a Positive Prospect	Satisfied but a Negative Prospect	Unsatisfied but a positive Prospect	Unsatisfied and a Negative Prospect
K2	○	○	○	○
J2	○	○	○	○
V3	○	○	○	○
Q4	○	○	○	○
W5	○	○	○	○

Figure C.3

Feedbacks From Questionnaires

A3 (see tooltip please)

	Satisfied and a Positive Prospect	Satisfied but a Negative Prospect	Unsatisfied but a Positive Prospect	Unsatisfied and a Negative Prospect
B3				
E3				
L3				
R4				
U5				

A4 (see tooltip please)

	Satisfied and a Positive Prospect	Satisfied but a Negative Prospect	Unsatisfied but a Positive Prospect	Unsatisfied and a Negative Prospect
C4				
G4				
Y3				
X4				
Z5				

A5 (see tooltip please)

	Satisfied and a Positive Prospect	Satisfied but a Negative Prospect	Unsatisfied but a Positive Prospect	Unsatisfied and a Negative Prospect
H5				
O5				
M3				
N4				
IV				

Figure C.4

A6 (see tooltip please)

	Satisfied and a Positive Prospect	Satisfied but a Negative Prospect	Unsatisfied but a Positive Prospect	Unsatisfied and a Negative Prospect
i				
ii				
iii				
vi				
ix				

Page 4

Decision Maker Aspirations

Investment Cost would better be in the range of:

	1-5%	6-10%	11-15%	16-20%	21-25%	26-30%	31-40%	41-59%	60-80%	80-100%
A1										
A2										
A3										
A4										
A5										
A6										

Survival rate would better not be under? Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

A1 (P1, F1, D3, T4, S5)

Catastrophic Survive

A2 (K2, J2, V3, Q4, W5)

Catastrophic Survive

A3 (B3, E3, L3, R4, U5)

Catastrophic Survive

FIGURE C.5

A4 (C4, G4, Y3, X4, Z5)

Catastrophic — Survive

A5 (H5, O5, M3, N4, IV)

Catastrophic — Survive

A6 (i, ii, iii, vi, ix)

Catastrophic — Survive

Recovery rate would better not be under? Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

A1 (P1, F1, D3, T4, S5)

Not recovered — Recovery

A2 (K2, J2, V3, Q4, W5)

Not recovered — Recovery

A3 (B3, E3, L3, R4, U5)

Not recovered — Recovery

A4 (C4, G4, Y3, X4, Z5)

Not recovered — Recovery

A5 (H5, O5, M3, N4, IV)

Not recovered — Recovery

A6 (i, ii, iii, vi, ix)

Not recovered — Recovery

Figure C.6

Adaptability would better be over? Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

A1 (P1, F1, D3, T4, S5)

Anticipate Adapt to

A2 (K2, J2, V3, Q4, W5)

Anticipate Adapt to

A3 (B3, E3, L3, R4, U5)

Anticipate Adapt to

A4 (C4, G4, Y3, X4, Z5)

Anticipate Adapt to

A5 (H5, O5, M3, N4, IV)

Anticipate Adapt to

A6 (i, ii, iii, vi, ix)

Anticipate Adapt to

Defective rate would better not be over? Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

A1 (P1, F1, D3, T4, S5)

(0) (100)

A2 (K2, J2, V3, Q4, W5)

(0) (100)

A3 (B3, E3, L3, R4, U5)

(0) (100)

Figure C.7

A4 (C4, G4, Y3, X4, Z5)

(0) ______________________ (100)

A5 (H5, O5, M3, N4, IV)

(0) ______________________ (100)

A6 (i, ii, iii, vi, ix)

(0) ______________________ (100)

Page 5

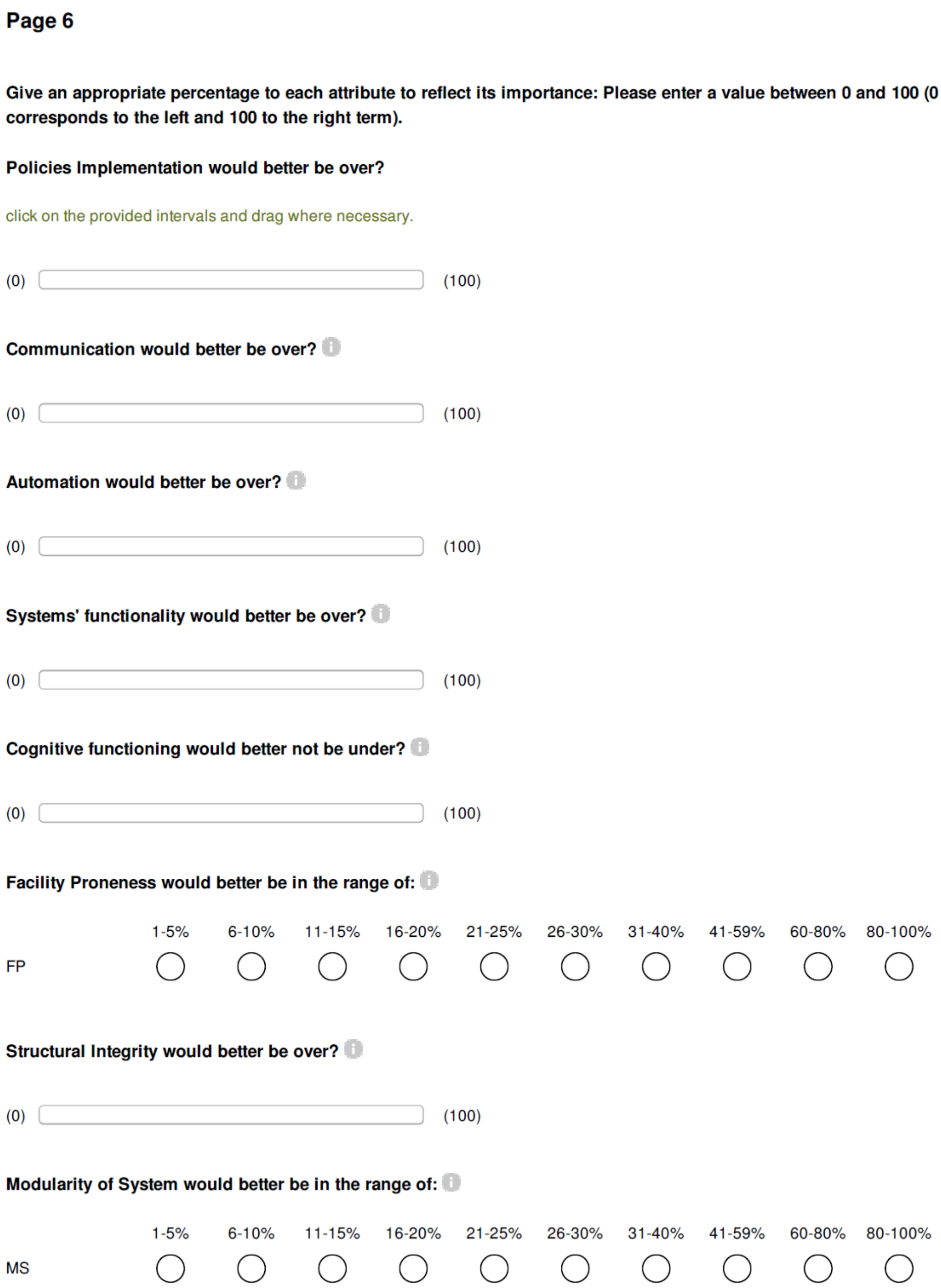
What is your current service time:

	Less than 5 years	6-10 years	11-15 years	16-20 years	More than 21 years
Senior Manager	○	○	○	○	○
Junior Manager	○	○	○	○	○
Academician	○	○	○	○	○
Academic and industrial experience	○	○	○	○	○

Academic qualifications?

- ○ Diploma
- ○ Bachelors
- ○ Masters
- ○ PhD
- ○ Professor

Figure C.8



Page 6

Give an appropriate percentage to each attribute to reflect its importance: Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

Policies Implementation would better be over?

click on the provided intervals and drag where necessary.

(0) (100)

Communication would better be over?

(0) (100)

Automation would better be over?

(0) (100)

Systems' functionality would better be over?

(0) (100)

Cognitive functioning would better not be under?

(0) (100)

Facility Proneness would better be in the range of:

	1-5%	6-10%	11-15%	16-20%	21-25%	26-30%	31-40%	41-59%	60-80%	80-100%
FP	○	○	○	○	○	○	○	○	○	○

Structural Integrity would better be over?

(0) (100)

Modularity of System would better be in the range of:

	1-5%	6-10%	11-15%	16-20%	21-25%	26-30%	31-40%	41-59%	60-80%	80-100%
MS	○	○	○	○	○	○	○	○	○	○

Figure C.9

Page 6

Give an appropriate percentage to each attribute to reflect its importance: Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

Policies Implementation would better be over?

click on the provided intervals and drag where necessary.

(0) (100)

Communication would better be over?

(0) (100)

Automation would better be over?

(0) (100)

Systems' functionality would better be over?

(0) (100)

Cognitive functioning would better not be under?

(0) (100)

Facility Proneness would better be in the range of:

	1-5%	6-10%	11-15%	16-20%	21-25%	26-30%	31-40%	41-59%	60-80%	80-100%
FP										

Structural Integrity would better be over?

(0) (100)

Modularity of System would better be in the range of:

	1-5%	6-10%	11-15%	16-20%	21-25%	26-30%	31-40%	41-59%	60-80%	80-100%
MS										

Figure C.10

Strategic Decision Support for Oil Terminal Operations (OTOs) Resilience Strategy Selection

1. Give an appropriate percentage to each attribute to reflect its importance: Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

   Policies Implementation

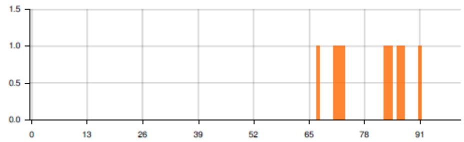
   Number of participants: 9

   0 = (0)
   100 = (100)

   Arithmetic average: 79.33

   Mean absolute deviation: 7.63

   Standard deviation: 8.59



2. Communication

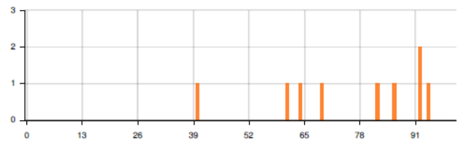
   Number of participants: 9

   0 = (0)
   100 = (100)

   Arithmetic average: 75.56

   Mean absolute deviation: 15.16

   Standard deviation: 18.32



3. Automation

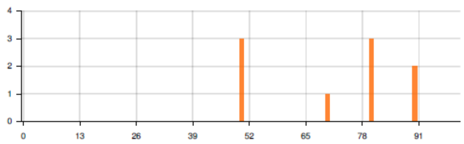
   Number of participants: 9

   0 = (0)
   100 = (100)

   Arithmetic average: 71.11

   Mean absolute deviation: 14.32

   Standard deviation: 16.91



4. Systems' functionality

   Number of participants: 9

   0 = (0)
   100 = (100)

   Arithmetic average: 80.00

   Mean absolute deviation: 13.33

   Standard deviation: 15.81

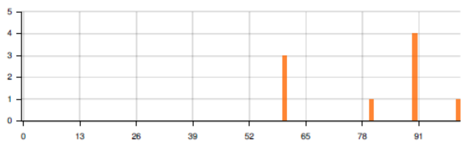


Figure C.11

5. Cognitive functioning

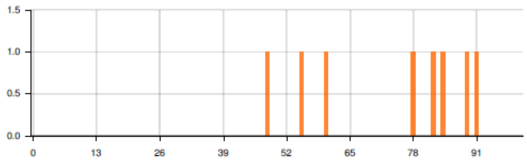
Number of participants: 8

0 = (0)
100 = (100)

Arithmetic average: 73.38

Mean absolute deviation: 14.28

Standard deviation: 16.58



6. Facilities Proneness

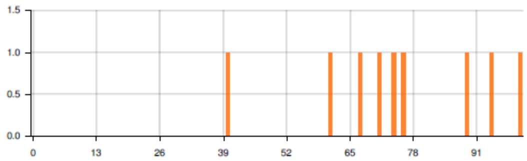
Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 74.67

Mean absolute deviation: 13.41

Standard deviation: 18.32



7. Structural Integrity

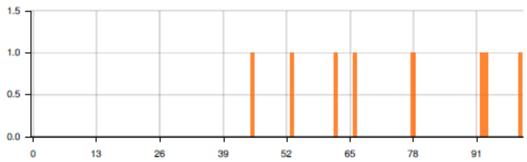
Number of participants: 8

0 = (0)
100 = (100)

Arithmetic average: 73.63

Mean absolute deviation: 17.13

Standard deviation: 20.23



8. Modularity in Systems

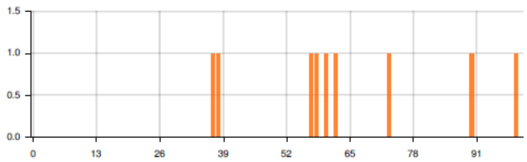
Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 63.78

Mean absolute deviation: 15.70

Standard deviation: 20.89



9. System Redundancy

Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 70.89

Mean absolute deviation: 14.79

Standard deviation: 17.96

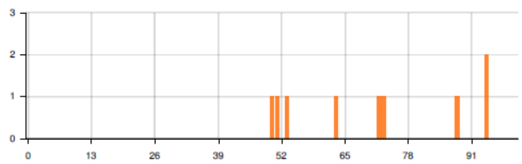


Figure C.12

10. High Integrity Prevention System

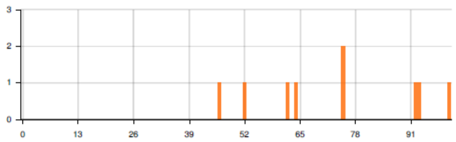
Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 73.22

Mean absolute deviation: 15.31

Standard deviation: 18.94

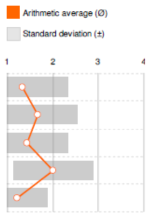


11. The following strategies should be adopted for resilience strategic decisions for these Alternatives: A1, A2, A3, A4, A5, A6 respectively.

A1 (see tooltip please)

Number of participants: 9

	Satisfied and a Positive Prospect (1)		Satisfied but a Nagetive prospect (2)		Unsatisfied but a Positive Prospect (3)		Unsatisfied and a Nagative Prospect (4)			
	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
P1	8x	88.89	-	-	-	-	1x	11.11	1.33	1.00
F1	5x	55.56	2x	22.22	2x	22.22	-	-	1.67	0.87
D3	7x	77.78	-	-	2x	22.22	-	-	1.44	0.88
T4	3x	33.33	3x	33.33	3x	33.33	-	-	2.00	0.87
S5	8x	88.89	-	-	1x	11.11	-	-	1.22	0.67



12. A2 (see tooltip please)

Number of participants: 8

	Satisfied and a Positive Prospect (1)		Satisfied but a Negative Prospect (2)		Unsatisfied but a positive Prospect (3)		Unsatisfied and a Negative Prospect (4)			
	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
K2	7x	87.50	1x	12.50	-	-	-	-	1.13	0.35
J2	5x	62.50	1x	12.50	2x	25.00	-	-	1.63	0.92
V3	6x	75.00	-	-	1x	12.50	1x	12.50	1.63	1.19
Q4	7x	87.50	-	-	1x	12.50	-	-	1.25	0.71
W5	5x	62.50	-	-	3x	37.50	-	-	1.75	1.04

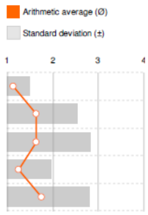
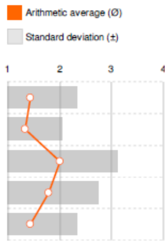


FIGURE C.13

13. A3 (see tooltip please)

Number of participants: 9

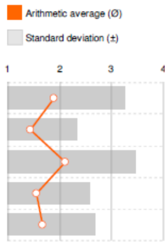
	Satisfied and a Positive Prospect (1)		Satisfied but a Negative Prospect (2)		Unsatisfied but a Positive Prospect (3)		Unsatisfied and a Negative Prospect (4)			
	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
B3	7x	77.78	-	-	2x	22.22	-	-	1.44	0.88
E3	7x	77.78	1x	11.11	1x	11.11	-	-	1.33	0.71
L3	4x	44.44	2x	22.22	2x	22.22	1x	11.11	2.00	1.12
R4	5x	55.56	1x	11.11	3x	33.33	-	-	1.78	0.97
U5	7x	77.78	-	-	2x	22.22	-	-	1.44	0.88



14. A4 (see tooltip please)

Number of participants: 9

	Satisfied and a Positive Prospect (1)		Satisfied but a Negative Prospect (2)		Unsatisfied but a Positive Prospect (3)		Unsatisfied and a Negative Prospect (4)			
	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
C4	6x	66.67	-	-	1x	11.11	2x	22.22	1.89	1.36
G4	7x	77.78	-	-	2x	22.22	-	-	1.44	0.88
Y3	5x	55.56	-	-	2x	22.22	2x	22.22	2.11	1.36
X4	6x	66.67	2x	22.22	-	-	1x	11.11	1.56	1.01
Z5	6x	66.67	-	-	3x	33.33	-	-	1.67	1.00



15. A5 (see tooltip please)

Number of participants: 8

	Satisfied and a Positive Prospect (1)		Satisfied but a Negative Prospect (2)		Unsatisfied but a Positive Prospect (3)		Unsatisfied and a Negative Prospect (4)			
	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
H5	5x	62.50	-	-	3x	37.50	-	-	1.75	1.04
O5	7x	87.50	-	-	1x	12.50	-	-	1.25	0.71
M3	5x	62.50	-	-	2x	25.00	1x	12.50	1.88	1.25
N4	7x	87.50	1x	12.50	-	-	-	-	1.13	0.35
IV	8x	100.00	-	-	-	-	-	-	1.00	0.00

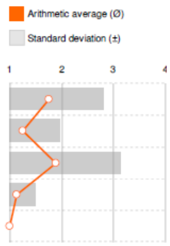
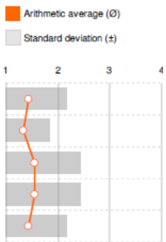


FIGURE C.14

16. A6 (see tooltip please)

Number of participants: 9

	Satisfied and a Positive Prospect (1)		Satisfied but a Negative Prospect (2)		Unsatisfied but a Positive Prospect (3)		Unsatisfied and a Negative Prospect (4)			
	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
i	6x	66.67	2x	22.22	1x	11.11	-	-	1.44	0.73
ii	6x	66.67	3x	33.33	-	-	-	-	1.33	0.50
iii	6x	66.67	1x	11.11	2x	22.22	-	-	1.56	0.88
vi	6x	66.67	1x	11.11	2x	22.22	-	-	1.56	0.88
ix	6x	66.67	2x	22.22	1x	11.11	-	-	1.44	0.73

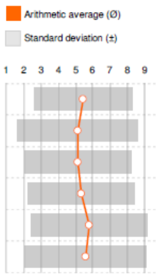


17. Decision Maker Aspirations

Investment Cost would better be in the range of:

Number of participants: 9

	1-5% (1)		6-10% (2)		11-15% (3)		16-20% (4)		21-25% (5)		26-30% (6)		31-40% (7)		41-59% (8)		60-80% (9)		80-100% (10)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
A1	-	-	2x	22.22	-	-	3x	33.33	-	-	-	-	1x	11.11	1x	11.11	2x	22.22	-	-	5.44	2.83
A2	2x	22.22	1x	11.11	1x	11.11	-	-	-	-	2x	22.22	-	-	-	-	3x	33.33	-	-	5.11	3.44
A3	-	-	3x	33.33	1x	11.11	1x	11.11	-	-	-	-	-	-	3x	33.33	1x	11.11	-	-	5.11	3.06
A4	1x	11.11	2x	22.22	-	-	1x	11.11	-	-	-	-	2x	22.22	2x	22.22	1x	11.11	-	-	5.33	3.08
A5	1x	11.11	1x	11.11	1x	11.11	1x	11.11	-	-	1x	11.11	-	-	1x	11.11	2x	22.22	1x	11.11	5.78	3.38
A6	1x	11.11	2x	22.22	1x	11.11	-	-	-	-	-	-	1x	11.11	2x	22.22	1x	11.11	1x	11.11	5.56	3.50



18. Survival rate would better not be under? Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

A1 (P1, F1, D3, T4, S5)

Number of participants: 9

0 = Catastrophic
100 = Survive

Arithmetic average: 63.22

Mean absolute deviation: 17.53

Standard deviation: 24.73

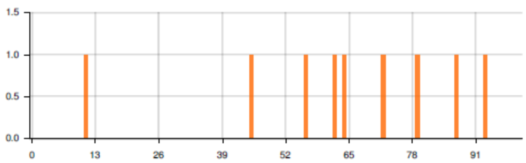


Figure C.15

19. A2 (K2, J2, V3, Q4, W5)

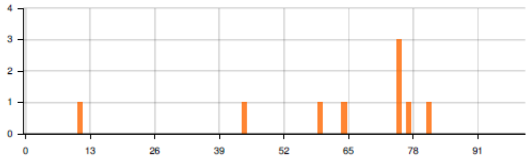
Number of participants: 9

0 = Catastrophic
100 = Survive

Arithmetic average: 62.33

Mean absolute deviation: 16.22

Standard deviation: 22.44



20. A3 (B3, E3, L3, R4, U5)

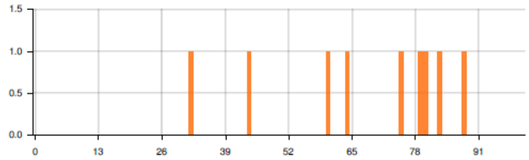
Number of participants: 9

0 = Catastrophic
100 = Survive

Arithmetic average: 67.22

Mean absolute deviation: 15.31

Standard deviation: 18.99



21. A4 (C4, G4, Y3, X4, Z5)

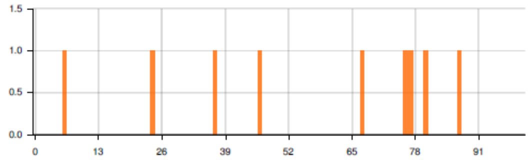
Number of participants: 9

0 = Catastrophic
100 = Survive

Arithmetic average: 55.56

Mean absolute deviation: 24.27

Standard deviation: 28.47



22. A5 (H5, O5, M3, N4, IV)

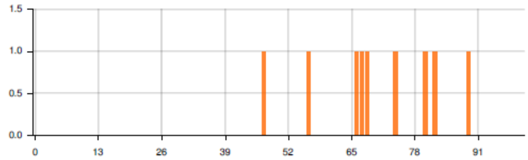
Number of participants: 9

0 = Catastrophic
100 = Survive

Arithmetic average: 69.89

Mean absolute deviation: 10.10

Standard deviation: 13.11



23. A6 (i, ii, iii, vi, ix)

Number of participants: 9

0 = Catastrophic
100 = Survive

Arithmetic average: 57.44

Mean absolute deviation: 14.17

Standard deviation: 20.65

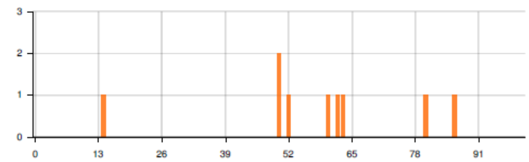


Figure C.16

24. Recovery rate would better not be under? Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

A1 (P1, F1, D3, T4, S5)

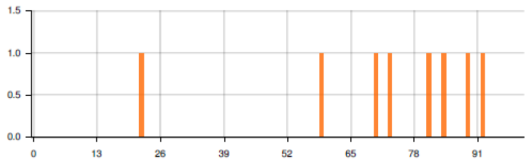
Number of participants: 8

0 = Not recovered
100 = Recovery

Arithmetic average: 71.25

Mean absolute deviation: 15.69

Standard deviation: 22.63



25. A2 (K2, J2, V3, Q4, W5)

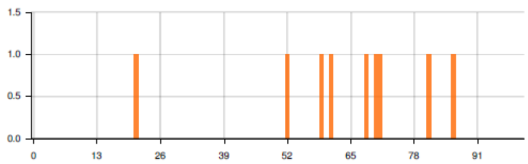
Number of participants: 9

0 = Not recovered
100 = Recovery

Arithmetic average: 63.22

Mean absolute deviation: 13.31

Standard deviation: 19.02



26. A3 (B3, E3, L3, R4, U5)

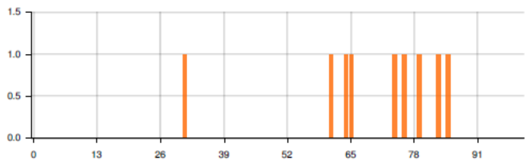
Number of participants: 9

0 = Not recovered
100 = Recovery

Arithmetic average: 68.67

Mean absolute deviation: 11.93

Standard deviation: 16.48



27. A4 (C4, G4, Y3, X4, Z5)

Number of participants: 9

0 = Not recovered
100 = Recovery

Arithmetic average: 58.44

Mean absolute deviation: 18.52

Standard deviation: 24.63

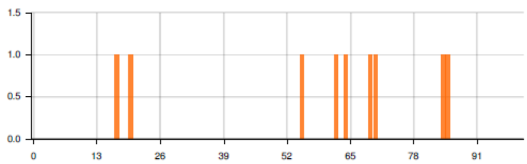


FIGURE C.17

28. A5 (H5, O5, M3, N4, IV)

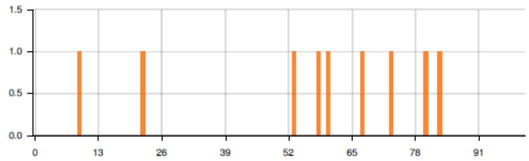
Number of participants: 9

0 = Not recovered
100 = Recovery

Arithmetic average: 56.11

Mean absolute deviation: 18.74

Standard deviation: 25.27



29. A6 (i, ii, iii, vi, ix)

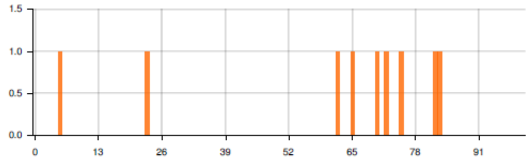
Number of participants: 9

0 = Not recovered
100 = Recovery

Arithmetic average: 59.67

Mean absolute deviation: 20.30

Standard deviation: 27.17



30. Adaptability would better be over? Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

A1 (P1, F1, D3, T4, S5)

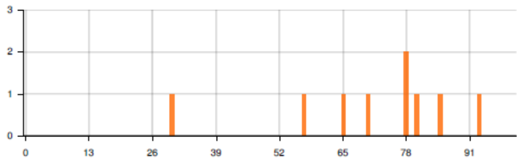
Number of participants: 9

0 = Anticipate
100 = Adapt to

Arithmetic average: 70.67

Mean absolute deviation: 13.48

Standard deviation: 18.61



31. A2 (K2, J2, V3, Q4, W5)

Number of participants: 9

0 = Anticipate
100 = Adapt to

Arithmetic average: 66.56

Mean absolute deviation: 10.49

Standard deviation: 13.60

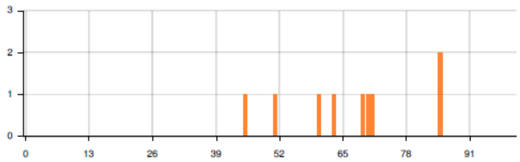


Figure C.18

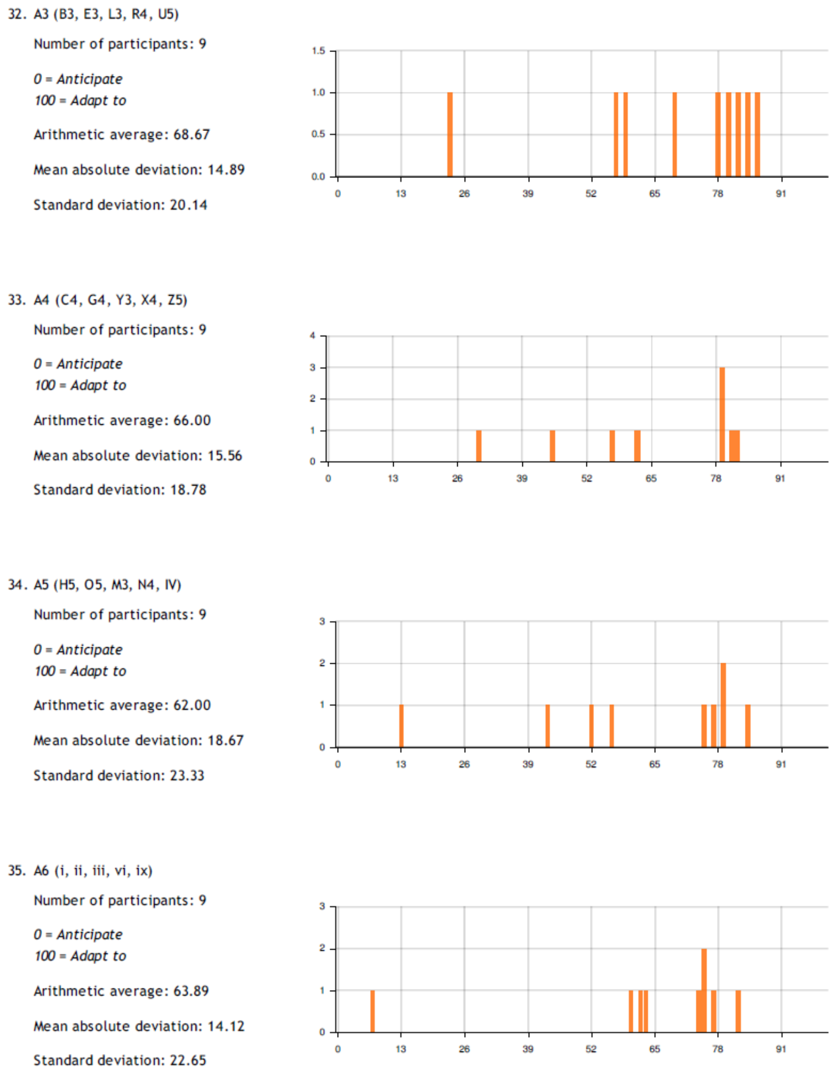

32. A3 (B3, E3, L3, R4, U5)
Number of participants: 9
0 = Anticipate
100 = Adapt to
Arithmetic average: 68.67
Mean absolute deviation: 14.89
Standard deviation: 20.14
33. A4 (C4, G4, Y3, X4, Z5)
Number of participants: 9
0 = Anticipate
100 = Adapt to
Arithmetic average: 66.00
Mean absolute deviation: 15.56
Standard deviation: 18.78
34. A5 (H5, O5, M3, N4, IV)
Number of participants: 9
0 = Anticipate
100 = Adapt to
Arithmetic average: 62.00
Mean absolute deviation: 18.67
Standard deviation: 23.33
35. A6 (i, ii, iii, vi, ix)
Number of participants: 9
0 = Anticipate
100 = Adapt to
Arithmetic average: 63.89
Mean absolute deviation: 14.12
Standard deviation: 22.65

Figure C.19

36. Defective rate would better not be over? Please enter a value between 0 and 100 (0 corresponds to the left and 100 to the right term).

A1 (P1, F1, D3, T4, S5)

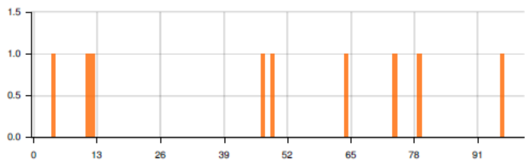
Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 48.44

Mean absolute deviation: 26.62

Standard deviation: 33.16



37. A2 (K2, J2, V3, Q4, W5)

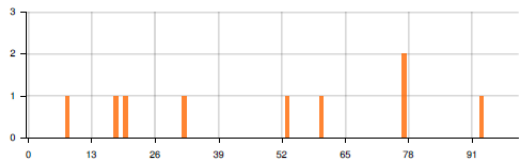
Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 48.67

Mean absolute deviation: 25.93

Standard deviation: 30.44



38. A3 (B3, E3, L3, R4, U5)

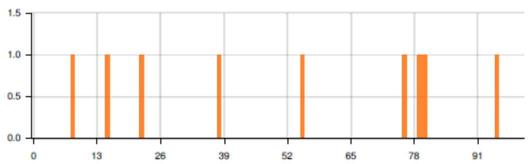
Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 52.00

Mean absolute deviation: 27.78

Standard deviation: 32.30



39. A4 (C4, G4, Y3, X4, Z5)

Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 55.44

Mean absolute deviation: 23.83

Standard deviation: 29.45

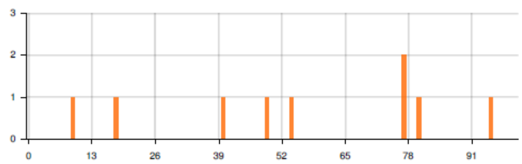


FIGURE C.20

40. A5 (H5, O5, M3, N4, IV)

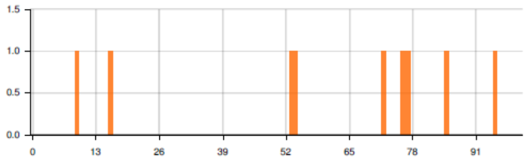
Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 59.67

Mean absolute deviation: 23.70

Standard deviation: 29.92



41. A6 (i, ii, iii, vi, ix)

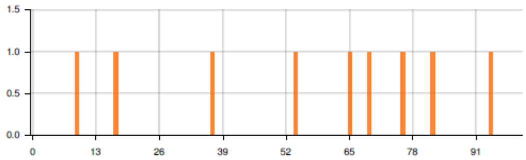
Number of participants: 9

0 = (0)
100 = (100)

Arithmetic average: 55.89

Mean absolute deviation: 23.68

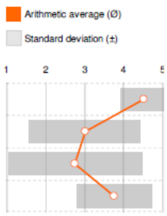
Standard deviation: 29.29



42. What is your current service time:

Number of participants: 9

	Less than 5 years (1)		6-10 years (2)		11-15 years (3)		16-20 years (4)		More than 21 years (5)			
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Ø	±
Senior Manager	-	-	-	-	-	-	2x	50.00	2x	50.00	4.50	0.58
Junior Manager	-	-	1x	50.00	-	-	1x	50.00	-	-	3.00	1.41
Academician	1x	25.00	1x	25.00	1x	25.00	-	-	1x	25.00	2.75	1.71
Academic and industrial ...	-	-	-	-	2x	50.00	1x	25.00	1x	25.00	3.75	0.96



43. Academic qualifications?

Number of participants: 9

- (0.0%): Diploma

- (0.0%): Bachelors

4 (44.4%): Masters

4 (44.4%): PhD

1 (11.1%): Professor

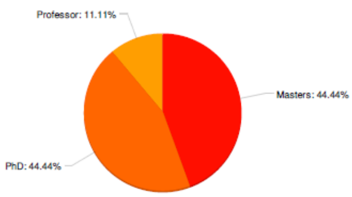


FIGURE C.21

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